Pattern and origin of the present-day tectonic stress in the Australian sedimentary basins

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SUMMARY

The present-day stress field of Australia has been the subject of great interest in the three past decades because it shows a variable pattern for the orientation of maximum horizontal stress (S_{Hmax}) that is not parallel to absolute plate motion. The last prior release of the Australian Stress Map (ASM) project, published in 2003, contained 549 data records in 16 stress provinces and highlighted the role of plate boundary forces on the regional stress pattern of continental Australia. However, smaller scale rotations of the S_{Hmax} orientation in Australian sedimentary basins were not investigated in great detail in previous studies. Herein, we present the latest release of the ASM with 2140 data records in 30 stress provinces, with a particular emphasis on newly compiled data in eastern Australian basins. The new release of the ASM has stress data from 20 Australian sedimentary basins, which further confirms the regional variability of S_{Hmax} orientations in the Australian continent, and reveals four major trends for the orientation of S_{Hmax} including NE-SW in northern, northwestern and northeastern Australia, E-W in southern half of Western Australia and South Australia, ENE-WSW in most parts of eastern Australia and NW-SE in southeastern Australia. In addition, the 2016 ASM reveals significant rotation of stress within various sedimentary basins due to different geological structures, including basement structures, faults, fractures and lithological contrasts. Understanding and predicting local stress perturbations has major implications for determining the most productive fractures in petroleum and geothermal systems, and for modelling the propagation direction and vertical height growth of induced hydraulic fractures in unconventional reservoirs.

Key words: Australian stress map, present-day stress field, Australian sedimentary basins, localised perturbation of stress.

INTRODUCTION

The present-day stress field of Australia is highly variable and unique when compared to other continents (Coblentz et al., 1995; Hillis and Reynolds, 2003; Richardson, 1992; Zoback et al., 1989). The Australian Stress Map project (ASM) was initiated in 1996 at the University of Adelaide under leadership of Richard Hillis and has been updated three times including the most recent previous public release of the project in 2003 (Hillis et al., 1998; Hillis and Reynolds, 2000, 2003). The 2003 release of the ASM was comprised of 549 S_{Hmax} data records and successfully constrained the S_{Hmax} orientation in 16 stress provinces through Australia and Papua New Guinea (Hillis and Reynolds, 2003). In addition, numerous geomechanical-numerical models highlighted that the stress pattern of continental Australia, at the first order, is controlled by complex plate boundary forces around the Indo-Australian Plate (Coblentz et al., 1995; Coblentz et al., 1998; Dyksterhuis et al., 2005; Reynolds et al., 2002, 2003). However, most of our knowledge on the Australian stress field, prior to this study, was confined to ten mature petroleum basins and there were significant uncertainties on the stress pattern throughout Australia and in other sedimentary basins.

This current phase of the ASM project was started in 2012 to improve our understanding of the stress pattern in parts of the continent that previously had sparse or no published stress data. During the past four years, we compiled a significant amount of new stress data in 20 sedimentary basins across the Australian continent, and present the new release of the ASM with 2140 data records and 30 stress provinces. In particular, we have compiled numerous data from coal seam gas basins of eastern Australia, including the Clarence-Moreton, Gunnedah, Gloucester, Sydney, Surat, Bowen and Galilee basins to investigate the pattern of S_{Hmax} orientation where there was limited stress information prior to this study.

In this paper we present the new release of the ASM and explain the four major trends of S_{Hmax} in the Australian continent. We compare the new stress map of Australia with published geomechanical-numerical models of the Australian stress field and show that the published models are unable to satisfactorily predict the state of stress in most of eastern Australia. We then explain the role of different orders of stress sources on the Australian stress field and highlight that significant localised perturbations of stress exist at different scales due to smaller stress sources, including basement structures, faults, fracture and lithological contrasts.

