A novel approach for geomechanical modelling in the absence of stress magnitude data

Mojtaba Rajabi[A*], *Moritz Ziegler*[B,C], *Rasoul Ranjbarkarami*[A], *Parisa Tavoosiiraj*[A]

[A]School of the Environment, University of Queensland, St Lucia, QLD, Australia

[B]Technical University of Munich, Arcisstrasse 21, Munich, Germany

[C]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany

*Correspondence to Mojtaba Rajabi. Email: m.rajabi@uq.edu.au AND m.rajabi@hotmail.com

Abstract. Geomechanics play an important role in any underground activity, such as CO_2 and H_2 geo-storage, owing to the considerable hazards linked to the injection and withdrawal of fluids into and from the subsurface. In order to quantify these risks, knowledge of full stress tensor is required. Yet, most of our stress information in the Australian target basins for geo-storage, is limited to the stress orientations, whereas stress magnitude data is sparse.

3D geomechanical modelling is proved to be an invaluable tool for prediction of full stress tensor. Nevertheless, a model requires some stress magnitude data in order to tune the model to be representative of real stress state. In situations where stress magnitude data is lacking, this means that the model is susceptible to significant uncertainties. Herein, we present a novel strategy for stress modelling, which involves the utilization of indirect data such as borehole breakouts, drilling-induced fractures, seismic activity records, and formation integrity tests to calibrate 3D geomechanical model. We employ northern Bowen Basin that is an onshore basin in Queensland, Australia, as a case study for a comprehensive 3D geomechanical modelling approach. We assess all the indirect information in the model's volume to narrow down the model predictions and find the most reliable stress state. This innovative approach is an important step forward in stress modelling of Australian basins, where lack of stress magnitudes is a great challenge for geomechanical assessment of geo-storage.

Keywords: 3D geomechanical-numerical modelling, Bowen Basin, In-situ stress, Stress magnitudes

Introduction

Knowledge of in-situ stress is essential for any subsurface activities such as geomechanical analysis of geo-storage reservoirs (i.e., CO_2 and hydrogen), geothermal exploration and production, waste disposal, and safety and stability of mines (Rutqvist 2012; Vilarrasa *et al.* 2019; Jolie *et al.* 2021; Rajabi *et al.* 2024). Nevertheless, stress magnitude data in a basin commonly display sparsity, the existing data often suffer from considerable uncertainties, and acquiring new stress data is costly. This underscores the significance of predictive tools for estimating stress magnitudes within a specific region.

3D geomechanical-numerical modelling is widely recognized as a well-established method for predicting various geomechanical parameters. However, to ensure the reliability of such a model, extensive datasets of stress magnitudes are necessary for model calibration (Rajabi *et al.* 2017a; Morawietz *et al.* 2020; Ziegler and Heidbach 2023; Ziegler *et al.* 2023). The most recent update of the Australian Stress Map has highlighted a significant gap in stress magnitude data across all Australian basins (Rajabi *et al.* 2017a; Rajabi *et al.* 2017b). Consequently, developing reliable stress models for these basins poses a great challenge, as the absence of stress magnitude information increases the uncertainty of the model.

This study examines indirect observation of stress data in addition to, and even instead of, stress magnitudes, as a proxy for 3D geomechanical model calibration (Ziegler and Heidbach 2023). Our research focuses on the northern Bowen Basin, benefiting from a recent comprehensive geomechanical and geological analysis (Rajabi *et al.* 2023; Rajabi *et al.* 2024), which presents a unique opportunity for this study.

Study area

The Early Permian - Late Triassic Bowen Basin is an important basin in eastern Australia (Figure 1), with vast potential across energy and resources sectors including mining, natural gas, and CO_2 storage (Boreham *et al.* 1998; Salmachi *et al.* 2021; Rajabi *et al.* 2024). The basin contains up to 10 km of sedimentary fills and it extends from northern New South Wales to northern Queensland. This study examines the northern part of the Bowen Basin (i.e., north of 24°S) to test an innovative approach for 3D stress modelling. We used this part of the Bowen Basin due to the recent increase in geological, geomechanical and geophysical data (Rajabi *et al.* 2023).

