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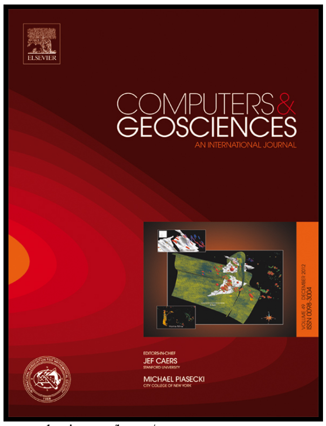

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Michele M.C. Carafa, Gabriele Tarabusi, Vanja Kastelic

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SHINE: Web Application for Determining the Horizontal Stress Orientation

Michele M. C. Carafa[1], Gabriele Tarabusi[2,3] , Vanja Kastelic[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia - INGV, Via dell'Arcivescovado 8, L'Aquila, Italy

[2]Istituto Nazionale di Geofisica e Vulcanologia – INGV, Via di Vigna Murata 605, Roma, Italy

[3]Università degli Studi di Ferrara, Dipartimento di Fisica e Scienze della Terra, Via Saragat 1, Ferrara, Italy

Corresponding Author:
Michele M.C. Carafa
Email: *michele.carafa@ingv.it;*

ABSTRACT

Interpolating the orientation of the maximum horizontal compressive stress with a well-established procedure is fundamental in understanding the present-day stress field. This paper documents the design principles, strategies and architecture of SHINE (http://shine.rm.ingv.it/), a web-based application for determining the maximum horizontal compressive stress orientation. The interpolation using SHINE can be carried out from a global database or from a custom file uploaded by the user. SHINE satisfies the usability requirements by striving for effectiveness, efficiency and satisfaction as defined by the International Organization for Standardization (ISO) covering ergonomics of human-computer interactions. Our main goal was to build a web-based application with a strong "outside-in" strategy in order to make the interpolation technique available to a wide range of Earth Science disciplines. SHINE is an easy-to-use web application with a straightforward interface guaranteeing quick visualization of the results, which are downloadable in several formats. SHINE is offered as an easy and convenient web service encouraging global data sharing and scientific research

collaboration. Within this paper, we present a possible use of SHINE, determining fault kinematics compatibility with respect to the present-day stress field.

Keywords: Present-day stress, web application, maximum horizontal compressive stress, horizontal stress interpolation, stress maps.

1. Introduction

An important measure of the deformation state within the Earth's crust is the orientation of the maximum horizontal compressive stress (SHmax), which is determined from different types of geophysical data, such as earthquake focal mechanisms, well bore breakouts, and fault-slip analysis. Several local, regional or world-wide SHmax databases are available; the most complete and detailed compilation of the contemporary crustal stress field is the World Stress Map Release 2008 (WSM08; Heidbach et al., 2008). The WSM08 database contains 21,750 quality-ranked stress data records using a constantly updated and refined scheme based on different measurement aspects, such as the accuracy or the depth (Zoback and Zoback, 1989; Sperner et al., 2003). Each stress data record has a quality factor assigned, ranging from A (the highest; standard deviations of data records within ±15°) to E (the lowest; standard deviations greater than ±40°). This quality ranking scheme is usually used as a reference standard for local compilations and stress indicators comparisons on a global scale.

Despite the large number of SHmax data sources, none of the available databases can estimate the state of stress for points not corresponding to the exact location of the SHmax data record. To obtain SHmax orientation for any point on the Earth's surface, it is necessary to perform an interpolation or smoothing procedure. Several such methods (Lee and Angelier 1994, Coblentz and Richardson 1995, Bird and Li, 1996; Mueller et al. 2003; Carafa and Barba 2013) have been proposed, but none of them have been implemented into a freely available web application. The scope of this paper is the description of SHINE (SH INtErpolation) web application, that calculates the SHmax orientation for any chosen point worldwide.

2. Theory

SHINE implements the Carafa and Barba (2013) interpolating method. We present the main aspects of this interpolation scheme, which modified and extended the clustered data analysis technique used by Bird & Li (1996). We refer the readers to the Carafa and Barba (2013) study for an extensive explanation of the method, while we only point out its main aspects.

Let x be a point where we wish to estimate the stress orientation, and let us select only the data points within a θ range (angular distance or searching radius), varying from 0° to 180°. Carafa and Barba (2013) conducted an extensive study to determine the probability of finding an azimuth at x, given one datum r located at range θ. The probability P^* can be expressed as:

$$P^*(k(\alpha_r)|\alpha_s) \equiv P^*(k_r|s) = P_0^* + P_1^* exp(-\theta/\theta_0), \tag{1}$$

where θ_0, P_0^* and P_1^* are constants determined from a nonlinear least-squares fit of the empirical probabilities determined on the global scale by Carafa and Barba (2013) using the WSM08 dataset.

After data selection, it is important to decluster the input data to avoid overweighting the local sources of stress characterized by numerous measurements (and data record entries) close together. In the method proposed by Bird and Li (1996) and Carafa and Barba (2013), a pair of stress data points r and s form a cluster if:

$$P^*(s|r) > \max_{\mathrm{i}=r,s} P^*(i|x)\,, \tag{2}$$

i.e. the conditional probability of r and s is larger than the highest possible conditional probability with respect to the interpolation point x. The opposite defines the two data records as independent clusters. In equation 2, we simplify the notation by using the indices r and s in place of azimuths α_r and α_s. We adopt such notation for the following equations. After clusters have been defined, a two-pass procedure is applied to find the SHmax orientation at x. In the first step, the clustered data are pre-averaged, resulting in a set of fully independent SHmax orientations. In the second step, the SHmax orientation is interpolated on x. The pre-averaged values of the clustered data are obtained in the first step using two-point conditional probability distributions, assuming no azimuthal dependence between the data. The SHmax orientation of the cluster is assigned to its geographical centre.

In the next step, the SHmax orientations are interpolated on x. To identify the now fully independent orientations, identified as “clusters” and labelled as c regardless of whether they arose from pre-averaging, we calculate the probability for each trial azimuth, defined by an integer value of k_x ($k_x = 1, \ldots, 60$ with 3° bins), as:

$$\boldsymbol{P}^*_{\boldsymbol{N_c}}(\boldsymbol{k_x}) = \frac{\prod_{c=1}^{N_c} \boldsymbol{P}^*(\boldsymbol{k_x}|\boldsymbol{c})}{\sum_{j=1}^{60} \prod_{c=1}^{N_c} \boldsymbol{P}^*(\boldsymbol{j_x}|\boldsymbol{c})}, \tag{3}$$

where N_c is the number of clusters within the θ_n range (Eq. 2). The maximum likelihood estimate of the SHmax orientation at the interpolation point x is:

$$\alpha_x = \left(k_x - \tfrac{1}{2}\right) 3°, \tag{4}$$

where k_x is the integer that maximises $P^*_{N_c}(k_x)$ in Eq. (10). The 90% confidence interval $\Delta\alpha$ is determined as:

$$\int_{\alpha_x-\Delta\alpha}^{\alpha_x+\Delta\alpha} \boldsymbol{p^*_N(\alpha'_x mod 180°)\, d\alpha'_x = 0.90}, \qquad (5)$$

where $p^*_N(\alpha'_x mod 180°)$ is the functional form corresponding to the discrete $P^*_N(k_x)$ and "mod" is the remainder of the integer division used to account for the periodicity of α'_x. This procedure allows the uncertainties due to data scattering to propagate into the posterior uncertainties $\Delta\alpha$.

A well-defined SHmax orientation, especially at the local scale, is ensured by three factors: 1) a relative high cluster number N_c, 2) a narrow 90% confidence interval $\Delta\alpha$ and 3) a small relative range (or searching radius). These three are the most important factors in obtaining a SHmax orientation for any chosen point on the Earth's surface. Therefore, they need to be entered in the SHINE engine and carefully set by the user.

3. WEB site design principles, strategies and architecture

3.1. Designing principles for SHINE website

The main goal of SHINE website (http://shine.rm.ingv.it/) is to determine SHmax at any chosen interpolation point worldwide using the approach of Carafa and Barba (2013) (Figure 1). A distinct advantage of SHINE is the integration of significant amount of information and theory in a single package which provides all users with an advanced analysis tool regardless of their individual theoretical background. We follow the guidelines prescribed by Part 11 of the ISO 9241 standard (BSI, 1998) to define SHINE usability as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use."