METHODOLOGY

In this study we compiled and interpreted the in-situ stresses from five well-known methods used by the World Stress Map (WSM) project (Heidbach et al., 2010) to investigate the orientation of S_{Hmax} in the Australian continent from the near surface down to 40 km depth in the lithosphere. The majority of new data are from the interpretation of drilling-related stress indicators, including borehole breakouts and drilling-induced fractures (Figure 1) in 750 mineral, petroleum and geothermal wells. Each stress indicator in the database has been ranked based on the WSM quality ranking system from A to E quality. A-quality data indicate the S_{Hmax} orientation accurate to within ±15°, B-quality to within ±15-20°, C-quality to within ±20-25°, D-quality to within ±25-40° and E-quality indicates no reliable information (Heidbach et al., 2010). In order to determine the regional state of stress throughout the continent, different techniques including *definition of stress provinces*, *wavelength analysis of stress orientation* and *mapping of stress trajectories* have been applied. The new release of the ASM has 30 stress provinces that are located in different sedimentary basins.

CONTINENTAL SCALE PATTERN OF STRESS

Analysis of stress data throughout the Australian continent reveals four major S_{Hmax} orientations across the continental Australia. The mean S_{Hmax} orientation in the northern, northwestern and northeastern Australia is NE-SW. There is a prevailing E-W S_{Hmax} orientation in the Browse Basin in North West Shelf, southern half of Western Australia (Perth and Carnarvon basins) and most studied parts of South Australia (Officer, Cooper-Eromanga, Arckaringa and Darling basins). The mean S_{Hmax} orientation in most parts of eastern Australia is ENE-WSW across many different sedimentary basins, with S_{Hmax} then rotating to NW-SE in southeastern Australia (Gippsland, Bass and Otway/Sorell basins). Statistical analysis (Rayleigh analysis) of the stress provinces shows that the mean S_{Hmax} orientation in 25 provinces is of type 1 or 2 according to the Hillis and Reynolds (2003) classification, and is thus considered highly reliable. The majority of stress provinces in the western half of the continent, as well as southeastern Australia, show low standard deviation. However, most of stress provinces in eastern Australia show higher standard deviation, indicating a higher variability of the S_{Hmax} orientation in these regions. In addition, the Flinders Ranges, Southeast and Southwest Seismogenic zones, which are based on focal mechanism solutions of earthquakes (FMS), show significant deviations of the S_{Hmax} orientation that are probably due to either the standard inherent uncertainty in S_{Hmax} orientation determined from the FMS method (Barth et al., 2008; McKenzie, 1969), or due to local stress perturbations generated by neotectonic activity.

CONTROLS ON THE AUSTRALIAN STRESS PATTERN

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 (Coblentz et al., 1995; Coblentz et al., 1998; Dyksterhuis et al., 2005; Reynolds et al., 2002, 2003). However, recent studies on the stress pattern of eastern Australian basins highlights that the new observational data are not consistent with model predictions (Brooke-Barnett et al., 2015; Rajabi et al., 2016a, b). For example, Rajabi et al. (2016) highlighted the inconsistency between plate scale models and observational data in NSW, and explained the inability of the previous models to replicate the stress pattern due to lack of model-independent data (for model calibrations) or poor modelling strategies. Although there is poor consistency between published models and the newly observed data in eastern Australia, comparison between the regional stress pattern of stress in the Australian continent and the plate boundary forces around the Indo-Australian plate (Figure 2) further confirm the role of plate boundary forces as the first order stress sources for Australia. Thus, this new 2016 ASM dataset further highlights that previous models need to be adjusted in terms of modelling strategy and boundary conditions to fit the stress data in the Australian continent (Rajabi et al., 2016a, b).

In addition, extensive analysis of borehole image logs in different sedimentary basins reveals variable patterns of stress due to the presence of geological structures. Detailed analysis of borehole image logs in the Clarence-Moreton Basin of NSW revealed the role of faults and fractures in the present-day pattern of S_{Hmax} (Rajabi et al., 2016b). Basin geometry and basement structures play a critical role in perturbation of stress in the Gunnedah, Bowen and Surat basins (Rajabi et al., 2016a). Igneous intrusions into sedimentary layers are also important sources of stress perturbation at smaller scales in several basins of eastern Australia (Rajabi et al., 2016b). Hence, we suggest four orders of stress sources for the pattern of the Australian stress field (Table 1) that affect the present-day stress orientation at any location.

CONCLUSIONS

The new 2016 release of the ASM database contains 2140 (A-E) data records and 30 stress provinces, and has made significant improvements in characterizing the Australian present-day stress field, both in quality and quantity. Statistical analysis of the stress data shows four major patterns of stress across the Australian continent. The new findings suggest that plate boundary forces and gravitational potential energy are the major controls on the long wavelength stress pattern of the continent, but that local stress sources due to geological structures are also highly significant and can lead to substantial changes in the orientation of the S_{Hmax} at the basin, field and well scale.

