New Advancement of the World Stress Map Project on the Stress Perturbation in Sedimentary Basins*

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Abstract

Crustal stresses are of extreme importance for understanding both natural processes (e.g. neotectonics, earthquake cycle and seismic hazard assessment) and anthropogenic activities of underground usage (e.g. petroleum exploration and production, geothermal energy extraction, CO2 sequestration, mine stability and design of radioactive waste repositories). The World Stress Map (WSM) is the only public-domain project that compiles since 1986, global information on the crustal stress state. It has had three major phases so far to mainly compile the orientation of maximum horizontal stress (SHmax). The first phase of the project (1986-1992) with ~7,700 data records revealed that plate-scale stress fields are controlled by forces exerted at plate boundaries (e.g. mid-ocean ridges, continental collision zones), often resulting in regional stress orientations sub-parallel to absolute plate motion. Further studies by the WSM team during the second phase (1995-2008) of the project provided 21,750 data records across the world and highlighted that “the large plate boundary forces are not enough” to explain the stress pattern of smaller scales such as sedimentary basins.

2016 marked the end of the third phase of the WSM project, and the 30th anniversary of the project. The new release of the WSM project contains approximately double the information of the 2008 release, with 42,870 data records from various sources of information and across the world. In particular, the new database contains more than 4,000 new data records from sedimentary basins in Australia, New Zealand, China, Canada as well as new stress information from places that previously had limited data such as Eastern South America, Africa and Iceland. This compilation increased the in-situ stress data density significantly and allows revisiting the analysis of stress pattern across spatial scales ranging from plate-wide to basin. Detailed analysis of present-day stresses from over 100 sedimentary basins reveals that significant and complex variations in the present-day stress orientation are commonly observed at both basin (10-200 km) and field (0.1-10 km) scales. Such localised stress rotations have significant petroleum implications, as the stability of wells, direction of induced hydraulic fractures and reactivation potential of faults may vary greatly, even within a single field or well.

Herein, we present the details of the new release of the WSM and the results of a global comparison between absolute plate motion and the mean orientation of maximum horizontal stress on a global regular grid. We also show the newly compiled Australian Stress Map project that contains in-situ stress information from 20 Australian sedimentary basins. In particular, we show that in-situ stress orientation in Australia is controlled by the superposition of plate boundary forces, major intra-plate stress sources, basin geometry, mechanical stratigraphy and geological features. Finally, we demonstrate this relative contribution of the crustal stress sources with an example from Eastern Australia where the stress pattern changes due to different sources. This variability can be used as a proxy to identify and quantify local and regional stress sources and to constrain geomechanical-numerical models of the 3D stress tensor that describe the distance to a critical stress state.

The Stress State in the Earth's Crust

The crustal present-day stress is defined as the contemporary state of tectonic stresses within the subsurface, and is commonly described by four components, namely the magnitudes of overburden stress (Sv), minimum and maximum horizontal stresses (Shmin and SHmax, respectively); and the orientation of SHmax (Zoback, 2007). The stress at any given point has several sources, including 'long-term, ongoing and wide-scale' and 'short-term and local-scale' sources (Heidbach et al., 2007; Heidbach et al., 2018; Rajabi et al., 2017b; Zoback, 2007). In order to better understand the crustal stress state, the analyses of both local- and wide-scale sources are required. Because there is a direct relationship between the stress sources and the application of the present-day stresses in various aspects of human's life.

History of the World Stress Map Project

The World Stress Map (WSM) is the only public-domain project that has compiled, since 1986, global information on the crustal stress state. The WSM project has had three phases so far:

i. The first phase of the project (1986-1995) a project of the International Lithosphere Program and with collaboration of more than 30 scientists across the world that resulted to compilation of ~7700 data records. The key finding of this phase of the project was that the "forces that drive plate motions provide the first-order controls on the crustal stress pattern" (Zoback, 1992; Zoback et al., 1989).
ii. The second phase of the project (1996-2008) at the Heidelberg Academy of Sciences and Humanities. During this period, the project intensified the compilation from borehole data and started to include as well stress information from plate boundary zones. The second phase of the project resulted in 21,750 data records and revealed that "tectonic plate boundary forces are not enough to explain the crustal stress pattern", and highlighted the potentially significant role of 'third-order' stress patterns in some regions (Heidbach et al., 2007; Heidbach et al., 2010; Sperner et al., 2003).
iii. The third phase of the project (2009-2016) at the Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences. This phase of the WSM project involved intensified international collaboration and fully integrated new or updated national stress compilations from Australia, Canada, China, Germany, Iceland, Italy, New Zealand and Switzerland. The resulting current WSM database release 2016 has 42,870 data records, with more than 22,000 new data records (Heidbach et al., 2016).