For this application we defined:

- Effectiveness as the ability of researchers to obtain SHmax results from SHINE;
- Efficiency as a minimum amount of time consumed by researchers using SHINE in relation to the accuracy and completeness of SHmax results;
- Satisfaction as the "ease in operation" for researchers to apply SHINE as a useful research tool.

Our primary goal for SHINE was to optimize its usability by researchers who have the need for effective and efficient means to evaluate the intraplate stress field. In order to address this aim we contacted seven geosciences researchers as a representative sample of SHINE website users and involved them in the prototype development. They tested several versions of the web interface and provided valuable feedback. Consequently we made the website design and development process iterative to optimize the researchers' feedback.

During SHINE development, we followed the suggestions of Stone et al. (2010) for the main aspects of web design. The design principles for SHINE are based around the HOME RUN idea, which stands for High quality content, Often updated, Minimal download time, Ease of use, Relevant to user's needs, Unique to the online medium, and Net-centric corporate culture (Nielsen, 2000). A HOME RUN is, in other words, a criterion that SHINE had to pass at every stage to meet the users' requirements. Two SHINE examples of applying HOME RUN principles are: 1) web pages were designed to be read quickly and easily with a short loading time that was obtained by using no more graphics than necessary; and 2) SHINE works with any web browser.

3.2. Design strategies

During SHINE prototyping, the test-users/researchers needed to carefully analyze the interpolation scheme of Carafa and Barba (2013) and asked for detailed explanations on SHINE functionality. For this reason we adopted the strategy of building SHINE start page (Figure 2). We used it to meet the users' expectation for sufficient explanation of SHINE's basic characteristics. Moreover, the start page provides an opportunity to suggest additional stress tensor information, literature and web pages.

The core of SHINE website is the form on the input page, which opens once the user starts the session. We carefully considered design strategies for this part of the application because it is the user's main interaction with SHINE. We decided to create the interaction with an "outside-in" strategy, thus building SHINE from the perspective of a researcher not used to frequently interpolate data. Consequently, our strategic choice was a form composed of several sections in one long web page. To further help the users, each section and sub-section of the web form has an on-line help on a semi-transparent java script overlay, which can be opened, closed or moved within the web page and guides the user throughout the selection procedure.

In the web form, we used drop down lists and sliders with fixed step values and a geographical interface for selecting and displaying the input. We believe that this strategy guides the user and minimizes the possibility of error in choosing the input parameters. At the same time, the possibility of uploading custom SHmax data and selecting scattered points to perform the calculation allows for a high level of input data customization.

All the labels of the form are right or top-aligned. Wroblewki (2010) explained that forms with this mixed alignment of labels take longer to complete because they require a number of eye fixations to parse. We intentionally decided to use label mixing, because we strive for slower completion to increase the awareness of researchers filling in the form. In fact, during the prototyping phase, we observed that higher completion time obliged researchers to slow down and carefully consider each help text associated with each field of the form. For the help text, we needed to choose between dynamic help systems that can be automatically triggered/accessed by the user or always visible help text. Because we ask for complex inputs, we always chose the visible help text so users can benefit from it in every step.

To assure correctness of all the input parameters and to avoid duplicate entries throughout the input selection, we repeatedly used text messages that served as acceptance confirmation of the selected input parameters. After filling in the input parameters and confirming the form, the actual interpolation process takes place on the host server. A dense interpolation point grid selection implies considerable calculation time and a long wait time for the results. Nah (2004) showed that after 50 seconds of waiting, 90% of web users leave a webpage despite the presence of a feedback bar. Considering this observation, the user's awareness of SHINE's calculation complexity and feedback messages appearing before the results visualization, we set SHINE user tolerable wait time to 50 seconds. Currently (September 2014), the server hosting SHINE calculates 1000 SHmax orientations in 50 seconds; consequently, we forced the upper limit of the number of interpolation points to be 1000. In the future, we expect to raise this limit based on the computational performance of the SHINE hosting server and its related software. Because the calculation step takes time to complete and this fact has to be appropriately communicated to increase the user's wait time tolerance, we inserted a feedback bar that indicates the progress of calculations.

Our decision was to present the SHmax output through a graphical interface and to furnish a link for downloading the SHINE results as a zipped folder containing several GIS-supported formats.

3.3. Server Platform and programming languages

Currently SHINE website is developed in HTML and hosted on a 64-bit computer/server with PHP (vers. 5.1 or above), GNUWIN (http://gnuwin32.sourceforge.net), FWTools (http://fwtools.maptools.org/) and HTTP services. The server-side procedures are developed in the PHP language, the client-side in JavaScript language, using specific features of the jQuery (http://jquery.com/) and Dojo (http://dojotoolkit.org/) libraries and Google Maps API (https://developers.google.com/maps/) to provide a geographic interface. The actual calculation part of the application starts on the hosting server through the PHP. Two executables, developed with the Autoit software (http://www.autoitscript.com), analyze the uploaded TXT files and create geographic files in Mapinfo Professional MID/MIF format and the KML language (https://developers.google.com/kml/documentation/), which is an XML notation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers. A command line procedure uses FWTools to convert the MID/MIF files into Esri Shapefile format.

4. *HOW TO: SHINE functionality*

SHINE can be accessed at http://shine.rm.ingv.it/. After reading the basic description and functions of SHINE interpolation on the start page, the user can start his/her own session by pressing the "START SESSION" button. The user is redirected to the input page, which consists of the input form divided into three sections: "Data selection", "Geographical setting" and "Strategic parameters".

When opening the input page, three objects are displayed (Figure 2):

1) the "Data selection" section;
2) an interactive map based on Google Maps; and
3) a grey box at the top of the page, which, in real time, shows the choices made by the user during the form compilation. The "Restart" button on the right side of the grey box allows the user, at any time, to return to the home page, resetting the whole work session.

The interactive map is centred on L'Aquila city (central Italy). This is the authors' choice because they are currently paid by a project that started after the 2009 L'Aquila earthquake and studies Central Apennines neotectonics and seismic hazard. The interactive map allows the user to move anywhere across the world with the "PAN" command, as provided by GoogleMaps.

4.1. "Data selection": editing and loading SHmax input dataset

In the "Data selection" section, the user decides which dataset to use when performing the SHmax interpolation (Figure 3). By choosing"WSM08", the user decides to use the World Stress Map, release 2008 (Heidbach et al. 2008) (only A-, B- and C- quality data records); by choosing "FILE", the user decides to upload his/her own file (max 40000 data entries allowed) containing the SHmax orientation input dataset. After uploading their own file, the button "check file" performs a series of checks on the size, row number and file structure to ensure that the input file corresponds to the specifications required by the interpolation scheme. If all the requirements are present in the input file, the "PLOT" button appears. After pressing the “PLOT” button, SHINE plots the chosen dataset (WSM08 or custom file) on the interactive map, and the user gets to inspect the chosen input.

4.2. “Geographical setting”: choosing the study area

In the “Geographical setting” section, the user gets to decide whether to perform the interpolation calculation on a regular grid of points ("Regular area selection") or on a custom user-imported point file ("Custom input file").

By choosing "Regular area selection" (Figure 4), the user needs to set the limits of the study area by filling the "Longitude" and "Latitude" fields manually in a -180/180° and -90/90° convention, respectively, or by dragging and resizing the red rectangle displayed on the interactive map. After the area bounds definition, the user selects the desired grid spacing from the proposed values in the drop-down list. If the grid spacing selection has been performed appropriately, the "Check grid density" button is enabled. If the number of nodes is less than or equal to the upper limit, (currently set to 1000), the "PLOT" button is enabled, otherwise the user has to lower the grid resolution or to reduce the dimensions of the investigation area to be within the current maximum of 1000 interpolation points.

