Computers & Geosciences 74 (2015) 39–49

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

SHINE: Web application for determining the horizontal stress orientation

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ARTICLE INFO

Article history:
Received 19 March 2014
Received in revised form
23 September 2014
Accepted 1 October 2014
Available online 12 October 2014

Keywords:
Present-day stress
Web application
Maximum horizontal compressive stress
Horizontal stress interpolation
Stress maps
Active faults

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.

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 $\pm 15°$) to E (the lowest; standard deviations greater than $\pm 40°$). 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; Müller 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 SH INtErpolation (SHINE) web application, that calculates the SHmax orientation for any chosen point worldwide.

2. Theory

SHINE implements the Carafa and Barba (2013) interpolation method. We present the main aspects of this interpolation scheme, which modified and extended the clustered data analysis technique used by Bird and 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.

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http://dx.doi.org/10.1016/j.cageo.2014.10.001
0098-3004/

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

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

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 Eq. (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

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

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:

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

where k_x is the integer that maximises $P_{N_c}^*(k_x)$ in Eq. (3). The 90% confidence interval $\Delta\alpha$ is determined as

$$\int_{\alpha_x - \Delta\alpha}^{\alpha_x + \Delta\alpha} p_N^*(\alpha_x' \bmod 180°)\, d\alpha_x' = 0.90, \tag{5}$$

where $p_N^*(\alpha_x' \bmod 180°)$ 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) (Fig. 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 for 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. (2005) 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.

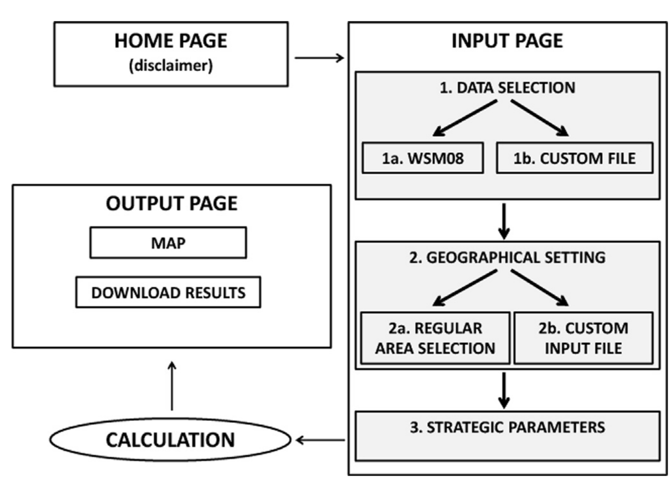

Fig. 1. System architecture described in this paper.