The 2016 Release of the World Stress Map Project

The 2016 release of the WSM project contains approximately double the information of the 2008 release, with 42,870 data records from various sources of information from across the world. In particular, the new database contains more than 3,500 new data records from deep boreholes in China, Australia and New Zealand as well as new stress information from places that previously had limited data such as Eastern South America, Africa and Iceland. One of the key findings of the first phase of the WSM project was the observation that SHmax was generally oriented parallel to absolute plate motion in stable parts of North America, Europe and South America. Herein we re-visited the question whether the plate boundary forces are the key control of the plate-wide stress pattern as indicated by the first release of the WSM in 1989. As the WSM has now more than 10 times data records and thus a better spatial coverage, we first filter the long-wave length stress pattern. For this analysis, we estimate on a regular grid the mean SHmax orientation using a constant search radius of 500 km as well as a data quality and distance weight. We determine at these grid points the difference between absolute plate motion azimuth using the global plate model HS3-NUVEL1A (Gripp and Gordon, 2002) and the mean orientation of the maximum horizontal stress. The preliminary results show that the earlier findings are still valid in principal. However, all plates show in some parts significant deviations from this general trend; some plates such as the Australian Plate show hardly any correlation at all (Figure 1). The increase in stress data density in the WSM enables us to investigate in detail the rotation of the SHmax orientation on regional scales from 50-500 km in a number of areas. In the following section, we present the state of in-situ stress in the Australian continent where we observed numerous stress perturbations at different scales from <1m to >500km.

Pattern of Crustal Stress in the Australian Sedimentary Basins

Analysis of the regional variability of the present-day tectonic stress in the Australian continent has been the subject of scientific debates for 25 years (Rajabi et al., 2017a; Rajabi et al., 2017b; Reynolds et al., 2002). Various studies on the Australian stress field, coupled with geomechanical-numerical modelling, highlighted that the complex plate boundary forces acting on the Indo-Australian plate provide a first-order control on the pattern of stress in the Australian continent (Rajabi et al., 2017a; Rajabi et al., 2017b). Recent exploration of unconventional reservoirs in Australia, particularly coal seam gas reservoirs in eastern Australia, has provided many new stress orientation data records, and provides an opportunity to make the first major update the Australian Stress Map (ASM) project in 13 years (Rajabi et al., 2017b). The new ASM database includes 2,150 data records in 20 sedimentary basins and 30 stress provinces (Figure 2). The 2016 release of the ASM, with its 934 new stress orientations determined from highly accurate wellbore image log data, confirms that the Australian continent shows a remarkable, and anomalous, regional variability in SHmax orientation that is not directly correlated with absolute plate motion (Figure 1 and Figure 2). In addition to this regional variability, high-density datasets in sedimentary basins of eastern Australia reveal substantial stress perturbations at smaller scales owing to the influence of different geological structures, including basement structures, faults, fractures and lithological contrasts (some examples in Figure 2c and d). See Rajabi et al. (2017b) for more details.