By choosing "Custom input file", the user decides to perform the interpolation on a custom set of geographical points saved in a properly structured input file. The proper structure is shown in an example file linked to the Custom input file" selection. The button "check file" starts a security check procedure before uploading the user file to the server. At this stage, if all checks are passed, the "PLOT" button is enabled, otherwise it is necessary to follow the warning indications displayed on the screen.

The final step for both the “Regular area selection” or the “Custom input file" choice is the visualization of the chosen interpolation points. This step occurs when the user presses the "PLOT" button and chosen interpolation points are displayed as red crosses on the geographical map.

4.3. “Strategic Parameters”: deciding the interpolation scheme

In this section (Figure 5), the user needs to properly set the three main parameters of the interpolation scheme of Carafa and Barba (2013) (see Section 2):

- “Searching radius": by moving the slider, the user sets the data-points maximum distance from the interpolation point. Data points not exceeding the user-determined distance are used in the interpolation scheme. Because the method of Carafa and Barba (2013) determines the probabilities on concentric annuli, the slider is set to fixed distances (corresponding to the external limit of the selected annulus). A suggested annulus value for local scale interpolation is two or three (corresponding to 58-96 km); a suggested annulus value for interpolation on a wider scale is six to eight (228-327 km).
- "Minimum cluster" slider: it sets the minimum number of clusters (not data) surrounding the interpolation point to accept the SHmax result as "stable". Suggested value is three.

- "90% confidence limits": by moving the slider, the user decides the maximum permissible uncertainty. Any SHmax input value with confidence level greater than the one set, is not considered stable or representative. A suggested value is between 30° and 50°.

After completing the “Strategic parameters” section, the user needs to click the "I agree and move forward" button to proceed with the calculation. A dialog box appears displaying all of the choices made by the user so far. At this step, two options are available:

- "Cancel": SHINE redirects the user to the "Strategic parameters" section;
- "OK": the user confirms all previous choices and the calculation procedure starts. After selecting the "OK" option, in a few seconds (depending on the number of interpolation points and the average data records falling inside the searching radius of each interpolation point) the results page opens and the stress map is presented.

4.4. Stress map visualization

On the results page, four main elements are displayed (Figure 6):

- a grey box at the top of the page displaying the choices made by the user in the input form;
- a Google Maps based graphical interface displays two distinct levels: the SHmax input dataset chosen by the user (black colored lines), while the interpolation calculation results (output layer) are presented in red for the maximum horizontal stress orientation values calculated for the points selected by the user.

By clicking on the tooltip (balloon) located at each interpolation point in the output layer, the user can read the geographic coordinates, SHmax orientation (in degrees) and related quantities (90% confidence level bounds, searching radius, cluster number and used stress-data records).

- "Download results in zip format" link allows the user to download results in different formats (including several spatial data formats supported by GIS software).
- - The “click here for a new interpolation/stress map” button redirects the user to the SHINE starting page.

5. *Application of SHINE in testing active fault's slip compatibility within the present-day stress regime*

In the study of active faults, an important parameter to consider is the compatibility of the recognized fault with respect to the present-day stress field. Geological methods, paired with geomorphic studies, provide data for the fault's existence, but may not be sufficient in evaluating its activity. In cases of lack of seismicity and where rocks or sediments do not provide a record of recent fault-related deformation, the interpolated local-stress orientation can provide important constrain for possible recent slip activity along the fault. SHINE provides a valuable tool for the calculation of the SHmax orientation along active faults. Notably, to avoid the potential for circular reasoning, the dataset used in the fault parameterization (e.g., fault-slip analysis or earthquake focal mechanisms) should not be the same dataset as the one used in SHINE to interpolate SHmax orientations.

We choose Slovenia as a case study to examine and compare the observational data on active faults with the SHINE-derived local stress field. The country is an amalgam of several structure units (i.e. Southern Alps, External Dinarides, and Panonian Basin). The predominant geometry of the active faults is NW-SE oriented trend, towards NE dipping and dextral strike-slip kinematics (Placer, 1998; Poljak, 2000; Kastelic et al., 2008; Kastelic and Carafa, 2012; Basili et al., 2013). This trend is particularly strong in the western and central part of the country, while the eastern sectors show the prevalence of the Mid-Hungarian tectonic imprint, with a NE-SE trend (Vrabec and Fodor, 2006). Slovenia has been seismically active during historic and instrument observation periods with frequent M>5 earthquakes (Živčić, 2010; Stucchi et al., 2013). To carry out SHINE analysis on fault compatibility, we utilized the European database on the European database of seismogenic faults - EDSF (Basili et al., 2013). From this database we extracted the seismogenic faults in Slovenia and its close vicinity. In total, we considered 42 seismogenic faults and their corresponding 258 interpolation points (representing sections of faults with slight changes in their geometrical parameters) that were fully parameterized in their geometric and kinematic characteristics. We assumed that the strike, dip and rake assigned to each interpolation point are defined by a uniform probability distribution in the minimum - maximum interval of the corresponding EDSF's fault characteristics.

We employed a forward analysis of the fault orientation data to evaluate the optimal theoretical stress orientation (bounded by the 90% confidence interval) corresponding to the slip on each fault. We applied the Wallace-Bott hypothesis that predicts the motion on a (fault) surface to be parallel to the direction of the greatest resolved shear stress. The underlying assumptions of this hypothesis are planar (fault) surfaces, rigid hosting rock, uniform stress state and absence of stress perturbations or rotations along the plane. Following Yamaji (2007), we assumed that this hypothesis is valid for newly forming and reactivated fault planes. Thus the shear τ and the normal vector σ_N

components of a stress tensor T acting on a fault plane are (e.g., Angelier, 1994; Xu, 2004; Alberti 2010):

$$\tau = \sigma - \sigma_N \quad (6)$$

$$\sigma_N = n^t(n\sigma) \quad (7)$$

where σ is the stress vector, n is the normal unit vector and n^t is the transpose.

Although the Wallace-Bott hypothesis is a simplification of the underlying rock mechanics, its validity has been shown by field observations and empirical demonstrations (e.g., Zoback et al., 1981; Le Pichon et al., 1988) as well as by numerical models and comparisons with different methods (Dupin et al., 1993; Pollard et al., 1993; Pascal, 2002).

Applying this approach, the maximum shear stress direction is assumed to be the likely sense of motion between the fault blocks and can be compared to the fault's rake. Because the shear stresses on faults depend on the orientations of the stress field axes with respect to the fault's orientation and on the stress ratio $R = (S_2 - S_3)/(S_1 - S_3)$, the stress tensor has a theoretical maximum shear stress direction on any fault plane. However, the Coulomb-Navier criterion states that a failure fracture occurs on the (fault) plane where the critical shear stress reaches the cohesive strength (σ_0) of the hosting rock plus an increment of shear equal to the product of the normal stress (σ_N) acting on the plane and the hosting rock friction coefficient (μ). This criterion is graphically represented in stress space by Mohr's circle and two lines intersecting the shear axis at $\pm\sigma_0$ with the slope $\pm\mu$. The intersection of the Mohr's stress circle and the straight line of the Coulomb-Navier criterion occurs at an angle 2θ, where θ represents the angle between σ_1 and the fault plane (Ranalli, 1987). The Coulomb-Navier criterion gives a satisfactory account of shear fracture both in the laboratory and the field (Ranalli, 1987) and empirically shows that:

$$tan2\theta = 1/\mu \quad (8)$$

Applying Eq. 8 to all possible ranges of fault friction (e.g., between 0 and 1), the corresponding angle between S1 and the fault plane corresponds to $22.5° \leq \theta \leq 45°$.

The determination of the stress tensors compatible with parameters of each active fault was carried out in a three-step procedure. We first generated S1, S2 and S3 trends and plunge values at regular intervals to explore a wide range of possible stress tensors orientations. In the next step, we considered only the stress tensors satisfying the $22.5° \leq \theta \leq 45°$ conditions and S3 positioned in the compression quadrant. The resulting stress tensors were then used as input values in the ForwardStress code (Alberti, 2010) to calculate the maximum resolved shear stress for each interpolation point along the studied faults. We calculated the SHmax orientation using the "alpha" function of Lund and Townend (2007) for those faults with a rake interval (as defined in the EDSF database) corresponding to the maximum resolved shear stress. To calculate the SHmax *posterior* uncertainties based on the assumed uniform probability distribution of the strike and dip min-max intervals, we repeated the stress tensor selection at regular steps for both the strike and dip values. In the last step, we determined the final SHmax orientation as the central value of the most populated 1°-wide bin in the 0°-180° range. Accordingly, the 90% bounds of the generated SHmax orientations, defined as the 90% confidence level of the theoretical SHmax, represent the condition under which the faults are considered to be positively oriented.

