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Review Article

The World Stress Map database release 2016: Crustal stress pattern across scales

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ABSTRACT

Knowledge of the present-day crustal in-situ stress field is a key for the understanding of geodynamic processes such as global plate tectonics and earthquakes. It is also essential for the management of geo-reservoirs and underground storage sites for energy and waste. Since 1986, the World Stress Map (WSM) project has systematically compiled the orientation of maximum horizontal stress (S_{Hmax}). For the 30th anniversary of the project, the WSM database has been updated significantly with 42,870 data records which is double the amount of data in comparison to the database release in 2008. The update focuses on areas with previously sparse data coverage to resolve the stress pattern on different spatial scales. In this paper, we present details of the new WSM database release 2016 and an analysis of global and regional stress pattern. With the higher data density, we can now resolve stress pattern heterogeneities from plate-wide to local scales. In particular, we show two examples of 40°-60° S_{Hmax} rotations within 70 km. These rotations can be used as proxies to better understand the relative importance of plate boundary forces that control the long wave-length pattern in comparison to regional and local controls of the crustal stress state. In the new WSM project phase IV that started in 2017, we will continue to further refine the information on the S_{Hmax} orientation and the stress regime. However, we will also focus on the compilation of stress magnitude data as this information is essential for the calibration of geomechanical-numerical models. This enables us to derive a 3-D continuous description of the stress tensor from point-wise and incomplete stress tensor information provided with the WSM database. Such forward models are required for safety aspects of anthropogenic activities in the underground and for a better understanding of tectonic processes such as the earthquake cycle.

1. Introduction

Modern civilisation explores the Earth's crust to exploit raw materials and to withdraw or inject fluids. There is also a pressing demand to find deep geological repositories for high-level nuclear waste that are stable for one million years and to explore the possibility to sequestrate huge amounts of carbon dioxide into the underground to meet the Paris climate agreement (Kuckshinrichs and Hake, 2015; Martens et al., 2017; Pusch, 2008). These issues are major challenges for energy security and sustainability in the 21st century. In this context, the contemporary crustal in-situ stress state is a key parameter to quantify the processes that we induce into the subsurface, to mitigate e.g. induced seismicity and to provide options for an optimal usage of the underground (Hakimhashemi et al., 2014a; Henk, 2008; Müller et al., 2018; van Wees et al., 2017; Walsh and Zoback, 2016; Zoback, 2010).

Knowledge of the in-situ stress is also essential for the

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understanding of geodynamic processes such as global plate tectonics and earthquakes (Hardebeck, 2017; Harris, 1998; Heidbach et al., 2008; King et al., 1994; Richardson, 1992; Scholz, 1998; Steinberger et al., 2001; Zoback et al., 1989) as well as to mitigate induced seismicity (Hakimhashemi et al., 2014b; Gaucher et al., 2015; Segall and Fitzgerald, 1998; Zang et al., 2013). The stress evolution during the seismic cycle is one of the key processes that define the maturity of active faults and controls nucleation, rupture propagation and arrest of an earthquake (Hardebeck and Okada, 2018; Hergert and Heidbach, 2011; Oglesby and Mai, 2012; Schorlemmer and Wiemer, 2005; Stein, 1999). From the in-situ stress state the distance to a given failure criterion for any point in the subsurface can be derived. This distance is critical as it indicates the stress changes that are required for reactivation of a pre-existing fault or creation of a new fracture due to induced or natural processes (Morris et al., 1996; Schoenball et al., 2018; Walsh and Zoback, 2016).

The World Stress Map (WSM) is the only project that compiles globally the information on the crustal stress state. It is a collaborative public-domain project between academia and industry that aims to characterize the crustal stress pattern and to understand the stress sources. The year 2016 marked the end of the third phase of the WSM project, and also the 30th anniversary of the project. In this contribution we provide details and new findings of the WSM database release 2016 with a particular emphasis on the state of crustal stress across spatial scales.

The paper opens with a short review on the basics of the stress tensor and the WSM project history followed by the presentation of the new WSM database release 2016. We then perform a global and regional analysis of the stress pattern to revisit the question whether the direction of absolute plate motion is sub-parallel to the long wave-length pattern of the orientation of maximum horizontal stress S_{Hmax}. Afterwards we illustrate with two examples that the increase of data records enables us to resolve stress tensor rotations of 40° to 60° within < 70 km in some regions. The contribution closes with the perspective of the WSM project and how the database will be further developed in the future. Furthermore, we demonstrate with an example that a long-term vision is to derive from the sparse and incomplete point-wise stress information a 3-D continuous description of the stress tensor across different scales from boreholes to plate-wide regions. This is essential to quantify the criticality of the crustal stress state and to determine the distance to failure.

