The present-day state of tectonic stress in eastern Australia

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SUMMARY

Knowledge of the present-day stress is important to understand the dynamics of earthquakes, and to manage the safe and sustainable usage of the underground during storage and exploitation. Eastern Australia hosts several sedimentary basins with large coal-seam gas reserves as well as mines that are critical for Australia's energy and resources. Some of the eastern Australian basins such as the Surat, Gippsland and Otway basins have been proposed as potential CO_2 storage sites. In addition, the Sydney Basin in New South Wales is one of Australia's most seismically active areas.

This paper examines the state of present-day stress in eastern Australia from variety of sources including wellbore data, focal mechanism solution of earthquakes, hydraulic fracturing and overcoring tests. In particular, this paper presents the state of stresses in the Bowen, Surat, Clarence-Moreton, Sydney, Gunnedah, Gippsland, Galilee, Cooper, Eromanga, Darling and Otway basins. Analysis of stress data in northeastern Australia (i.e., Bowen and Surat basins) shows a regional orientation of NNE-SSW for the maximum horizontal stress (S_{Hmax}), which rotates to ENE-WSW in the Clarence-Moreton, Gunnedah, and Sydney basins. The S_{Hmax} orientation is E-W in the Galilee, Eromanga and Cooper basins, and rotates to NW-SE in the Gippsland and Otway basins in southeastern Australia. In addition to regional variability, significant stress changes (both orientation and magnitudes) at local scales have been observed due to presence of geological structures, which highlight the importance of geology for geomechanical assessment of the basins.

Key words: Australian stress field, Eastern Australia, Present-day stress, Neotectonic.

INTRODUCTION

Analysis of crustal stress at large-scales (i.e., >500 km) provides information on the neotectonic deformation, geodynamic process, and seismic hazard assessments (Heidbach et al., 2018; Heidbach et al., 2019; Rajabi et al., 2017b). While the study of *in-situ* stress at smaller-scales has significant applications in civil engineering and mining projects, as well as geomechanics of geo-reservoir (Bell, 1996; Rajabi et al., 2017b). Eastern Australia has a complex stress pattern that has been the subject of considerable debate in the last three decades (Brooke-Barnett et al., 2015; Hillis et al., 1999; Rajabi et al., 2016a, b; Rajabi et al., 2017b; Rajabi et al., 2017c; Tavener et al., 2017).

Recent *in-situ* stress analyses in Australian continent have revealed massive stress perturbation in Australian sedimentary basins. In particular, wellbore stress data in eastern Australian basins revealed that the analyses of a couple of borehole measurements in one area might not be a good representation of the regional stress pattern. Similarly, large scale stress analyses do not necessarily show the present-day stress pattern at smaller scales (Heidbach et al., 2018; Rajabi et al., 2017b). It means the scale matters for the analyses of crustal stress.

Since the latest update of the Australian Stress Map (ASM) in 2017 by Rajabi et al., (2017b), more than 250 wellbore image log data in eastern Australian sedimentary basins including Surat, Bowen, Gunnedah and Galilee have been interpreted. Hence, the current database contains 1259 data records for the maximum horizontal stress (S_{Hmax}) orientation for eastern Australia. In addition, 201 *in-situ* stress magnitude (and stress regime information) data inferred from leak off tests, extended leak off tests, and hydraulic measurement tests have been compiled and interpreted in order to better understand the stress pattern in the Australian crust. This *in-situ* stress information has massive implications in eastern Australian geomechanical studies.

The result of this study indicates massive perturbation of S_{Hmax} orientation across the eastern Australian basins. In addition, most of the data records show thrust faulting stress regime in shallower intervals that change to strike-slip and normal faulting in the deeper intervals. Hence, this study further highlights the importance of local stress studies in future exploration and productions in these basins.

METHODS

The *in-situ* stress in the Earth's crust is described by four components, namely the orientation of maximum horizontal stress (S_{Hmax}), and the magnitudes of overburden stress (S_v), minimum and maximum horizontal stresses (Engelder, 1993).

There are numerous methods to analyse the present-day crustal stress state at different depth ranges (Engelder, 1993). Civil engineering projects and mining industry activities generally require the *in-situ* stress state at shallower depths (typically <1 km depth), while geo-reservoir activities (such as petroleum, geothermal, and geo-storage projects) involve understanding of the stress state at intermediate depths (typically 1-5 km depth), and seismological analysis generally focusses on deeper stresses (typically deeper than 5 km depth)

In-situ stress data in this paper are compiled and analysed from five standard methods used by the World Stress Map (WSM) Project including focal mechanism solutions of earthquakes (FM), borehole breakouts (BO), drilling-induced tensile fractures (DIF), overcoring (OC), hydraulic fracturing measurements (HF). Each stress-measurement indicator has been ranked using the WSM quality ranking systems for both S_{Hmax} orientation (Heidbach et al., 2018) and S_{hmin} magnitude (Morawietz et al., 2020) from A to E quality.