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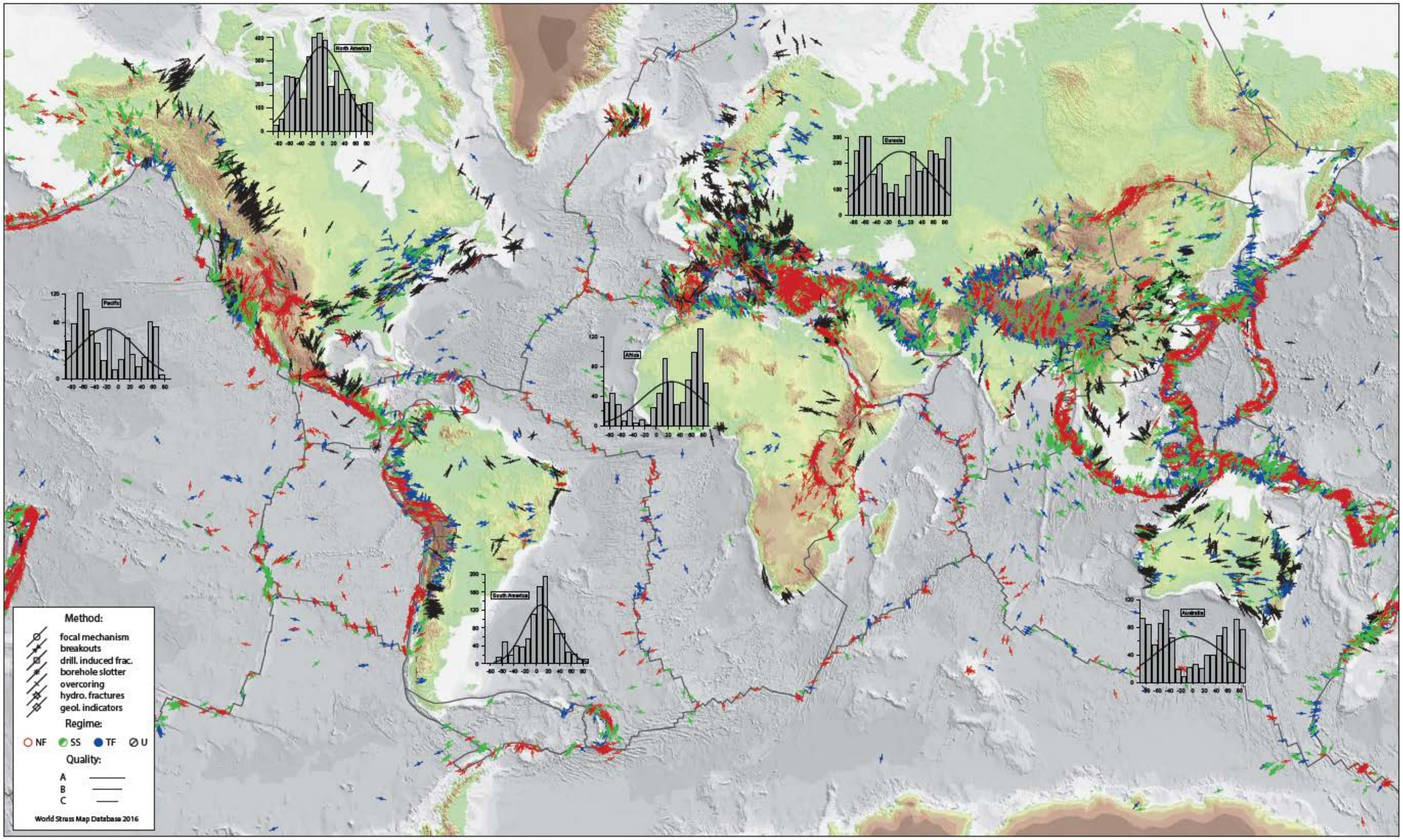

Figure 1. World Stress Map based on the new data compilation with 20,757 A-C quality data records. Note that in this map A-C quality data that are < 100 km away from any plate boundary were not shown (PBE of Heidbach, et. al., 2010). Lines represent the orientation of maximum horizontal stress (SHmax) and their length show proportional to data quality. Different colours indicate stress regimes with red for normal faulting (NF), green for strike-slip faulting (SS), blue for thrust faulting (TF), and black for unknown stress regime (U). Histograms show the deviation between the absolute plate motion azimuth from HS3-NUVEL and the mean SHmax orientation. The mean SHmax orientation is calculated on a 1° grid using a search radius 500 km and applying weighted data quality and distance to the grid point. See Heidbach et al., (2018) for more details.