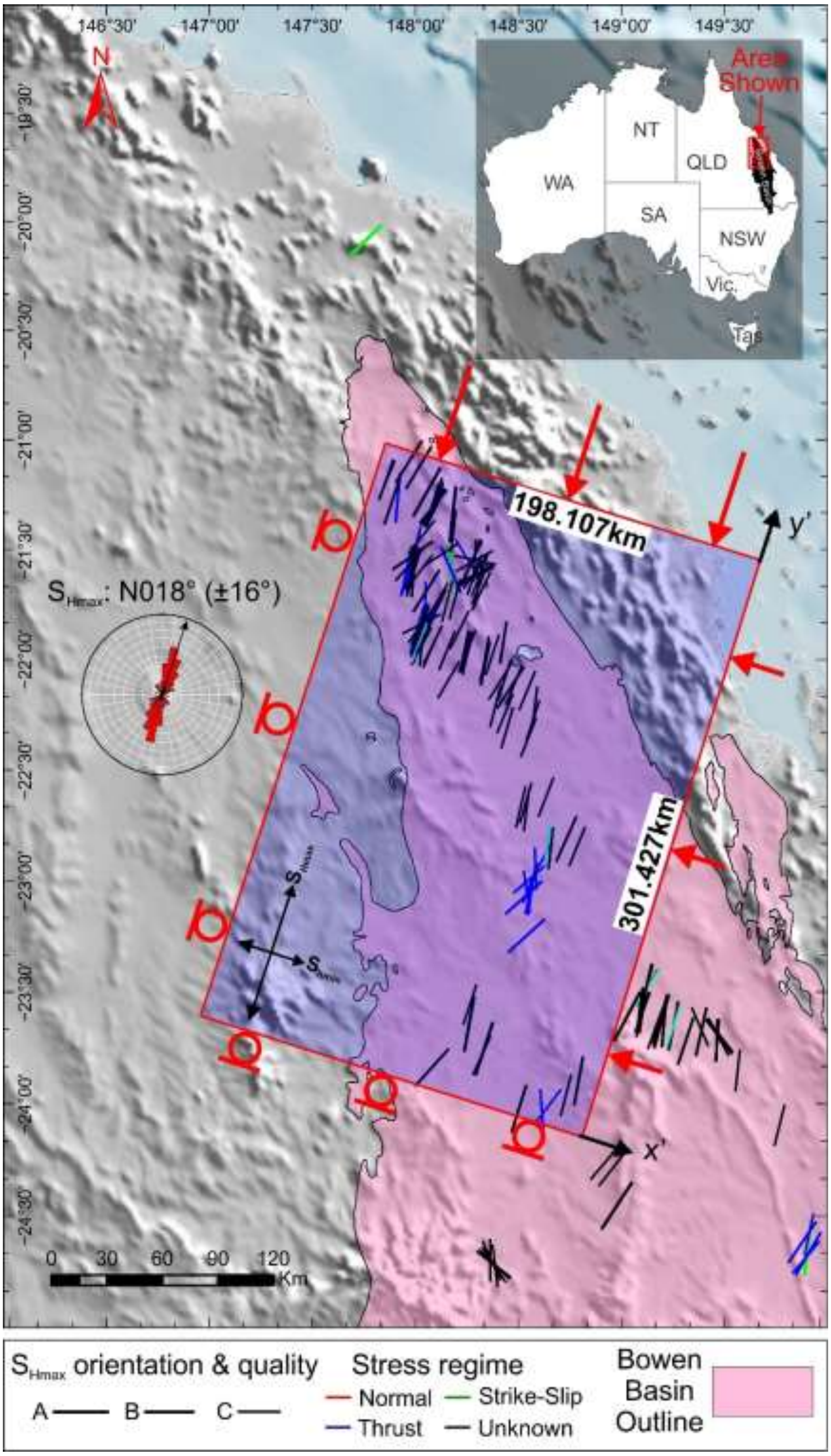

Fig. 1. Location of the study area relative to the Bowen Basin in eastern Australia. Lines in the Bowen Basin area, represent the orientation of maximum horizontal stress (SHmax), and the rose diagram shows the mean orientation of SHmax in northern Bowen Basin. The box illustrates the modelling area. The red circles and arrows around the box show the boundary conditions of the model (i.e., circle means lateral motions and arrows show the push).

Methodology

In this study, a 3D geological model that was constructed by Rajabi *et al.* (2023) was used, as the container model, to develop a 3D geomechanical-numerical model for the northern Bowen Basin. A comprehensive stress database on the study area has shown that the mean orientation of maximum horizontal stress in the northern Bowen Basin is N018° ± 16° (Rajabi *et al.* 2024). Hence, the model has been oriented in a way that the boundaries are parallel and perpendicular to the orientation of maximum and minimum horizontal stress orientations (S_{Hmax} and S_{hmin}, respectively) in the study area (Figure 1).