STATE OF THE PRESENT-DAY STRESS IN EASTERN AUSTRALIA

Over the past decade, several researchers have investigated the *in-situ* stress pattern of eastern Australian basins with particular emphasis on the coal seam gas reservoirs (Brooke-Barnett et al., 2015; Mukherjee et al., 2020; Rajabi et al., 2017c; Salmachi et al., 2016; Salmachi et al., 2021; Tavener et al., 2017). The 2017 release of the Australian Stress Map (ASM) database has shown massive stress perturbations in most of the Australian basins (Rajabi et al., 2017b). This paper presented an updated version of ASM over the eastern Australian basins including Bowen, Surat, Galilee, Darling, Clarence-Moreton, Sydney, Gunnedah, Gloucester, Cooper, Eromanga, Gippsland, Otway, Bass and Sorell basins. The 2021 version of ASM has over 1259 S_{Hmax} data records in eastern Australia that further highlights localised perturbation of S_{Hmax} at small scales (<1 km).

The *in-situ* stress information in eastern Australia is mostly based on the wellbore data in coal seam gas basins (wellbore image log data) and coal mines (image log data, overcoring and hydraulic fracturing measurements), and to a lesser extent from earthquake focal mechanism solutions. As explained by Rajabi et al. (2017b), the regional pattern of S_{Hmax} orientation in the northeastern Australia is NE-SW and rotates to ENE-WSW in most eastern Australia. The S_{Hmax} orientation in south-eastern Australia is NW-SE, and a predominant E-W S_{Hmax} orientation exists in many parts of central Australia including Cooper-Eromanga Basins (Figure 1).

Statistical analyses of stress data in eastern Australia resulted in the classification of nine stress provinces. Wavelength analysis of stress pattern at basin scale, presented in Figure 1, shows that the mean S_{Hmax} orientations in eastern Australian basins are highly variable. Northern part of the Bowen Basin shows a NNE-SSW orientation for the S_{Hmax} orientation that rotates to ENE-WSW in most southern part of the Bowen Basin as well as the Surat Basin. The regional S_{Hmax} orientation in New South Wales' sedimentary basins has a regional NE-SW trend, but there are significant variabilities similar to other basins across eastern Australia. As shown in Figure 1, the regional orientation of S_{Hmax} in the Clarence-Moreton and Gunnedah basins is ENE-WSW. The Sydney Basin in New South Wales shows two regional S_{Hmax} trends including NE-SW and ENE-WSW. Southeastern Australia including Gippsland, Otway, Bass and Sorell basins show a NW-SE orientation. As outlined above, the S_{Hmax} orientation in central Australia and central western part of New South Wales including Cooper, Eromanga, Galilee and Darling basins is E-W.

In addition to stress variability from basin to basin (see Figure 1), significant stress perturbations, at basin and wellbore scales, have been identified in most of coal seam gas basins. High-density *in-situ* stress data when compared with geological information and seismic lines can be used to explain the role of geological structures (such as faults and fractures, as well as changes in lithologies) in stress perturbations at smaller scales (Rajabi et al., 2017b).

In the new version of ASM, stress magnitude data is also being compiled and interpreted in more details. The current database contains 201 A-E quality *in-situ* stress magnitude data (following the new WSM ranking for stress magnitude data) inferred from leak off tests, extended leak off tests, overcoring and hydraulic measurements in mine sites (Figure 1). The majority of stress magnitude data are from shallower parts of the crust (less than 1 km). These stress magnitude data (and stress regime) show a prevailing thrust regime in the shallower intervals and some changes to strike-slip and normal stress regime in deeper intervals. These new stress magnitudes are consistent with a large-scale 3D geomechanical model for Australian crust (Rajabi et al., 2017a). Note that similar to S_{Hmax} data, the stress magnitudes and stress regimes also show stress variabilities mainly due to lithology changes and geological structures. Similar changes of stresses have been previously reported in eastern Australian basins (Brooke-Barnett et al., 2015; Hillis et al., 1999; Mukherjee et al., 2020; Rajabi et al., 2016a, b; Rajabi et al., 2017b; Rajabi et al., 2017c; Tavener et al., 2017).

Generally, *in-situ* stresses have numerous implications in geomechanics of geo-reservoirs and mines. For example, *in-situ* stresses control mine stability, subsurface fluid flow in fractured reservoirs (such as coal seam gas reservoirs), wellbore stability, hydraulic fracture design, and induced seismicity (Heidbach et al., 2018; Morawietz et al., 2020). This is particularly important for eastern Australia, which contains vast unconventional reserves and mine sites. Hence, the state of stress is critical for exploration and production in these regions.

CONCLUSIONS

This paper presented new *in-situ* stress orientations and magnitudes information over eastern Australian sedimentary basins. New stress data further highlights the stress variabilities in eastern Australian basins due to presence of geological structures, basement features and lithology changes. The relationship between the stress variability and the complexity in geology clearly highlights that geological understanding is an important part of any stress analysis, particularly at basin and wellbore scales.