In the following text, we refer to SHmax orientations obtained by this method as the theoretical SHmax.

On the same 258 nodes along the fault's upper edges, we interpolated the SHmax data records with SHINE using WSM08 (Heidbach et al, 2008). Therefore, in the data selection part of SHINE, we chose the WMS08 dataset, while in the "Geographic setting" we chose the "Custom input file" option. We defined the "Searching radius" as three (data records within a 96 km radius), the "Minimum cluster" as three and the 90% confidence bounds as 40°. We kept the confidence level reasonably low to ensure stable results. Application of these parameters resulted in 257 SHmax orientations (Figure 7), we note that only one point did not satisfy the chosen SHINE input parameters (its 90% confidence bound reached 47° and was therefore excluded from further consideration). In the following text we refer to SHmax orientations obtained by this method as SHINE SHmax.

To compare SHINE and theoretical SHmax orientations, we calculated the angular difference β between both median values at each interpolation point. The value of β is therefore a measure of the compatibility between the SHINE and theoretical SHmax orientation. For each interpolation, we ranked the compatibility between both SHmax orientations in five classes; A ($0° \leq \beta \leq 15°$), B ($15° < \beta \leq 25°$), C ($25° < \beta \leq 35°$), D ($35° < \beta \leq 45°$), E ($\beta > 45°$). The A-C classes imply a kinematically correlated fault slip sense in the present-day stress regime. We consider faults with D class results still being able to be active in a given stress regime, while we set E class faults to have uncorrelated theoretical slip direction in the present-day stress regime.

The class-type breakdown of the the 257 analyzed nodes shows 104 to belong to class A, 52 to B and C classes, 37 to D and 12 to E (Figure 8). The E- ranked interpolation points belong to four active faults. Half of them belong to ATCS011, a fault that also has the maximum 72° β misfit. The other three faults with E class nodes lie on faults in the northern and central part of the study area. The spatial distribution of hosting D class fault nodes shows a similar pattern, with the majority of them located in the northern and central parts, and some belonging to ITCS101, SICS006, SICS010 and HRCS037 faults. A majority of faults hosting A- and B- ranked interpolation points lie in the southern part of the study area, with exception of few faults in the centre and north (for exampleSICS007, SICS008, SICS012, SICS023).

The ATCS011 is an active fault with considerable length. The fault length appears to have an influence on the SHmax orientation discordance given the fault's minimum-maximum strike interval is between 260° and 300° over distances larger than 100 km, while its rake varies between 130°-170°. Such conditions do not capture the local conditions well because they generalize characteristics over long distances. Along the ATCS011 down-dip projection, a focal mechanism of the 2nd February, 2013 M_W 4.05 gives a P-axis azimuth of 199° (http://www.eas.slu.edu/eqc/eqc_mt/MECH.EU/20130202133535/index.html) which is in better agreement with the SHINE than the theoretical SHmax orientation. Overall, this approach provides a practical example of applying SHINE to test the relationship between an observed set of faults and the in-situ stress field.

The ITCS101 fault has D class misfit nodes in its north-western section. The location of this fault corresponds to the intersection of the NW-SE oriented dextral strike-slip faults of the External Dinarides and the E-W oriented thrust of the Southern Alps. In this case a more detailed revision of the available geological, seismic and seismological data might offer a better understanding of the geometry and kinematics of active faults.

The faults in central Slovenia host both the highest and lowest β value points. These differences are due to the low density and scattered orientations of the input data-records for the area. The focal mechanism solutions (Ložar Stopar and Živčić, 2007; Ložar Stopar and Živčić, 2008) confirm the ESFD geometric and kinematic fault parameters, whereas SHINE SHmax orientation suggests thrust kinematics for some of those faults (SICS013).

Using SHINE it is possible to evaluate the degree of kinematic compatibility between active faults and the in-situ stress field. In the case of strong incompatibility, we recommend that the contributing researchers further investigate this discrepancy, paying attention to the original fault data. Similarly, we suggest double checking the original stress data records that were used for the determining SHmax orientation. As shown by Carafa and Barba (2013), the spatial distribution and density coverage of input stress data records significantly influences the reliability of the SHmax orientation. Such considerations might be important when planning and funding future fault data analyses and SHmax measurements.

6. *Conclusions*

The dissemination and sharing of knowledge is facilitated by an effective and coherent plan for the development of software tools intended for use by the community. With this work, we described all steps we performed to create an effective web service (http://shine.rm.ingv.it/). The primary goal of the SHINE software is to provide an efficient stress interpolation technique - this goal was optimized by focusing on the end user perspective. For any geoscientist, SHINE sets a base level for determining SHmax orientations because it incorporates robust analytical formulations into stress map creation, thereby offering discrete quantitative results, not just a visual comparison of

SHmax orientations distributions on a map. Moreover, the logfile that is included in the final downloadable zipped file registers all of the selected input parameters of each interpolation, which satisfies the reproducibility principle for any calculated SHmax map.

A SHINE application for a comparison between the theoretical and observed fault SHmax orientations was provided as an illustrative example of its utility and applicability for active tectonics research. In this case, SHINE was used as a tool to test fault compatibility in the present-day stress regime. This is just one of the potential applications, which is useful for researchers working in different disciplines ranging from geodynamics to field geology. SHINE's underlying rationale can be summed up by three words: usability, effectiveness and efficiency. These principles will be the road map for future SHINE development and integrations.

Acknowledgments

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References

Alberti, M. (2010), Analysis of kinematic correlations in faults and focal mechanisms with GIS and Fortran programs, *Comput. Geosci.*, *36*(2), 186–194, doi:10.1016/j.cageo.2009.06.006.

Angelier, J. (1994), Paleostress analysis of small-scale brittle structures., in *Continental Deformation*, edited by P. Hancock, pp. 53– 100, Pergamon.

Basili, R. et al. (2013), The European Database of Seismogenic Faults (EDSF) compiled in the framework of the Project SHARE, , doi:10.6092/INGV.IT-SHARE-EDSF. Available from: http://diss.rm.ingv.it/share-edsf/

Bird, P., and Y. Li (1996), Interpolation of principal stress directions by nonparametric statistics: Global maps with confidence limits, *J. Geophys. Res.*, *101*, 5435–5443.

BSI (1998), ISO 9241-11:1998, Ergonomic requirements for office work with visual display terminals (VDTs) - Part 11: Guidance on usability,

Carafa, M. M. C., and S. Barba (2013), The stress field in Europe: optimal orientations with confidence limits, *Geophys. J. Int.*, *193*(2), 531–548, doi:10.1093/gji/ggt024.

Coblentz, D., and R.M. Richardson, Statistical Trends in the Intraplate Stress Field, *Journal of Geophysical Research*, 100, 20,245-20,255, 1995.

Dupin, J.-M., W. Sassi, and J. Angelier (1993), Homogeneous stress hypothesis and actual fault slip: a distinct element analysis, *J. Struct. Geol.*, *15*(8), 1033–1043, doi:10.1016/0191-8141(93)90175-A.

Heidbach, O., M. Tingay, A. Barth, J. Reinecker, D. Kurfeß, and B. Müller (2008), The World Stress Map database release 2008, , doi:10.1594/GFZ.WSM.Rel2008.

Kastelic, V., and M. M. C. Carafa (2012), Fault slip rates for the active External Dinarides thrust-and-fold belt, *Tectonics*, *31*, TC3019, doi:10.1029/2011TC003022.

Kastelic, V., M. Vrabec, D. Cunningham, and A. Gosar (2008), Neo-Alpine structural evolution and present-day tectonic activity of the eastern Southern Alps: The case of the Ravne Fault, NW Slovenia, *J. Struct. Geol.*, *30*(8), 963–975, doi:10.1016/j.jsg.2008.03.009.

