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The World Stress Map – A Freely Accessible Tool For Geohazard Assessment

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Abstract. The World Stress Map (WSM) database contains over 16,000 indicators on contemporary crustal tectonic stress and provides an essential parameter for geohazard assessment. This paper focuses on the importance of database accessibility for geohazard assessment and presents the basic concepts and availability of the WSM. The WSM can be applied to several key aspects of geohazard assessment, in particular the mapping of stress patterns and places of stress concentration for improved delineation of zones of seismic hazard. Furthermore, contemporary tectonic stresses can be used in combination with numerical modeling to identify faults or sections of fault systems with high failure potential and can help to predict the likely type of fault reactivation. This approach is especially valuable for assessing the likelihood of strong and rare seismic events for which probabilistic hazard assessment will fail and physically based methodologies are required. Herein, we use the Caspian-Caucasian region as an example to apply WSM data for geohazard assessment. The Caspian-Caucasian area is characterized by the occurrence of a number of stress related geohazards on different spatial scales, in particular crustal earthquakes, seismically triggered landslides and mud volcanism.

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INTRODUCTION

Tectonic stress and its variation in time and space control a number of geohazards that range from rock failure at local engineering scale (e.g. in tunnels and mines) to large-scale catastrophic earthquakes. However, stress is not commonly used in the assessment of stress-related geohazards. Stress information has been applied to examine the occurrence and alignment of magmatic volcanoes and the opening of underground fluid pathways that lead to leakage of stored fluids, such as in reservoirs and hazardous waste repositories. However, in contrast, stress has not been used to examine mud volcanism and even more, despite the fact that seismotectonic geohazards are the most abundant and catastrophic stress-related geohazards, stress information is rarely used in the quantitative assessment of these hazards. Early forms of seismic hazard determination (historical determinism) involved the mapping of the effects of historic earthquakes, under the assumption that those represent the highest intensity in future. The second generation of seismic hazard assessment, the historical probabilism, provided recurrence rates and probabilities of exceeding a ground motion, acceleration or intensity. In the third generation of hazard assessment, the

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seismotectonic probabilism, geological evidence, paleoseismic studies and physical causes of earthquake generation are incorporated into a seismic source model. The next approach, termed non-Poissonian probabilism, is time-dependent and takes into account that preceding earthquakes may affect the likelihood of other events in the vicinity [1, 2]. However, different hazard methodologies are applied in different parts of the Earth depending, for example, on the state of seismotectonic knowledge [2]. Future generations of seismic hazard assessment will further utilize observational and statistical components, but will also involve numerical modeling of stress evolution in time and space to better examine the seismic process and more accurately predict the possible locations, magnitudes and propensity of seismic events. For this numerical modeling comparable high quality stress data are needed as independent constraints.

Several fundamental public-domain global databases of geo-information already exist, for example gravity data (GRIM5-S1 data set, GFZ Potsdam), the Heat Flow Data Set, compiled by Pollack et al. [3], sediment thickness [4], the crustal thickness data base CRUST 5.1 [5], the Centroid-Moment Tensor solutions of the Harvard CMT catalogue (http://www.seismology.harvard.edu/CMTsearch.html), the USGS National Earthquake Information Center (NEIC) database (http://neic.usgs.gov/), and the World Stress Map database (WSM, Fig. 1) [6].

In this paper we argue that the knowledge of the contemporary tectonic stresses is a major contribution to the improvement on seismotectonic knowledge and present several examples of stress related geohazards for the Caspian Caucasian region. Our main emphasis is that a) the evaluation, ranking and maintenance of relevant data, b) the consistency of data presentation, and c) the unlimited and facile access to this basic research data are prerequisites for physically based hazard assessment methodologies.