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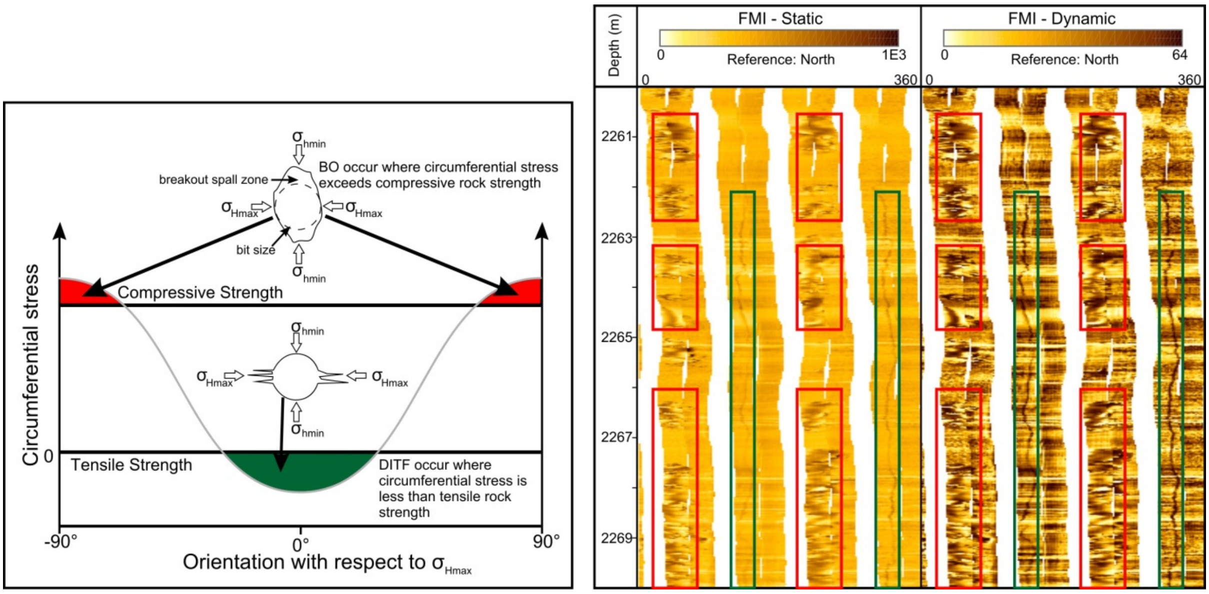

Figure 1: Left) Orientation of borehole breakouts (BOs) and drilling induced tensile fractures (DIFs) with respect to the circumferential stress around the wellbore (Hillis and Reynolds, 2000). Right) Typical examples of BOs and DIFs in FMI log observed on opposite sides of the wellbore (separated by approximately 180°).