Le Pichon, X., F. Bergerat, and M.-J. Roulet (1988), Plate kinematics and tectonics leading to the Alpine belt formation: A new analysis, in *Processes in Continental Lithospheric Deformation*, edited by S. P. Clark, J. B. C. Burchfiel, and J. Suppe, pp. 111–131.

Lee, J.-C., and J. Angelier (1994), Paleostress trajectory maps based on the results of local determinations: the “lissage” program, *Comput. Geosci.*, *20*(2), 161–191, doi:10.1016/0098-3004(94)90004-3.

Ložar Stopar, M., and M. Živčić (2007), Fault plane solutions of some stronger earthquakes in Slovenia in 2005, in *Earthquakes in 2005*, edited by Environmental Agency of the Republic of Slovenia Seismology and Geology Office, pp. 57–62.

Ložar Stopar, M., and M. Živčić (2008), Fault plane solutions of some stronger earthquakes in Slovenia in 2006 and 2007, in *Earthquakes in 2007*, edited by Environmental Agency of the Republic of Slovenia Seismology and Geology Office, pp. 48–53.

Lund, B., and J. Townend (2007), Calculating horizontal stress orientations with full or partial knowledge of the tectonic stress tensor, *Geophys. J. Int.*, 1328–1335, doi:10.1111/j.1365-246X.2007.03468.x.

Müller, B., V. Wehrle, S. Hettel, B. Sperner, and K. Fuchs (2003), A new method for smoothing orientated data and its application to stress data, *Geol. Soc. London, Spec. Publ.*, *209*(1), 107–126, doi:10.1144/GSL.SP.2003.209.01.11.

Nah, F. (2004), A Study on Tolerable Waiting Time: How Long Are Web Users Willing to Wait?, *Behav. Inf. Technol.*, *23*(3), 153–163.

Nielsen, J. (2000), *Web usability*, Apogeo Editore.

Pascal, C. (2002), Interaction of faults and perturbation of slip: influence of anisotropic stress states in the presence of fault friction and comparison between Wallace–Bott and 3D Distinct Element models, *Tectonophysics*, *356*(4), 307–322, doi:10.1016/S0040-1951(02)00413-4.

Placer, L. (1998), Contribution to the macrotectonic subdivision of the border region between southern Alps and External Dinarides, *Geologija*, *41*, 223–255.

Poljak, M. (2000), Structural-Tectonical Map of Slovenia 1 : 250.000, *Geol. Surv. Slov.*

Pollard, D. D., S. D. Saltzer, and A. M. Rubin (1993), Stress inversion methods: are they based on faulty assumptions?, *J. Struct. Geol.*, *15*(8), 1045–1054, doi:10.1016/0191-8141(93)90176-B.

Ranalli, G. (1995), *Rheology of the Earth*, Springer.

Sperner, B., B. Müller, O. Heidbach, D. Delvaux, J. Reinecker, and K. Fuchs (2003), Tectonic stress in the Earth's crust: advances in the World Stress Map project, The Geological Society, London.

Stone, D., C. Jarrett, M. Woodroffe, and S. Minocha (2005), *User interface design and evaluation*, Elsevier : Morgan Kaufmann, Amsterdam.

Stucchi, M. et al. (2013), The SHARE European Earthquake Catalogue (SHEEC) 1000–1899, *J. Seismol.*, *17*(2), 523–544, doi:10.1007/s10950-012-9335-2.

Vrabec, M., and L. Fodor (2006), Late Cenozoic Tectonics Of Slovenia: Structural Styles At The Northeastern Corner Of The Adriatic Microplate, edited by N. Pinter, G. Gyula, J. Weber, S. Stein, and D. Medak, pp. 151–168, Springer Netherlands.

Wroblewski, L. (2008), *WEB FORM DESIGN Filling in the Blanks*.

Xu, P. (2004), Determination of regional stress tensors from fault-slip data, *Geophys. J. Int.*, *157*(3), 1316–1330, doi:10.1111/j.1365-246X.2004.02271.x.

Yamaji, A. (2007), *An Introduction to Tectonophysics: Theoretical Aspects of Structural Geology*, Terrapub.

Živčić, M. (2010), Earthquake catalogue, unpublished material, *Off. Seismol. Geol. Agency Repub. Slov. Environ.*

Zoback, M. D., and M. L. Zoback (1981), State of stress and intra-plate earthquakes in the central and eastern United States, *Science*, *213*, 96–104.

Zoback, M. Lou, and M. D. Zoback (1989), Tectonic stress field of the continental United States, *Geol. Soc. Am. Mem.*, *172*, 523–540, doi:10.1130/MEM172-p523.

Figure Captions

Figure 1. System architecture described in this paper.

Figure 2. A view of the SHINE start page.

Figure 3. A view of the Data Selection section.

Figure 4. A view of the Geographical Setting section.

Figure 5. A view of the Strategic Parameters section.

Figure 6. A view of the Results visualization. At the bottom of the Results page, in blue, there is the link for downloading the results (provided in several GIS formats) as a zip file.

Figure 7. SHmax orientation (thin blue lines) resulting from SHINE interpolating the WSM08 data, (thick red lines). Fault upper edge traces, shown as name-labeled orange lines, taken from EDSF (Basili et al., 2013).

Figure 8. Angular difference (β) between the theoretical SHmax and SHINE SHmax for interpolation points of the studied active faults. Different β classes are color-coded as shown in the legend.

HIGHLIGHTS

- SHINE incorporates an innovative interpolation technique and a user-friendly GUI;
- SHINE quickly visualizes results, downloadable in several formats;
- SHINE rationale is summed up by 3 words: usability, effectiveness and efficiency.

Figure 1

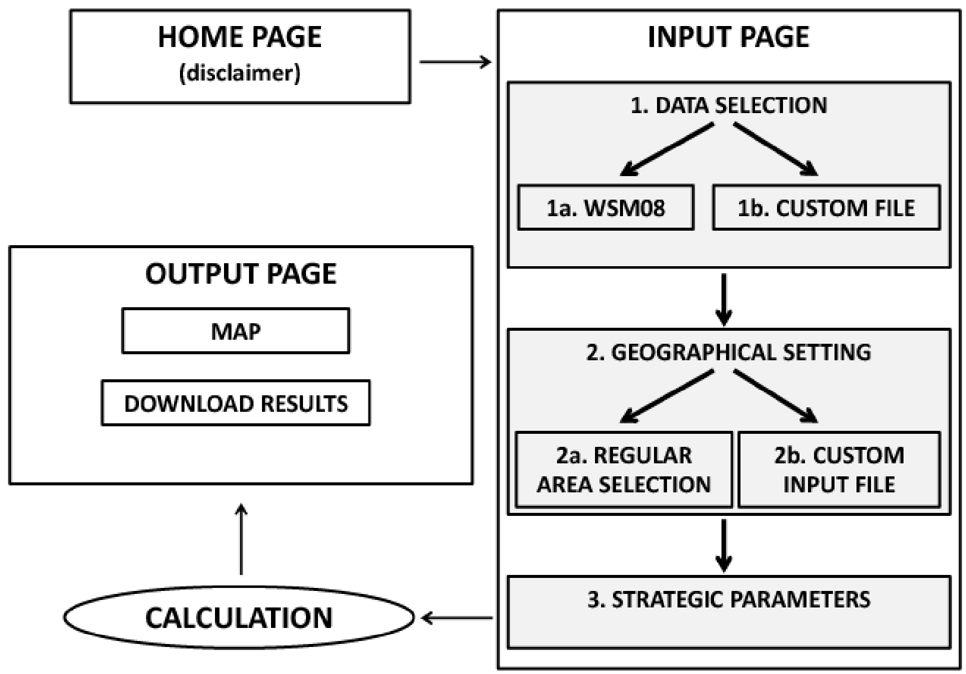

HOME PAGE
(disclaimer)
INPUT PAGE
1. DATA SELECTION
1a. WSM08
1b. CUSTOM FILE
2. GEOGRAPHICAL SETTING
2a. REGULAR AREA SELECTION
2b. CUSTOM INPUT FILE
3. STRATEGIC PARAMETERS
CALCULATION
OUTPUT PAGE
MAP
DOWNLOAD RESULTS