KEY FEATURES OF WSM PERFORMANCE

The WSM Project is a collaborative project between academia, industry and government. The WSM is a major scientific project as well as a public domain, non-profit service for the geoscience and engineering community. Its basic principle is to maintain and extend a comprehensive global database of present-day stress information in order to analyze the state and sources of contemporary tectonic stress in the lithosphere. The WSM has, since 1986, built the global compilation of the contemporary tectonic stress information. The WSM contains information on the principal tectonic stresses which are given with relation to the Earth's surface as vertical stress (S_v), maximum and minimum horizontal stresses (S_H and S_h, respectively). The major finding of the project is a regional uniformity of intra-plate S_H orientations that reflects the influence of plate boundary forces [7]. The WSM has compiled a database of over 16,000 quality-ranked stress indicators of the present-day stress and which provides the stress database itself, numerous pre-defined stress maps, software and services free of charge [6]. The WSM website has rapidly become a widely used and invaluable resource for scientists and engineers investigating present-day stress or applying the in-situ stress to geological and engineering applications. The WSM is accepted as the global reference for contemporary tectonic stress.

The WSM project has provided key insights into the state of, and forces controlling, the plate-scale and regional stress field [7]. The present-day stress orientations contained in the WSM database are estimated from many different types of stress indicators, including earthquake focal mechanism solutions, borehole breakouts and drilling-induced fractures (from borehole image or multi-arm caliper log data), in-situ stress measurements (overcoring, hydraulic fracturing) and geological indicators (fault slip, volcanic vent alignment). Thus, the WSM database contains information from a variety of different sources, different depth sections and different tectonic units. The success of the WSM is based on three main factors: a) global comparability including quality control; b) non-restricted free of charge access to the data, and; c) user assistance through providing software tools for data processing and interpretation as well as data visualization.

WSM data are globally comparable

All data in the WSM are compiled in a standardized, easy to handle structure that can be downloaded as ASCII-format file or pdf-format file [6]. All data of the WSM are quality ranked according to an internationally accepted quality-ranking table [7, 8] The minimum information for each stress data stored in the database is the orientation of the maximum horizontal principal stress, the quality of the stress information, the depth of the measurement, the type of stress indicator and the locality. The stress maps display the orientation of the maximum horizontal compressional stress (S_H), the data quality, the stress indicator type, and the tectonic regime of each data set (Fig. 1). The tectonic regime is an expression of the relative magnitudes of the three principal stresses S_H, S_v and S_h based on the Andersonian fault classification scheme [9]. The vertical stress is the maximum principal stress in a normal faulting stress regime ($S_v>S_H>S_h$), the intermediate stress in a strike-slip faulting stress regime ($S_H>S_v>S_h$) and least stress in a thrust faulting stress regime ($S_H>S_h>S_v$).

Non-restricted and easy access to WSM data base

The WSM is freely available to the public via the Internet (www.world-stress-map.org). This web-page contains the database itself and information on data details, such as the stress measurement types, quality-ranking criteria and methods for tectonic regime assignment. The WSM website and database are updated annually and, thus, the WSM is an up to date database on contemporary tectonic stress. A description of the WSM structure and format is given in the sequential order of the database format as well as for each type of individual stress indicator. Furthermore abstracts of data interpretation for regional stress fields are given. For the yearly database release a description on the state of the WSM, the database statistics and new aspects is provided. In addition to the database itself, 66 predefined stress maps are available for the World, Europe (28 maps), America (14 maps), Africa (4 maps), Asia (14) and Australia (6 maps) and their sub-regions. These maps are downloadable in different resolutions and data formats and over 60,000 stress maps have been downloaded from the WSM website since it went online in 1999.