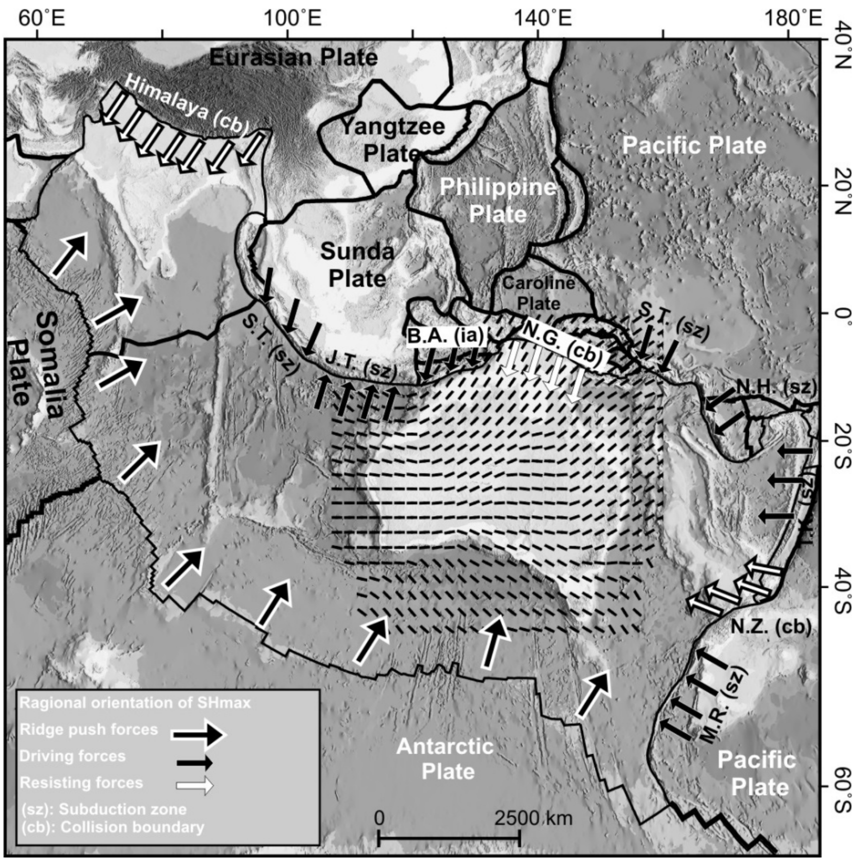

Figure 2: Plate tectonic setting and plate boundary forces around the Indo-Australian plate. The smoothed pattern of maximum horizontal stress orientation across the Australian continent is also plotted in this figure. The force arrows are not drawn to scale. The background image is the ETOPO 1 from Amante and Eakins (2009).

<table>
<tr><th>Order of stress sources</th><th>First
>500 km</th><th>Second
500-100 km</th><th>Third
100-1 km</th><th>Fourth
<1 km</th></tr>
<tr><td>Stress Sources</td><td>• Plate boundary forces: (ridge push, slab pull, trench suction)
• Gravitational potential energy
• Basal tractions originating from density driven mantle convection</td><td>• Lithospheric flexure
• Localized lateral density contrasts/buoyancy forces, lateral strength contrasts (anisotropy of material properties)
• Large fault zones
• Erosion and topography
• Local density or strength contrasts,
• Basin geometry and basement topography</td><td>• Faults
• Lowering of the water table
• Impoundment dams
• Man-made excavation,
• Man-made downhole pressure changes
• Other geological structures such as diapirs, folds, basal detachment mechanical contrasts basment structures</td><td>• Various geological structures with localized effects on small scales in couple of meters up to 1000 m</td></tr>
<tr><td>Effects</td><td>Plate to continent</td><td>Continent to inter-sedimentary basins</td><td>Intra-sedimentary basins to inter-wells</td><td>Wellbore scale</td></tr>
<tr><td rowspan="3">Implications</td><td>• Geodynamics and plate driving forces
• Intra-plate characteristics</td><td>• Intraplate deformation
• Geomechanical characterization of large geo-reservoirs</td><td rowspan="2">• Geomechanical characterization of petroleum basins
• Geothermal exploration
• CO_2 storage
• Mine safety
• Stability of tunnels</td><td rowspan="2">• Geomechanical characterization of unconventional and geothermal reservoirs (particularly in hydraulic fracture designe)</td></tr>
<tr><td colspan="2">• Lithosphere characteristics
• Geological structures
• Neotectonic evolution</td></tr>
<tr><td></td><td colspan="3">• Geomechanical assessment of geo-reservoirs
• Earthquake hazard assessment
• Induced seismicity (impoundment dams, mining operations, fluid injection or withdrawal)</td></tr>
</table>

Table 1: Orders of the stress sources for the Australian continent (modified from Heidbach et al., (2007), Reiter et al., (2014), Tingay et al., (2006), Zoback, (1992).

REFERENCES

Amante, C., Eakins, B.W., 2009, ETOPO1 1 arc-minute global relief model procedures, data sources and analysis. NOAA Technical Memorandum NESDIS NGDC-24: National Geophysical Data Center, NOAA.

Barth, A., Reinecker, J., Heidbach, O., 2008, Stress derivation from earthquake focal mechanisms: World Stress Map Project Guidelines, (12pp). Available on:
http://dc-app3-14.gfz-potsdam.de/pub/guidelines/WSM_analysis_guideline_focal_mechanisms.pdf.

Brooke-Barnett, S., Flottmann, T., Paul, P.K., Busetti, S., Hennings, P., Reid, R., Rosenbaum, G., 2015, Influence of basement structures on in situ stresses over the Surat Basin, southeast Queensland: Journal of Geophysical Research: Solid Earth, 120, 4946-4965.