Figure 2

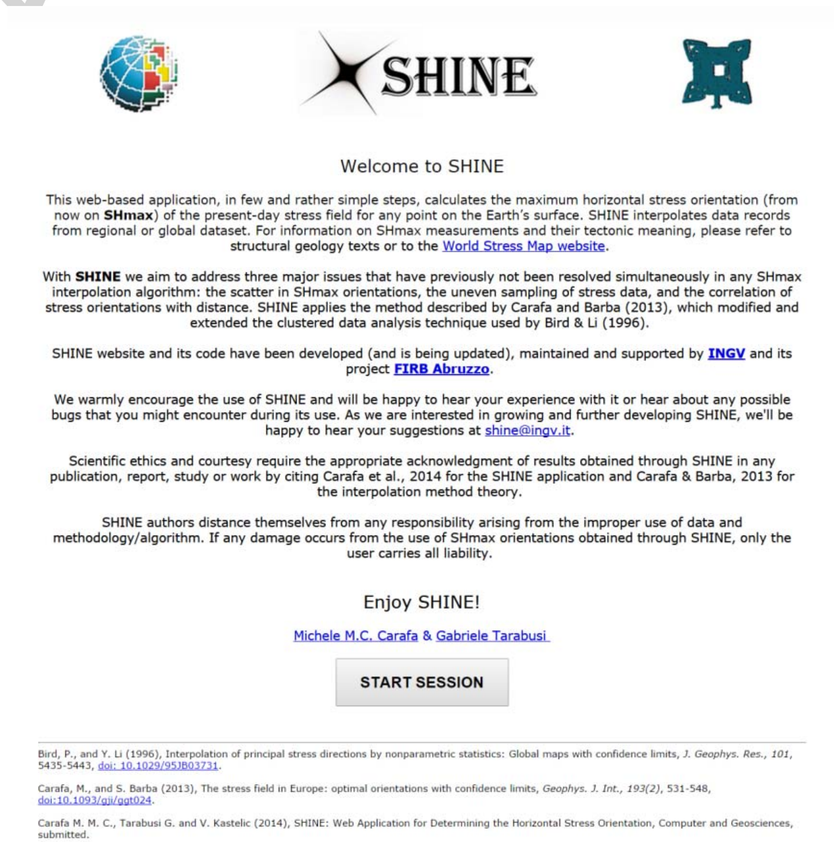

SHINE
Welcome to SHINE
This web-based application, in few and rather simple steps, calculates the maximum horizontal stress orientation (from now on SHmax) of the present-day stress field for any point on the Earth's surface. SHINE interpolates data records from regional or global dataset. For information on SHmax measurements and their tectonic meaning, please refer to structural geology texts or to the World Stress Map website.
With SHINE we aim to address three major issues that have previously not been resolved simultaneously in any SHmax interpolation algorithm: the scatter in SHmax orientations, the uneven sampling of stress data, and the correlation of stress orientations with distance. SHINE applies the method described by Carafa and Barba (2013), which modified and extended the clustered data analysis technique used by Bird & Li (1996).
SHINE website and its code have been developed (and is being updated), maintained and supported by INGV and its project FIRB Abruzzo.
We warmly encourage the use of SHINE and will be happy to hear your experience with it or hear about any possible bugs that you might encounter during its use. As we are interested in growing and further developing SHINE, we'll be happy to hear your suggestions at shine@ingv.it.
Scientific ethics and courtesy require the appropriate acknowledgment of results obtained through SHINE in any publication, report, study or work by citing Carafa et al., 2014 for the SHINE application and Carafa & Barba, 2013 for the interpolation method theory.
SHINE authors distance themselves from any responsibility arising from the improper use of data and methodology/algorithm. If any damage occurs from the use of SHmax orientations obtained through SHINE, only the user carries all liability.
Enjoy SHINE!
Michele M.C. Carafa & Gabriele Tarabusi
START SESSION
Bird, P., and Y. Li (1996), Interpolation of principal stress directions by nonparametric statistics: Global maps with confidence limits, J. Geophys. Res., 101, 5435-5443, doi: 10.1029/95JB03731.
Carafa, M., and S. Barba (2013), The stress field in Europe: optimal orientations with confidence limits, Geophys. J. Int., 193(2), 531-548, doi:10.1093/gji/ggt024.
Carafa M. M. C., Tarabusi G. and V. Kastelic (2014), SHINE: Web Application for Determining the Horizontal Stress Orientation, Computer and Geosciences, submitted.

Figure 3

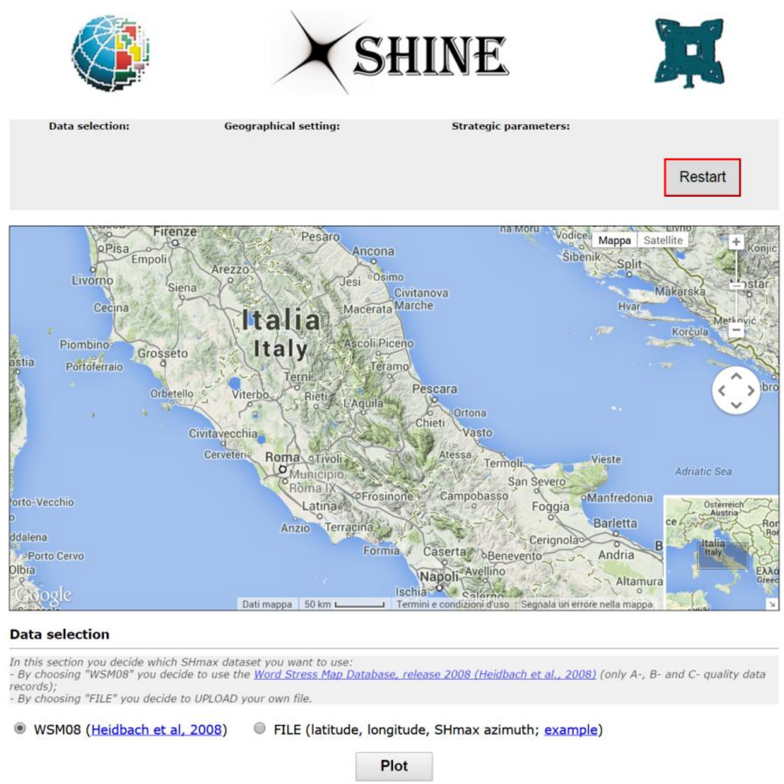

SHINE
Data selection:
Geographical setting:
Strategic parameters:
Restart
Mappa
Satellite
Italia
Italy
Adriatic Sea
Dati mappa
50 km
Termini e condizioni d'uso
Segnala un errore nella mappa
Data selection
In this section you decide which SHmax dataset you want to use:
- By choosing "WSM08" you decide to use the Word Stress Map Database, release 2008 (Heidbach et al., 2008) (only A-, B- and C- quality data records);
- By choosing "FILE" you decide to UPLOAD your own file.
WSM08 (Heidbach et al, 2008)
FILE (latitude, longitude, SHmax azimuth; example)
Plot