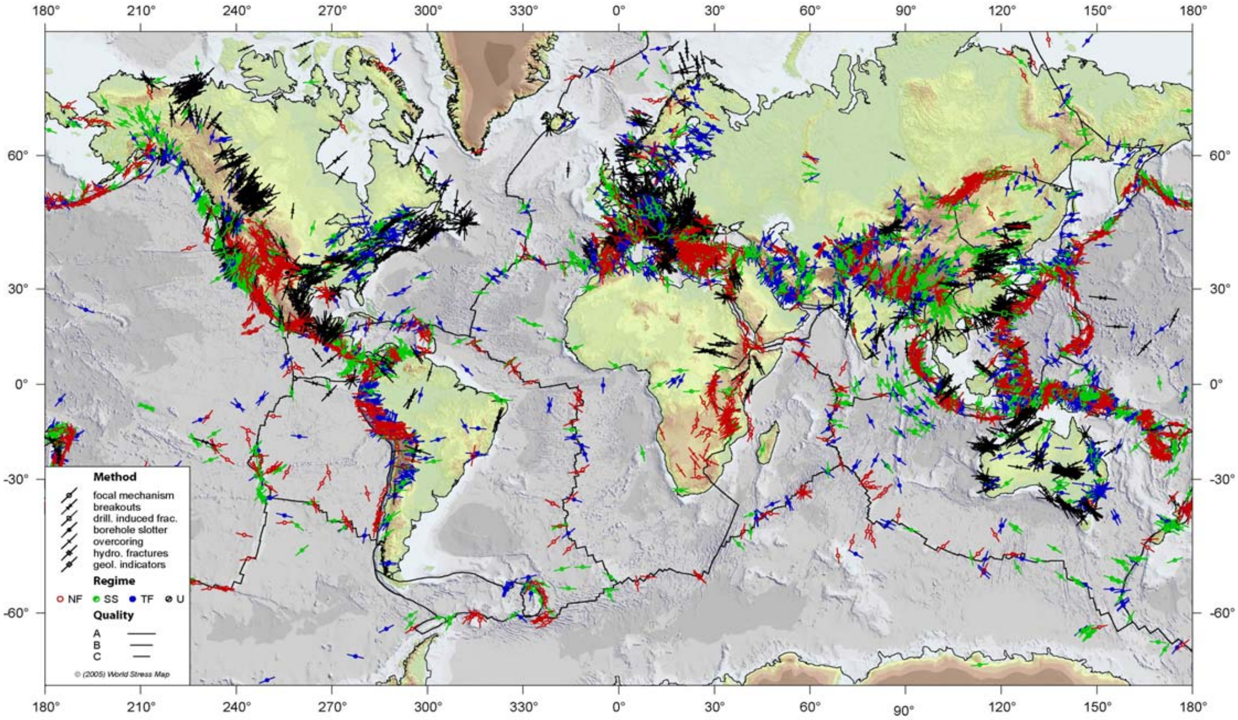

FIGURE. 1 World Stress Map 2005. The long axis of the symbols indicates the direction of the maximum horizontal stress S_H, the measurement technique is given by the symbol type, and the symbol length is a measure for the data quality. Only A to C quality data are shown for clarity. The color of the symbol represents the tectonic regime (see legend). Plate boundaries from the global plate model PB2002 [10] are included as solid lines. (NF=normal faulting, SS= Strike slip faulting, TF =thrust faulting).

WSM user support

The WSM provides support to users for the processing, interpretation and visualization of present-day stress information. Hence, the WSM has developed a range of guidelines and free software tools, which are all either directly downloadable from the WSM website or can be requested, free of charge, from the WSM team. Most important are the tools assisting in data visualization, such as CASMO, CASMI and GEOMOVIE. The WSM team has also created software to help to process and interpret stress data, such as the four- and six-arm caliper interpretation packages and a routine for ‘smoothing’ and mapping stress data [11, 12]. Based on Moos and Zoback [13], the methodology for regime assignment derived from borehole breakout depth distribution has been further developed [14].

CASMO and CASMI are the most popular and easily accessible WSM software. The database interface CASMO (**C**reate **A** **S**tress **M**ap **O**nline) is an online tool for the custom building of individual stress maps by simply selecting the region of interest, stress indicator type, depth range, and quality of the stress data. In addition, users can add their own stress data to this plot and assign an extra color to these data. Furthermore, there are options to display topography, political boundaries, and plate boundaries on the stress map. The stress map can be produced in various geographical projections using **G**eneric **M**apping **T**ools (GMT) [15] and different output formats (pdf, jpeg or postscript). The return time for a CASMO request is less than a minute, and the stress map is delivered via e-mail [16].

The alternative software tool, CASMI (**C**reate **A** **S**tress **M**ap **I**nteractively), is a stand-alone public domain program for UNIX/LINUX operating systems [17]. This software was developed as a user-friendly interface for stress mapping based on the free software GMT CASMI includes all features and selection criteria of CASMO. The user can add own stress data and a wide range of other data as provided by various GMT commands. This includes: topography, polygons, CMT solutions, text, plate boundaries from the global plate model PB2002 [10], coastlines and political boundaries. It also provides the plotting of relative or absolute plate motion as defined in the NUVEL-1A model [18].