The geomechanical model has been constructed based on the 3D geological model of the area (Rajabi *et al.* 2023). This 3D geomechanical model comprises 11 lithological units that are representative of various strata and geological formations. Using a methodology described by Ziegler *et al.* (2020), the model volume was discretised into ~3 million finite elements. To characterize different lithologies within the model, an extensive dataset of rock mechanical properties, including density, Young's modulus, and Poisson's ratio, was utilized to accurately represent each geological unit.

Calibration of 3D geomechanical-numerical models is a critical step to find a reliable stress state for a study region (Ziegler and Heidbach 2023). In an ideal situation, stress magnitude data is the best dataset for the calibration of the geomechanical models. However, having a comprehensive stress magnitude database at a basin-scale is not viable due to high cost of direct measurement of stress magnitudes. Even the sparse available stress magnitude data are subject to large uncertainties and, hence, could add more uncertainties in the model calibration (Ziegler and Heidbach 2023; Ziegler *et al.* 2023). In comparison to direct stress measurement, which is sparse and limited, there are wide variety of indirect observations (such as borehole breakouts, drilling induced tensile fractures, formation integrity test, and seismicity of the region), which can be used for model calibrations. As shown in Figure 2, in this study we use an innovative approach for the calibration of our 3D geomechanical model that aims to assess all the indirect observations in the model's volume to narrow down the model predictions and find the most reliable stress state (Ziegler and Heidbach 2023; Ziegler *et al.* 2023).

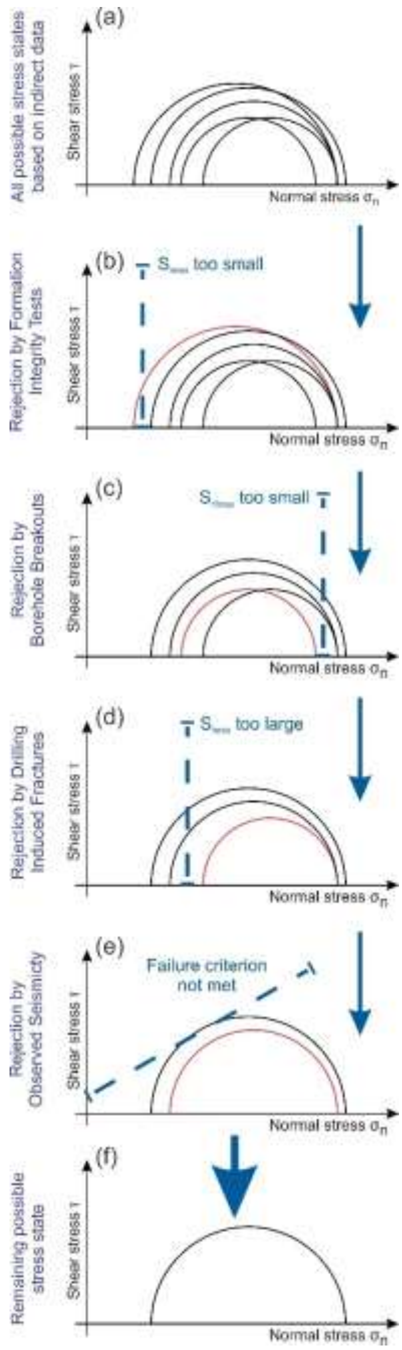

Fig. 2. The use of indirect observation for the calibration of the model simplified using the Mohr circles. (a) first all the possible stress states (i.e., black Mohr circles), based on the indirect observation, are defined in the model's volume. (b) the model rejects the scenarios that the predicted minimum principal stress, S3, is less than FIT at the location and depth of a successful FIT in the model's volume. Hence, the red Mohr circle that disagrees with our scenario is removed. (b) the model compares observed breakouts in the model's volume (based on image log interpretation) with the modelled circumferential stress state at the corresponding location and depth in conjunction with an assumption regarding the rock strength. A stress state that shows an agreement between the observations and model results is expected to be reliable (black Mohr circles). Similar scenarios are assessed for drilling induced tensile fractures (d), and observed seismicity in order to find the remaining possible stress state (f) in the model's prediction.