Figure 4

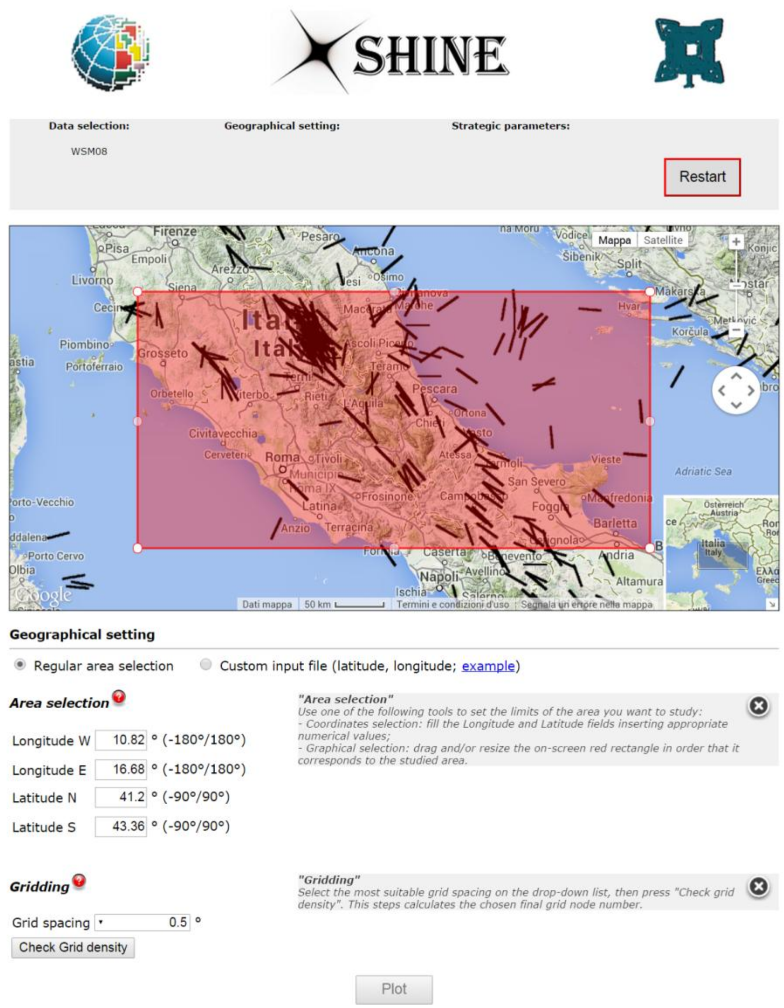

SHINE
Data selection:
WSM08
Geographical setting:
Strategic parameters:
Restart
Mappa
Satellite
Adriatic Sea
Geographical setting
Regular area selection
Custom input file (latitude, longitude; example)
Area selection
Longitude W 10.82 ° (-180°/180°)
Longitude E 16.68 ° (-180°/180°)
Latitude N 41.2 ° (-90°/90°)
Latitude S 43.36 ° (-90°/90°)
"Area selection"
Use one of the following tools to set the limits of the area you want to study:
- Coordinates selection: fill the Longitude and Latitude fields inserting appropriate numerical values;
- Graphical selection: drag and/or resize the on-screen red rectangle in order that it corresponds to the studied area.
Gridding
Grid spacing 0.5 °
Check Grid density
"Gridding"
Select the most suitable grid spacing on the drop-down list, then press "Check grid density". This steps calculates the chosen final grid node number.
Plot

Figure 5

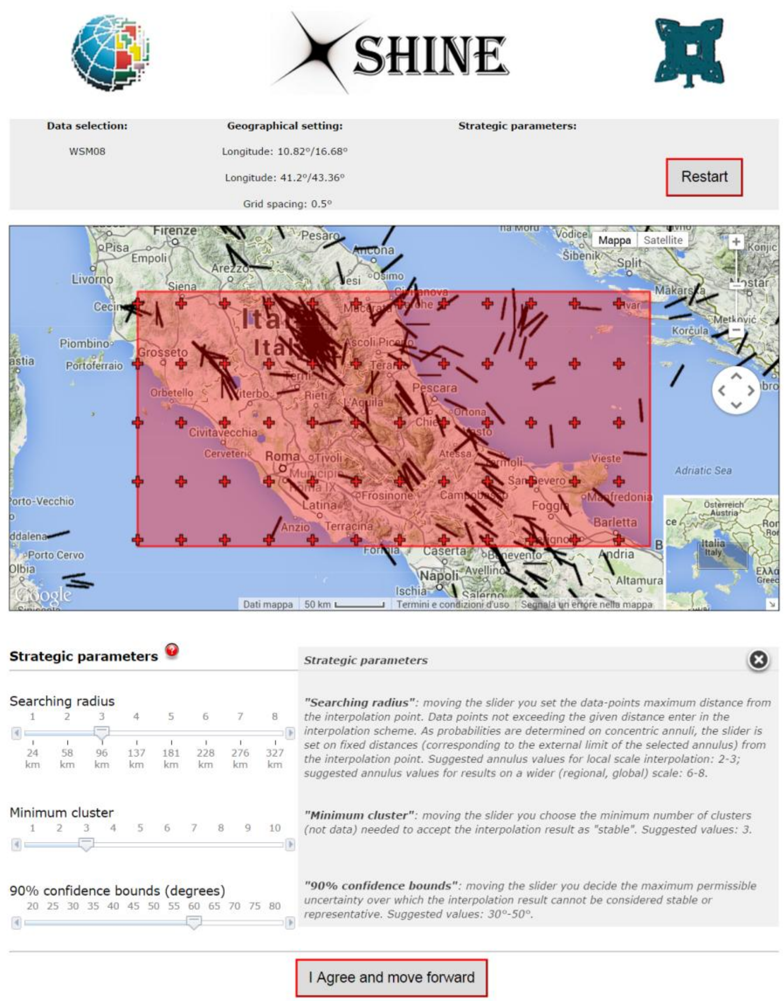
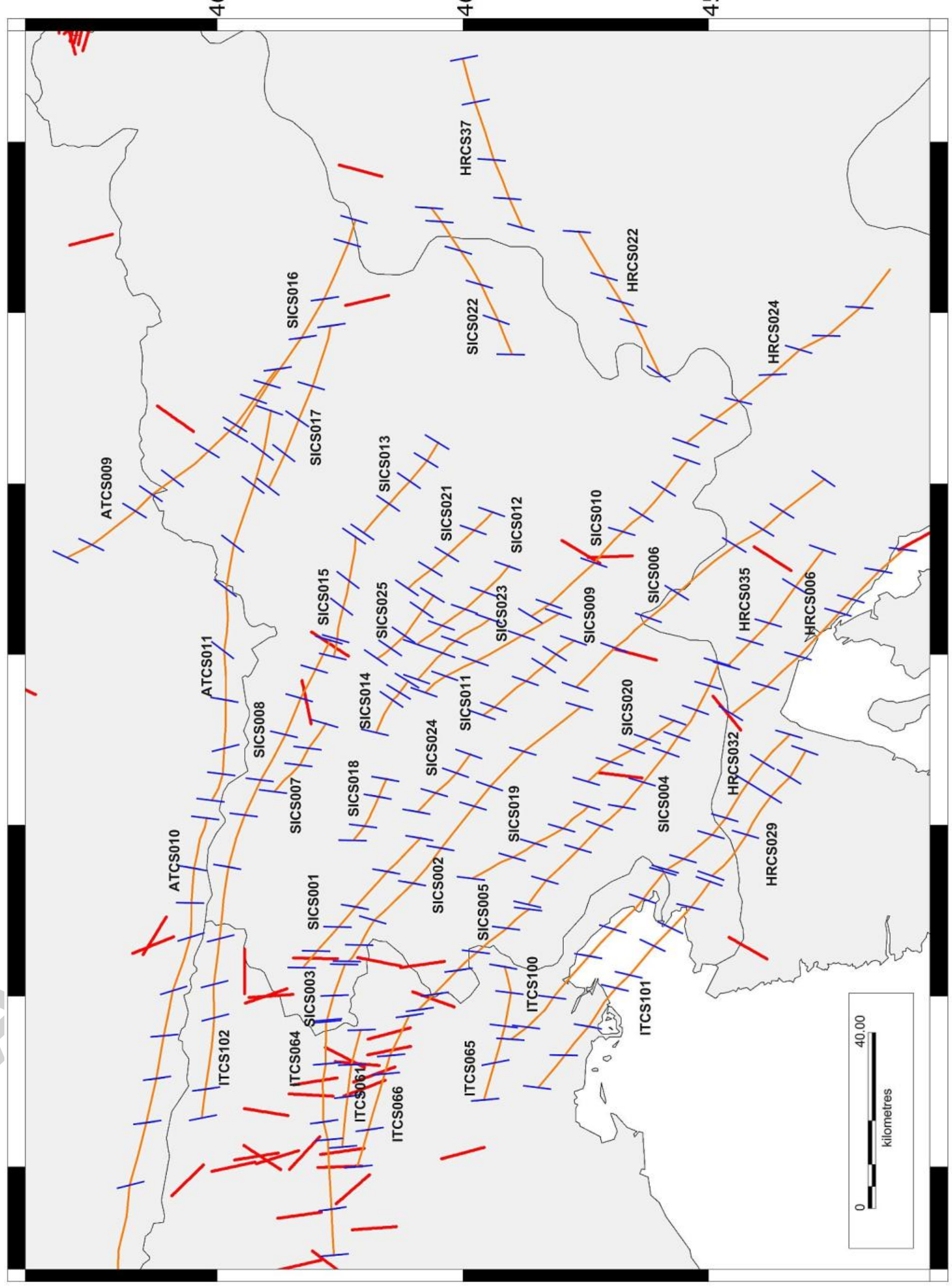