STRESS RELATED GEOHAZARDS IN THE CAUCASUS AND CASPIAN BASIN

Stress-related geohazards of the Caucasus show a wide range of spatial scales. On a regional scale, earthquakes are the most prominent geohazards. Earthquakes greater than magnitude 6 occur with a periodicity of 5-10 years [19]. The Spitak earthquake of 1988 in the Armenian part of the Caucasus, with magnitude 6.8, resulted in ca. 25,000 lives lost. The town of Shemakha in Azerbaijan was destroyed several times, once in 1667 with a loss of 80,000 lives and in 1903 the town of Shemakha was severely damaged again. In addition earthquakes can trigger mass sediment movement either onshore or offshore in the Caspian Sea. Thus, earthquakes and related mass movement can lead to destruction of on- and off-shore facilities of oil and gas industry, which may contribute to severe environmental problems in the Caspian [20].

On basin scale, gas hydrates near the base of the continental rise in the Caspian Sea control a large region of shallow deformation [21]. These methane clathrates exist in a narrow pressure-temperature (P/T) window in Azerbaijan 300 m beneath the sea floor in water depths of ca. 400-650 m, where they form a thermobaric seal for free gas in marine sediments. If P/T and stress conditions are altered, for example in the vicinity of critically stressed faults, these quasi-stable structures can dissociate slowly or explosively, releasing the gas trapped beneath this hydrate seal. P/T conditions may change on short lateral scales, since formation pressure in oil and gas deposits varies strongly in the Caspian region and in some places significantly exceeds the hydrostatic gradient. Gas hydrates are hazardous in a number of ways, firstly, they are major hazards for drilling and for the stability of offshore structures and can result in injury or death to oil-field workers and/or major economic loss. Secondly, gas hydrate dissociation can lead to slope instabilities and associated seabed slumping. Lastly, gas hydrate dissociation resulting in the escape of large volumes of methane into the atmosphere and may contribute to global climate change [22-24].

The South Caspian basin shows a large abundance of mud-volcanism, with occasional explosive eruptions that cause oil and gas to burn on the earth surface [25]. According to Aliyev [26], about 200 marine and 180 continental mud volcanoes have been observed on an area of 60,000 km^2. In magmatic volcanism, dykes propagate outward from the magma chamber and, in the absence of significant tectonic stress, dykes around volcanoes are distributed in a radial pattern. However, if tectonic stress is superimposed, dykes will initially leave the magma chamber radially, but rotate parallel to S_H as they propagate away from the magma chamber. Thus, the pattern of tectonic stress controls the orientation of volcanic dykes, joints and veins as well as the alignment of volcanic cinder cones [27]. Mud volcanism and the associated mobilization of subsurface shale are also strongly influenced by the state of tectonic stress. High stress magnitudes may result in overpressuring necessary for shale mobilization [28] and the state and orientation of stress controls the migration of mobile shale through shale dykes to the surface [29]. However, there has not yet been any systematic investigation of the influence of tectonic stress on mud volcanism in the Caspian region, and the mud and fluid migration in the mud volcanoes of Azerbaijan is a major item of research [20, 30-34]. The association of gas hydrates and explosive mud volcanism amplifies the chances for massive, and possibly tsunamogenic, slope failure in the Caspian Sea, and thus represents a major threat to petroleum exploration, production operations and to population centers [21].

At small-scales, the present-day stress controls the stability of underground openings, such as tunnels, mines and wells [27, 35]. Stresses become concentrated around any subsurface opening and can, if they exceed the rock strength, result in faulting, fracturing and collapse of the wellbore or tunnel wall. The Caspian is a region of intensive oil and gas exploration and the present-day stress can result in borehole instability issues such as stuck pipe and borehole collapse during drilling, sand production and borehole shearing during production [36]. Such borehole stability issues are major financial concerns to petroleum exploration companies, as they can severely lengthen drilling times or result in the total loss of boreholes. However, knowledge of the stress state can be used to determine borehole geometries, mud weights and production strategies to avoid such wellbore stability problems [37].