Coblentz, D.D., Sandiford, M., Richardson, R.M., Zhou, S., Hillis, R.R., 1995, The origins of the intraplate stress field in continental Australia: Earth and Planetary Science Letters, 133, 299-309.

Coblentz, D.D., Zhou, S., Hillis, R.R., Richardson, R.M., Sandiford, M., 1998, Topography, boundary forces, and the Indo-Australian intraplate stress field: Journal of Geophysical Research: Solid Earth, 103, 919-931.

Dyksterhuis, S., Albert, R.A., Müller, R.D., 2005, Finite-element modelling of contemporary and palaeo-intraplate stress using ABAQUS™: Computers & geosciences, 31, 297-307.

Heidbach, O., Reinecker, J., Tingay, M., Müller, B., Sperner, B., Fuchs, K., Wenzel, F., 2007, Plate boundary forces are not enough: Second- and third-order stress patterns highlighted in the World Stress Map database: Tectonics, 26, TC6014.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., Müller, B., 2010, Global crustal stress pattern based on the World Stress Map database release 2008: Tectonophysics, 482, 3-15.

Hillis, R.R., Meyer, J.J., Reynolds, S.D., 1998, The Australian stress map: Exploration Geophysics, 29, 420-427.

Hillis, R.R., Reynolds, S.D., 2000, The Australian Stress Map: Journal of the Geological Society, 157, 915-921.

Hillis, R.R., Reynolds, S.D., 2003, In situ stress field of Australia: Geological Society of America Special Papers, 372, 49-58.

McKenzie, D.P., 1969, The relation between fault plane solutions for earthquakes and the directions of the principal stresses: Bulletin of the Seismological Society of America, 59, 591-601.

Rajabi, M., Tingay, M., Heidbach, O., 2016a, The present-day stress field of New South Wales, Australia: Australian Journal of Earth Sciences, doi: 10.1080/08120099.2016.1135821

Rajabi, M., Tingay, M., King, R., Heidbach, O., 2016b, Present-day stress orientation in the Clarence-Moreton Basin of New South Wales, Australia: a new high density dataset reveals local stress rotations: Basin Research, doi: 10.1111/bre.12175

Reiter, K., Heidbach, O., Schmitt, D., Haug, K., Ziegler, M., Moeck, I., 2014, A revised crustal stress orientation database for Canada: Tectonophysics, 636, 111-124.

Reynolds, S.D., Coblentz, D.D., Hillis, R.R., 2002, Tectonic forces controlling the regional intraplate stress field in continental Australia: Results from new finite element modelling: Journal of Geophysical Research: Solid Earth, 107, ETG 1-1-ETG 1-15.

Reynolds, S.D., Coblentz, D.D., Hillis, R.R., 2003, Influences of plate-boundary forces on the regional intraplate stress field of continental Australia: Geological Society of America Special Papers, 372, 59-70.

Richardson, R.M., 1992, Ridge forces, absolute plate motions, and the intraplate stress field: Journal of Geophysical Research: Solid Earth, 97, 11739-11748.

Tingay, M., Muller, B., Reinecker, J., Heidbach, O., 2006, State and Origin of the Present-Day Stress Field in Sedimentary Basins: New Results from the World Stress Map Project, The 41st U.S. Symposium on Rock Mechanics (USRMS): American Rock Mechanics Association, Golden, Colorado

Zoback, M.L., 1992, First- and second-order patterns of stress in the lithosphere: The World Stress Map Project: Journal of Geophysical Research: Solid Earth, 97, 11703-11728.

Zoback, M.L., Zoback, M.D., Adams, J., Assumpcao, M., Bell, S., Bergman, E.A., Blumling, P., Brereton, N.R., Denham, D., Ding, J., Fuchs, K., Gay, N., Gregersen, S., Gupta, H.K., Gvishiani, A., Jacob, K., Klein, R., Knoll, P., Magee, M., Mercier, J.L., Muller, B.C., Paquin, C., Rajendran, K., Stephansson, O., Suarez, G., Suter, M., Udias, A., Xu, Z.H., Zhizhin, M., 1989, Global patterns of tectonic stress: Nature, 341, 291-298.