Contribution of mine borehole data toward high-resolution stress mapping: An example from northern Bowen Basin, Australia

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ABSTRACT

Most of in-situ stress data in the Australian continent comes from wellbore stress analysis in deep hydrocarbon reservoirs, and earthquake focal mechanism solutions near the Australian plate boundaries, where geophysical tools facilitate understanding of the present-day stress patterns. This resulted in a paucity of stress information in many other regions such as the northern Bowen Basin, which is an active mining province, but with low seismicity rates and limited deep petroleum exploration. The mining industry runs several hundred kilometres of boreholes annually to characterise geotechnical attributes. These logs provide an image from the borehole wall, which facilitates analysis of stress-related borehole deformations for in-situ stress characterisation. This paper examines the orientation of horizontal in-situ stress using different types of image logs in mine boreholes across the northern Bowen Basin. Analyses of 128 km of image logs in 680 vertical boreholes resulted in the interpretation of 9046 pairs of stress-related indicators including 735 drilling induced fractures and 8311 borehole breakouts. Our comprehensive database comprises 890 quality-ranked data records for the orientation of maximum horizontal stress (Smax), which makes the Bowen Basin as a basin with the highest data density in the world in terms of quality-ranked stress information according to the World Stress Map. Statistical analysis of Smax orientation reveals that the mean Smax orientation in northern Bowen Basin is N018° ± 16°. The results show that this orientation is consistent over long distances, which is in contrast with several eastern Australian basins. This uniform stress pattern agrees well with plate-scale geomechanical model predictions, which further highlights the impact of plate boundary forces in the contemporary stress pattern of this region. Detailed image log investigation did not show any systematic rotation of stress; however, some small-scale stress perturbations were observed in the vicinity of sharp stiffness contrasts and geological structures.

1. Introduction

The state of in-situ stress in the continental intraplate regions is generally thought to be consistent over vast distances, i.e., thousands of kilometres. However, several case studies from across the world have shown that intraplate stresses are not usually homogenous and can be perturbed by various stress sources at different spatial scales.

The Australian continent is a typical example of an intraplate region, exhibiting a significant variability in stress patterns across different spatial scales. In eastern Australia, for instance, the orientation of maximum horizontal stress (Smax) differ, ranging from NNE-SSW in the northeastern part to ENE-WSW in the central-eastern region, and NW-SE in the southeastern area (Fig. 1). Apart from these regional stress orientation variabilities, there are numerous smaller-scale stress re-orientations observed at basin, field, and borehole scales. For example, previous studies have shown stress perturbations due to the presence of small-scale geological structures within the Australian continent, such as plate boundary forces or plate interiors experience limited and sparse seismic activity. In contrast to regions located near tectonic plate boundaries, where frequent earthquakes offer ample opportunities to analyse in-situ stresses, plate interiors experience limited and sparse seismic activity.

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Hence, stress analysis in such areas heavily relies on alternative methods, such as borehole stress analysis and engineering techniques (e.g., overcoring and hydraulic fracturing in civil and mining projects). Australia with 2150 stress data records is considered as one of the well-studied regions for in-situ stress analysis. However, 64% of this data is from boreholes in mature petroleum basins, 30% inferred from earthquake focal mechanisms, mainly near the boundary of Australian Plate, and only 6% from mining and civil engineering sites.

Mining is one of the main industries in Australia where there are over 300 operating mines in different parts of the continent, and mining companies run several hundred kilometres of image logs annually for their geological and geotechnical analysis. However, in the public domain, there is not much in-situ stress information in mining regions in Australia. For example, the northern Bowen Basin which is considered as the richest coal basin in Australia is represented by only 26 reliable $S_{\text{Hmax}}$ data records in the latest release of the Australian Stress Map project. This sparse in-situ stress data in the public domain means that the stress pattern of this area is poorly understood. Even the available stress data shows different trends for the $S_{\text{Hmax}}$ azimuth including N-S, NE-SW, NW-SE, and ENE-WSW orientations (Fig. 2). In addition, statistical analysis of stress data revealed that there is a 60° clockwise rotation of $S_{\text{Hmax}}$ orientation from northern Bowen to southern Bowen and Surat basins (Fig. 1). Hence, understanding of the stress pattern in northern Bowen Basin is important for numerous implications including safety and stability assessment of mines such as slope stability, rock burst, designing the layout of mine workings, excavation methods, and details of support.