More importantly, massive stress perturbation at smaller scales in the study areas highlighted that detailed stress analyses should be conducted in any future exploration and production in these basins, because stress perturbations have important implications in different aspects of mining and geo-reservoirs in eastern Australia.

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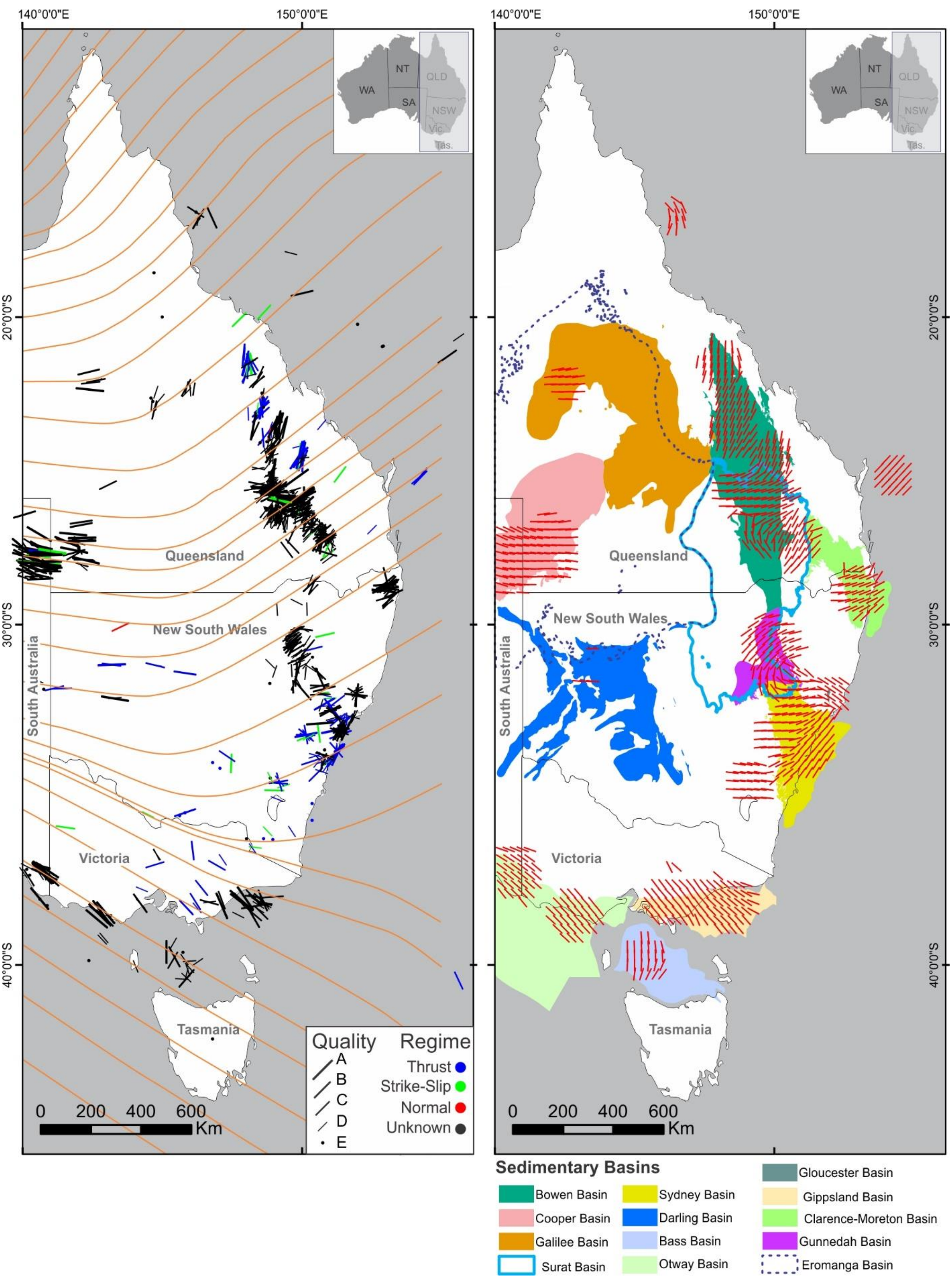

Figure 1: Present-day stress map of eastern Australia. Left) *In-situ* stress data records in different basins based on wellbore data, focal mechanism solutions of earthquakes, overcoring and hydraulic measurements. Length of the lines represent the World Stress Map quality from A to E; and different colours indicate stress regime (SS, strike-slip faulting; TF, thrust faulting; NF, normal faulting; and U, undefined). Orange lines show the regional orientation of maximum horizontal stresses (i.e., S_{Hmax}). Right) Location of the studied sedimentary basins in eastern Australia with the basin wide mean S_{Hmax} orientation (red lines). Detailed information on the methodology of the smoothing stress pattern (orange and red lines) can be found in Rajabi et al., (2017b) and Heidbach et al., (2018).