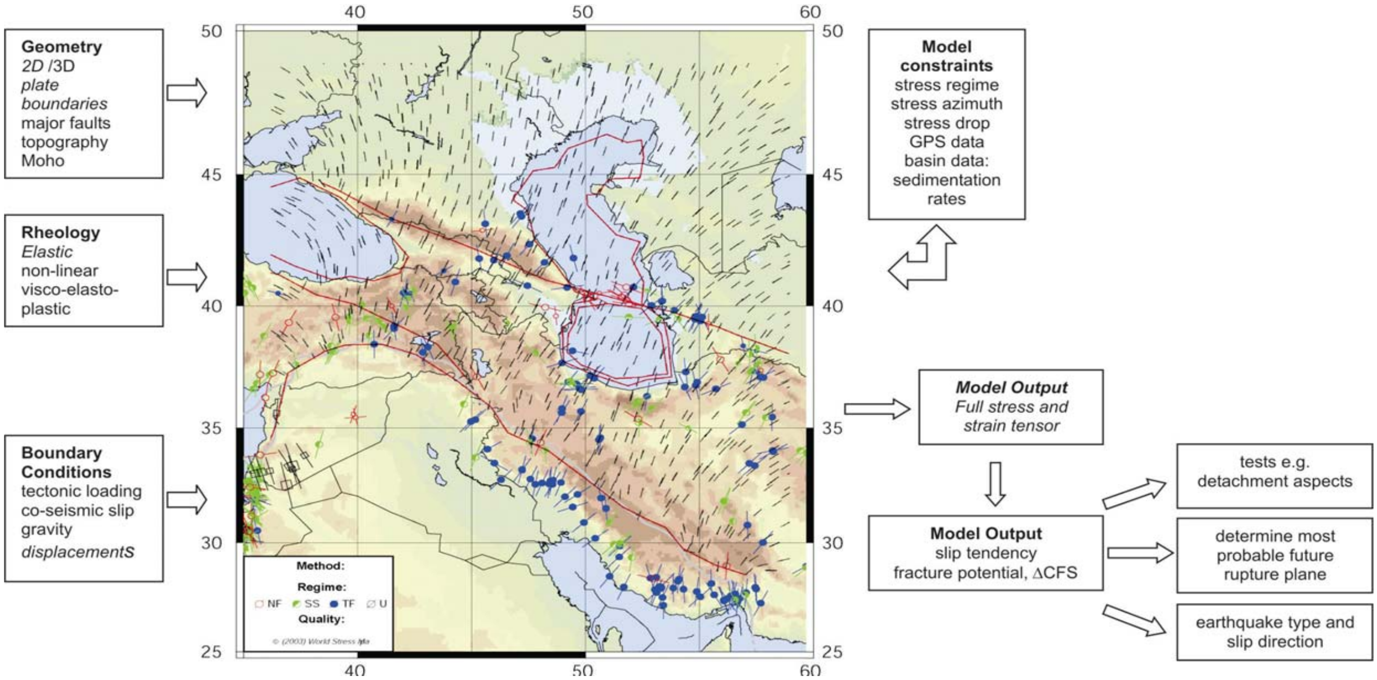

FIGURE. 2 Example for modeled S_H orientations of the Caucasian Caspian area (A. Eckert, pers. comm.). Modeled S_H orientations are indicated by black tick marks. Colored symbols display the observed S_H orientations of the WSM. In this approach, the northward moving stiff Arabian plate causes the stress pattern which fits remarkably good to the observations apart from the central Caspian where subduction tectonics is suggested [38]. This part of the region cannot be represented by this simple 2D elastic FE approach and lateral displacement boundary conditions as they have been applied in this study. Further improvements require 3D modeling, structural refinements (faults and more realistic material parameters) and different loading conditions. Further data as constraints for the modeling results such as the horizontal velocity patterns or stress drops of the earthquakes have to be taken into account.