2. The World Stress Map project

2.1. Basics of the stress tensor

The key definitions of the stress tensor concept that are needed to set the framework used in the WSM project are summarized in Fig. 1. To describe the stress state at an arbitrary point a second rank tensor with nine components is defined, but due to its symmetry properties only six components are independent from each other. A formal derivation and further details can be found in standard text books (Engelder, 1992; Fjaer et al., 2008; Jaeger et al., 2007; Zang and Stephansson, 2010; Zoback, 2010).

With the assumption that the vertical stress S_V is one of the three principal stresses (Fig. 1c) the S_{Hmax} orientation determines the orientation of the stress tensor. Given that S_V can be calculated when rock density as a function of depth is known the remaining unknowns are the magnitudes of S_{Hmax} and $S_{hmin,}$ the minimum horizontal stress. It is important to note that the S_{Hmax} orientation is the only component of the stress tensor that can be derived from all stress indicators that are used in the WSM database. Details on individual stress indicators can be found in standard text books (e.g. Amadei and Stephansson, 1997; Zang and Stephansson, 2010; Zoback, 2010) and key papers (Bell, 1996a; Célérier, 2010; Haimson and Cornet, 2003; Ljunggren et al., 2003; Maury et al., 2013; Schmitt et al., 2012; Sperner et al., 2003).

Further information which is provided for subsets of the WSM database is the stress regime, i.e. the relative magnitudes of the three principal stresses (Fig. 1d–f). A few data records also provide information on the stress magnitudes of S_{hmin} derived e.g. from hydraulic fracturing or all three principal stress magnitudes from overcoring methods, but this information is provided without a quality check for reliability or comparability of individual stress indicator.

2.2. History of the WSM project

The first stress data compilation of the intra-plate crustal stress state was published in the early seventies to investigate Voight's hypothesis, which stated that the contemporary compressive crustal stress pattern is controlled by the same forces that drive plate tectonics (Voight, 1966; Voight et al., 1968). Sbar and Sykes (1973) compiled 39 data records from earthquake focal mechanisms, overcoring and hydraulic fracturing measurements and could confirm this hypothesis for North America with this small data set. First global compilations were published by Hast (1973), Ranalli and Chandler (1975), Brown and Hoek (1978), and Richardson et al. (1979) using different stress indicator types and providing data sets on global crustal stress with up to 150 data records. These publications, the start of the systematic global estimation and compilation of earthquake focal mechanism (Dziewonski et al., 1981) and the finding that borehole breakouts can be used as a stress indicator (Bell and Gough, 1979; Plumb and Hickman, 1985; Zoback et al., 1985), initiated the WSM as a project of the International Lithosphere Program in 1986. Focus of the WSM in this initial phase was to compile intra-plate stress data information to investigate the long wave-length of the crustal stress pattern.

In comparison to earlier compilations, the major advancement of the WSM project in its first phase is the application of a quality-ranking scheme developed by Zoback and Zoback (1989, 1991). This WSM quality ranking ensures the global comparability of the different stress indicators that originate from geological and geophysical data as well as from engineering methods. This collaborative attempt resulted in the first comprehensive global compilation that had 3574 data records on the S_{Hmax} orientation (Zoback et al., 1989). The WSM also provides a defined approach for the stress regime assignment based on the spatial orientation in terms of trend and plunge of the P-, T- and B-axes derived from earthquake focal mechanisms (Müller et al., 1992; Zoback, 1992). The analysis of this comprehensive global compilation of crustal stress information showed that most intraplate regions are characterized by compressional or strike slip stress regime except for areas with high elevation where normal stress regime is prevailing. They also found that the wave-lengths of the S_{Hmax} stress pattern can be several thousand kilometres and that the trend of the S_{Hmax} orientation in some tectonic plates is sub-parallel with the direction of absolute plate motion (Richardson, 1992; Richardson et al., 1979; Zoback, 1992; Zoback et al., 1989).

The second phase of the WSM project took place from 1996 to 2008 at the Heidelberg Academy of Sciences and Humanities. During this period, the project intensified the compilation from borehole data and started to include stress information from plate boundary zones as well (Heidbach et al., 2010; Sperner et al., 2003). In 1998, the WSM project went online to make the data publically available and to provide the fully automatic online service CASMO (Create A Stress Map Online) for user-specific stress map production (Heidbach et al., 2004). The complementary stand-alone tool CASMI (Create A Stress Map Interactively) for user-specific stress map generation with an extended functionality was released at the end of the second WSM project phase (Heidbach and Höhne, 2008). The significant increase to 21,750 data records in the WSM database release 2008 revealed that plate boundary forces are not enough to fully explain the crustal stress pattern of the S_{Hmax} orientation (Heidbach et al., 2007; Heidbach et al., 2010; Tingay et al., 2005). Density and rock strength contrasts, detachment horizons due to low shear strength lithologies (e.g. salt layer), faults, flexural stresses and