Results, discussions, and implications

3D geomechanical modelling has proven to be an invaluable tool for predicting the full stress tensor in sedimentary basins. However, limited knowledge of stress magnitude data, which is the case for most of the Australian basins, is one of the most significant obstacles in developing reliable geomechanical models. Such stress magnitude data provide an important constraint on the calibration of the models and, hence, finding a reliable modelled stress state. This study examined a novel approach in 3D stress modelling by using indirect stress observations for model calibration.

The preferred configuration model showed an extremely good fit with observed stress magnitudes data, which were not used in any stage of the modelling. In addition to the increase in the predictive quality of the modelled stress state, the use of indirect data provides this opportunity to find local and regional anomalies of stress.

The final model can then be used in various geomechanical aspects of study area such as investigating the stress regime (Figure 3), calculating slip tendency (ratio of shear to normal stress acting on the fault plane), fracture potential (relative tendency of a pre-existing fault to reach re-activation by shear failure), and dilation tendency (i.e., relative tendency of a pre-existing fault to reach re-activation by shear failure).

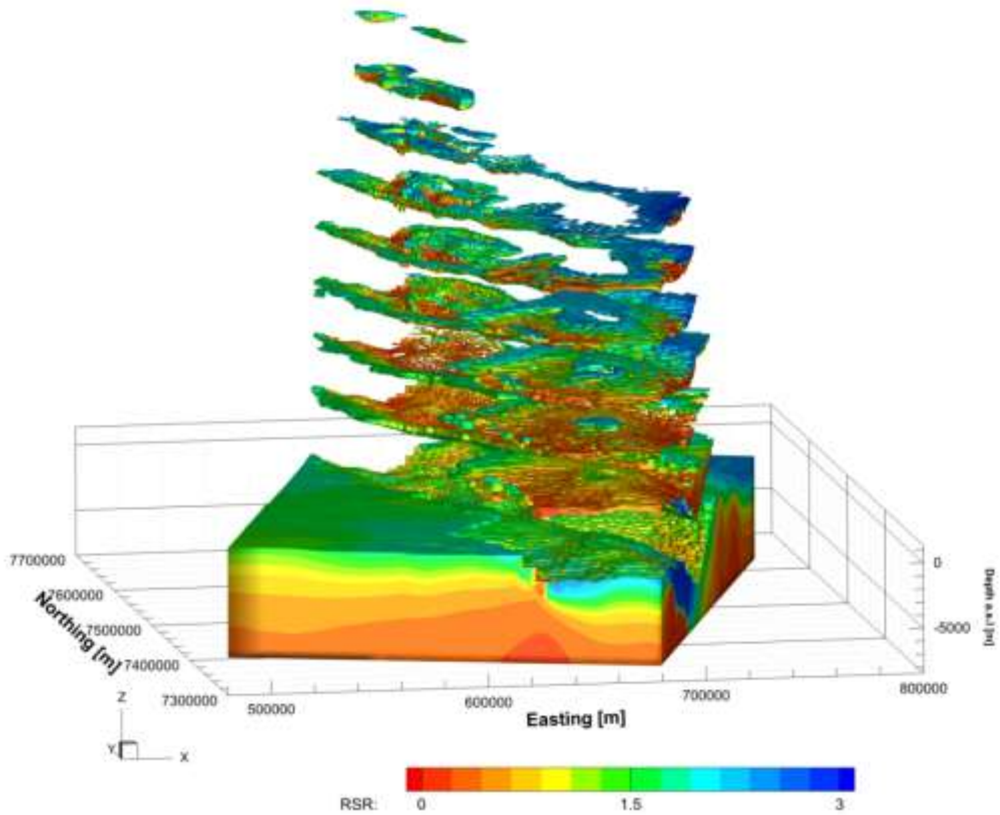

Fig. 3. The best-fit model of the northern Bowen Basin, depicting the regime stress ratio (RSR) across different sedimentary units. RSR quantifies stress regimes on a scale from 0 to 3, with RSR=2.5 indicating thrust faulting, RSR=1.5 signifying strike-slip faulting, and RSR=0.5 denoting a normal faulting stress regime.

Data availability statement

The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of interest

All authors confirm there are no conflicts of interest.

Declaration of funding

MR acknowledges support through an ARC Discovery Early Career Researcher Award (DE200101361), and an ACARP project (project no. C29011). MZ acknowledges funding from BGE SpannEnD 2.0 project and the German Research Foundation (DFG grant PHYSALIS 523456847).

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