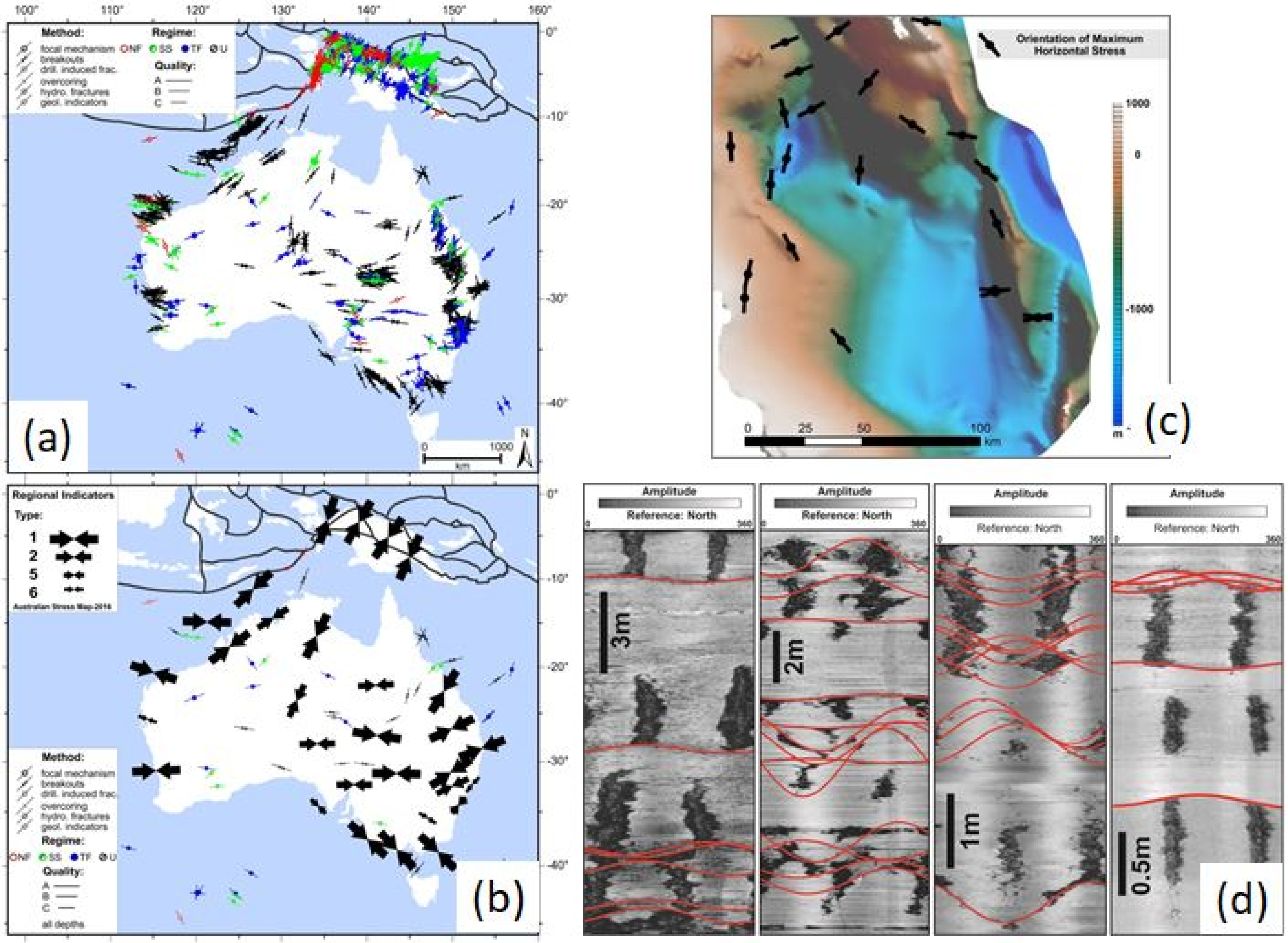

Figure 2. (a) Map showing the 2016 release of the Australian Stress Map with A–C data records and (b) shows the mean orientation of maximum horizontal stress (SHmax) within 30 stress provinces in the Australian continent. Different colours in the map show different stress regimes (SS: strike-slip, NF: normal, TF: thrust and U: undefined tectonic stress regimes). The azimuth of each line shows the SHmax orientation in each location; length of the lines indicates the quality and reliability of SHmax orientations according to the World Stress Map quality-ranking scheme. (c) Significant perturbations in the orientation of SHmax in the Gunnedah Basin, Eastern Australia. The SHmax orientations in this area (c) show a circular trend that follows the basement topography (i.e. background image). (d) Examples of borehole breakout rotations with depth observed in some studied wells in Eastern Australian coal seam gas wells. Red sinusoids show interpreted faults and fractures (See Rajabi et al. (2016) and Rajabi et al. (2017) for more details).