RELEVANCE OF STRESS OBSERVATIONS FOR HAZARD ASSESSMENT

The use of contemporary tectonic stress as a tool for geohazard assessment is based on three basic concepts: a) failure occurs if stresses concentrate and exceed the failure level [39], which is the tensile strength under tensile stress conditions and the shear strength under anisotropic compressional conditions; b) the concept of frictional failure equilibrium in the crust requires that the state of stress is limited by the strength of those faults that are most favorably oriented for slip, i.e. faults with the maximum shear to normal stress ratio [40-43] and, c) the concept that open fractures are controlled by the stress orientation. Thus, stress orientations control underground pathways for fluid migration either through a crack system aligned parallel to the maximum stress or along sheared faults under an angle of 30°-45° to the maximum stress [44]. Evidence for the crustal frictional failure equilibrium comes from the observations of a) reservoir-induced seismicity, where even small perturbations due to reservoir depletion or injection of fluids into boreholes can trigger seismicity; b) stress measurements in deep boreholes [45, 46] and; c) studies of the nucleation of earthquakes [47, 48].

The current seismotectonic probabilistic approach of earthquake hazard assessment consists of the 1) definition of a source area with 2) observed magnitude frequency relationship data acquired either by modern monitoring systems or by analysis of historic events or paleoseismological evidence and 3) prognosis of ground motion parameters such as peak accelerations for different localities depending on the earthquake magnitude, the hypocentral distance and knowledge of the geological properties between the earthquake hypocenter and the locality of interest, including its immediate subsurface, which are responsible for the seismic wave propagation.

The ground motion prognosis is, in particular, one of the most important parameters for assessing and mitigating seismic hazard, however, accurate analysis of the potential ground motion requires numerical models. Finite Element (FE) models are used to determine the stress evolution over time, the present-day tectonic stress pattern (Fig. 2) and the location, orientation and size of the most probable future failure planes and the likely mode of fault reactivation by slip tendency analysis [49], fracture potential analysis [50, 51], stress regime ratio determination [52], or the calculation of Coulomb Failure Stress changes (ΔCFS) [47, 53] to examine the stress change on given fault systems after a major earthquake [48]. The standard ΔCFS analysis is independent of the regional tectonic stress because it uses the difference in stress states along previously defined (known) faults or parts of fault systems before and after an event. However, these faults are not required to be the most critically stressed faults. Hence, determining the faults most likely to slip following a major earthquake requires a combination of ΔCFS analysis with the regional stress pattern and, for example, slip tendency analysis. The seismic wave propagation and the ground motion can be predicted using Finite Difference (FD) models that are based on the rupture process determined by the FE models and the conditions for seismic wave propagation (velocities, intrinsic or stress induced anisotropies, damping) between the rupture plane and the area of interest.

Benefits achieved by mapping of the contemporary state of tectonic stress in order to improve seismotectonic hazard assessment are:

1) Mapping of stress orientation patterns enables the identification of zones of abrupt changes in stress orientation, singularities of the stress pattern and likely places of stress concentrations [54]. The density of stress trajectories is a measure of principal stress magnitudes. Hence, the identification of stress concentrations can be used to improve seismic zoning and as model constraints.
2) Contemporary tectonic stresses can be used to identify faults, or sections of fault systems, where high shear stress concentrations occur due to secular tectonic loading. This can be achieved to a limited extent from direct observations, but can be assessed at higher resolutions and in areas of sparse observational data by means of numerical modeling of slip tendencies [49] or fracture potential [51].
3) When shear stress on a fault plane exceeds the failure level, the fault slips and modifies the state of stress in its immediate vicinity. This stress redistribution loads or unloads fault segments and thus controls the location and spatial succession of earthquakes [48, 55] ΔCFS analysis can be applied not only on pre-defined faults, but also on fault sections with high shear stress to normal stress ratios.
4) The type of fault reactivation can be derived from the tectonic regime information, either from direct observation or from numerical modeling. The type of rupture (normal, strike slip or thrust faulting) of the seismic source creates different source radiation patterns that can be included in the prognosis of ground motion parameters.
5) The investigation of stress induced anisotropy on seismic wave velocities and damping of seismic wave propagation further constrains predictions and assessments of seismic hazard.