SHINE
Data selection:
WSM08
Geographical setting:
Longitude: 10.82°/16.68°
Longitude: 41.2°/43.36°
Grid spacing: 0.5°
Strategic parameters:
Restart
Mappa
Satellite
Adriatic Sea
Strategic parameters
Searching radius
1 2 3 4 5 6 7 8
24 km 58 km 96 km 137 km 181 km 228 km 276 km 327 km
Minimum cluster
1 2 3 4 5 6 7 8 9 10
90% confidence bounds (degrees)
20 25 30 35 40 45 50 55 60 65 70 75 80
Strategic parameters
"Searching radius": moving the slider you set the data-points maximum distance from the interpolation point. Data points not exceeding the given distance enter in the interpolation scheme. As probabilities are determined on concentric annuli, the slider is set on fixed distances (corresponding to the external limit of the selected annulus) from the interpolation point. Suggested annulus values for local scale interpolation: 2-3; suggested annulus values for results on a wider (regional, global) scale: 6-8.
"Minimum cluster": moving the slider you choose the minimum number of clusters (not data) needed to accept the interpolation result as "stable". Suggested values: 3.
"90% confidence bounds": moving the slider you decide the maximum permissible uncertainty over which the interpolation result cannot be considered stable or representative. Suggested values: 30°-50°.
I Agree and move forward

Figure 6

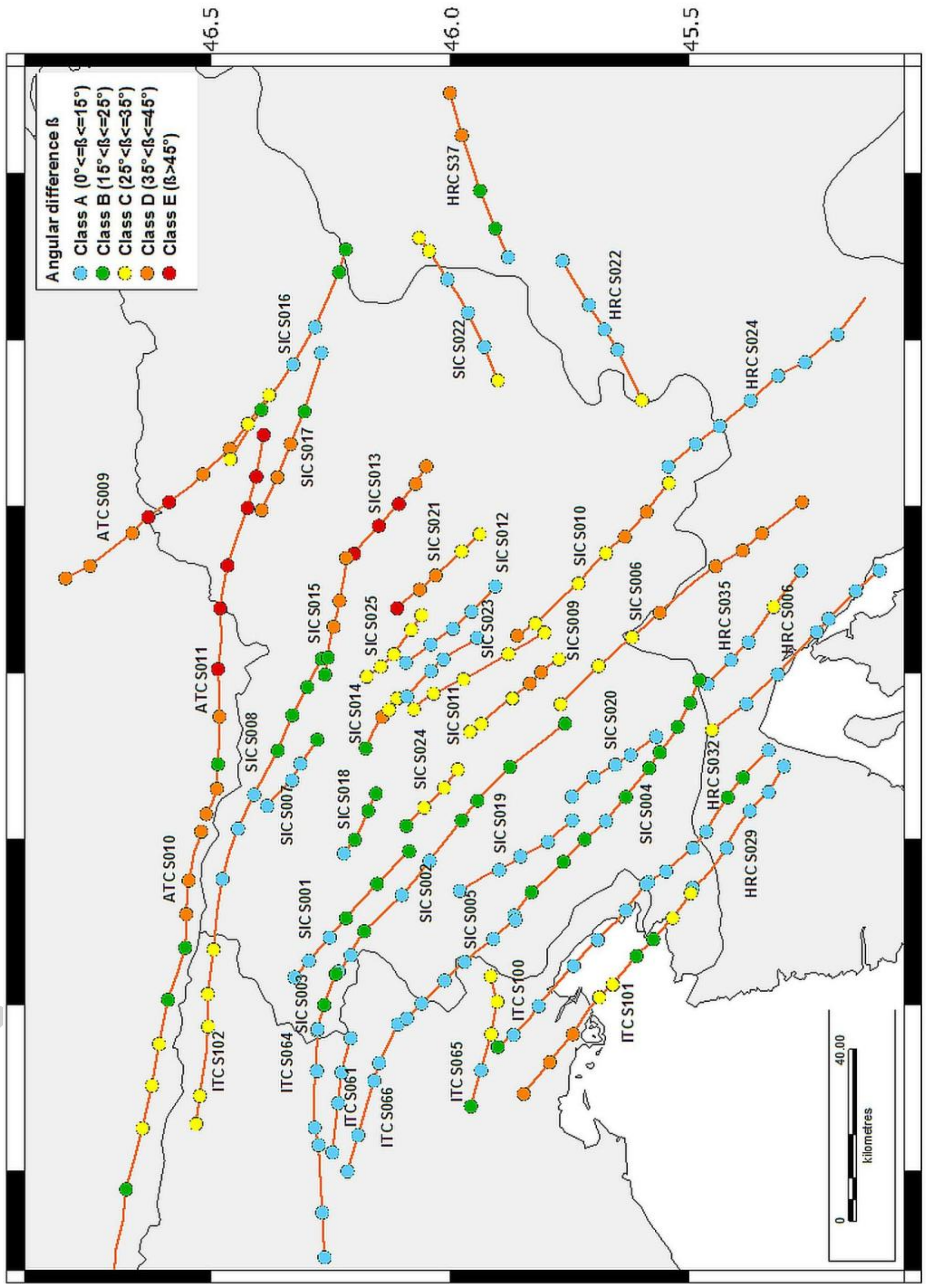

SHINE
Data selection:
WSM08
Geographical setting:
Longitude: 10.82°/16.68°
Latitude: 41.2°/43.36°
Grid spacing: 0.5°
Strategic parameters:
Searching radius: 3
Minimum cluster: 3
90% confidence bounds: 60°
Input layer
Output layer
Mappa
Satellite
Adriatic Sea
Download results in zip format
Click here for a new interpolation/stress map

Figure 7



46.5
46.0
45.5
13.0
13.5
14.0
14.5
15.0
15.5
16.0
ATCS009
ATCS010
ATCS011
ITCS102
ITCS064
ITCS061
ITCS066
ITCS065
ITCS100
ITCS101
SICS001
SICS002
SICS003
SICS004
SICS005
SICS006
SICS007
SICS008
SICS009
SICS010
SICS011
SICS012
SICS013
SICS014
SICS015
SICS016
SICS017
SICS018
SICS019
SICS020
SICS021
SICS022
SICS023
SICS024
SICS025
HRCS37
HRCS022
HRCS024
HRCS035
HRCS006
HRCS032
HRCS029
0
40.00
kilometres

Figure 8


Angular difference ß
Class A (0°<=ß<=15°)
Class B (15°<ß<=25°)
Class C (25°<ß<=35°)
Class D (35°<ß<=45°)
Class E (ß>45°)
46.5
46.0
45.5
13.0
13.5
14.0
14.5
15.0
15.5
16.0
0
40.00
kilometres
ATC S009
ATC S010
ATC S011
ITC S102
SIC S008
SIC S016
SIC S017
SIC S015
SIC S013
SIC S025
SIC S021
SIC S012
SIC S022
HRC S37
HRC S022
HRC S024
SIC S010
SIC S006
SIC S009
SIC S023
SIC S011
SIC S014
SIC S024
SIC S018
SIC S007
SIC S001
SIC S003
ITC S064
ITC S061
ITC S066
SIC S002
SIC S005
SIC S019
SIC S020
SIC S004
HRC S035
HRC S006
HRC S032
HRC S029
ITC S065
ITC S100
ITC S101

http://shine.rm.ingv.it/