FUTURE OF WSM AS TOOL FOR GEOHAZARD ASSESSMENT: PROSPECTS AND REQUIREMENTS

A closer look on the WSM data distribution indicates that the database requires a higher spatial resolution of data in many regions for future widespread application in geohazard assessment as well as for other applications. In particular, the three-dimensional stress pattern in the crust is poorly known or absent in many continental regions (e.g. SE Asia and the Middle East) and throughout the world's oceans. Furthermore only 500 entries in the WSM database contain information on absolute stress magnitudes whereas 11,692 (73%) of the data provide information on the relative stress magnitudes (*i.e.* the tectonic regimes). Further refinement of the stress maps also requires additional ways of data visualization, such as 3D stress plots or the development of maps displaying absolute or relative stress magnitudes.

Tectonic stress data is already widely used in the mitigation of geotechnical hazards. Engineers collect and use stress information to avoid technical problems in underground constructions, such as tunnels, mines and sites for waste disposal. Tectonic stress data is also routinely used to improve the stability of boreholes and to improve the productivity and efficiency of petroleum and geothermal reservoirs. The value of stress data will become even greater in the future as petroleum exploration expands to deeper waters, increasingly uses deviated drilling techniques and becomes more dependent on Enhanced Oil Recovery (EOR) techniques, such as hydraulic fracturing and water flooding, to add value and increase the life of oil fields. However, despite the value of tectonic stress information for oil exploration, practical and legal issues such as confidentiality and data ownership hinder the ability of the WSM to compile data in many parts of the world (e.g. the Middle East).

In the currently widely used seismotectonic probabilistic approach of seismic hazard assessment, the main foundation lies in the utilization of the statistical distribution of earthquakes in conjunction with geological evidence. However, this seismotectonic probabilistic approach is only successful for localities with frequent earthquakes. This statistical approach to seismic hazard assessment is poor for assessing the risk of low probability extreme magnitude events and for prediction of earthquakes where seismicity has not been previously recorded (e.g. intra-cratonic earthquakes). Especially for strong events, it is necessary to incorporate the cause for earthquake generation with focus on the physics of rupture or reactivation of existing fault plane under the contemporary tectonic stress conditions. An improvement in the estimate of the location, size and orientation of the reactivated fault patch from stress analysis including stress migration effects and time dependent loading conditions of will provide a refinement of the acceleration pattern for an individual event. Thus, knowledge of the contemporary tectonic stress pattern can help to organize or install preventive mitigation measures, reducing the importance of the knowledge of the exact time of the rupture occurrence in the hazard assessment process.

Numerical modeling of local and regional tectonics, stress and strain patterns or geomechanical models on reservoir scale uses stress data either as boundary conditions or constraints. Hence, numerical modeling can help to predict the stress orientation pattern in places where stress observations are sparse. Furthermore, the results of the numerical modeling can be used to quantitatively assess stress concentrations and their evolution in space and time.

Risk mitigation requires not only early warning systems with properly monitoring and alert systems based on the hazard assessment. A major issue is the type and the quality of the information delivered to governmental and local decision makers. In the case of earthquakes, the distribution of peak ground acceleration is valuable information for seismologists, but local decision makers would prefer to have an idea of the expected spatial distribution of collapsed buildings or infrastructure that may be destroyed. Assessment of tsunami impact requires the determination of potential wave heights and inundation. Hence, it is critical in hazard assessment to deduce publicly relevant types of information from basic scientific data. In order to develop such models and predictions researchers must have access to basic scientific information in advance of the event. A prerequisite for such work is an unlimited access to all fundamental geo-databases. This requires open and accessible databases that are continuously maintained to ensure the high quality of the data on a long-term perspective. The data must be transferable to be integrated in different types of application. However, scientific databases often are restricted in access or they are in such a shape that only experts in the immediate field of research can use it. Furthermore scientific databases that are not part of active research become obsolete and moulder in archives, ultimately resulting in an unprofitable investment of money, time and man-power.

Today, one is used to have access to all kinds of information – anywhere at any time. In contrast, research projects based on observational data often end with publications of the main results of the data analysis but without providing access to the data for further studies. The World Stress Map compilation is one example of a sustainable database for fundamental and applied research data because it is an active database that is continuously maintained and expanding and rigorously quality controlled, it enables unrestricted access with free support for a wide range of applications, including geohazard assessment.

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