The in-situ stress also poses significant control on subsurface fluid flow, induced seismicity, fault reactivation, and fracture propagation in geo-storage sites and geo-reservoirs. Finally, such knowledge provides important information to understand how northern and northeastern boundaries of the Australian Plate control the stress pattern of northeastern Australia (Fig. 1).

This paper aims to improve the knowledge of the stress state in the northern Bowen Basin. Such knowledge has direct implications in safety and sustainability of mining operations in this region. Therefore, we systematically analyse borehole image logs in different mines of northern Bowen Basin. We analyse 680 image logs including 556 Acoustic Televiewers (ATV), 4 Optical Televiewers (OTV) and 120 resistivity-based image logs to examine the stress orientation pattern of this region. In particular, our study examines borehole breakouts (BOs) and drilling induced tensile fractures (DIFs) to determine horizontal stress orientations. We calculate the horizontal stress azimuth in each borehole and determine the mean regional $S_{\text{Hmax}}$ orientation in the study area. We then use statistical methods and smoothing tools to calculate a reliable mean $S_{\text{Hmax}}$ orientation and its standard deviation on a regular grid in the region. Finally, we conduct detailed statistical analyses on point-wise data to understand the horizontal stress variabilities in different depth intervals of the northern Bowen Basin. Given the closely spaced nature of boreholes in the mining industry, this study offers a unique opportunity to explore stress variability across a wide range of scales, from a very small-scale to the basin-wide level.

Fig. 1. (a) Location of the Bowen Basin in relation to the present-day tectonic setting of the Australian Plate, modified from Note that force arrows are not drawn to scale. NZ, New Zealand; SNZ, south of New Zealand; TK, Tonga-Kermadec Trench; H, Himalaya; J, Java Trench; S, Sumatra Trench; NG, New Guinea; B, Banda Arc; NH, New Hebrides; SM, Solomon Trench; LHR, Lord Howe Rise. (b) Mean Orientation of maximum horizontal stress ($S_{\text{Hmax}}$) based on statistical analysis, in eastern Australian basins (modified from and Background images are from .
2. Geological setting of the Bowen basin

The Permo-Triassic Bowen Basin is a significant energy-rich basin in eastern Australia that covers a North-South distance of >1000 km with a maximum width of ~250 km. It contains a substantial sedimentary fill of up to 10 km. The basin is a part of the Sydney-Gunnedah-Bowen basins system in eastern Australia that extends from northern Queensland to southern New South Wales (Fig. 1). The basin in considered as one of the most important basins in Australia for its potential in energy, resources, and CO$_2$ storage.

From at least as far back as the Cambrian through to the Early Cretaceous, the eastern Australian continental margin was characterized...
by subduction. The subduction process was complex, with episodes of accretion, slab retreat leading to widespread crustal extension and slab advance causing thick-skinned thrusting and crustal loading as reviewed and discussed by Donchak, Purdy, Withnail, Blake, Jell. The Bowen Basin developed in a continental back-arc setting during the Early Permian to Mid-Triassic in response to first crustal extension, then thermal relaxation and foreland loading. Fig. 3 summarises the basin’s structural history from its inception to the present-day.

During the early Permian, rift-controlled extension caused abundant volcanic activity to the east of the future Bowen Basin and formed numerous fault bounded grabens and half-grabens filled with thick fluvial and lacustrine sediments including rare thick coal seams. Some of the rift basins occur at the base of the Bowen Basin, while others are entrained in the basement terranes to the east. Rifting subsided and was followed by a period of thermal relaxation that was associated with a regional marine transgression across the Bowen Basin. The surviving basin fill from this time includes sandy deltas in the west and marine shelf deposits in the west, suggesting that much of the eastern part of the basin has been eroded.

A prolonged period of intermittent compression, the Hunter-Bowen Orogeny, started during the late Permian with the stacking of thick thrust sheets in the eastern basement terranes, causing foreland loading in the Bowen Basin. As subsidence in the basin accelerated, marine sediments were followed by the thick coal measures that host most of Australia’s coking coal wealth. Influx of sediments from the east eventually buried the coal measures, and fluvial/lacustrine deposits dominated the Bowen Basin until the Mid-Triassic. A phase of east-west compression caused the mid-Triassic closure of the Bowen Basin, when regional-scale folds exposed basement and large isolated thrust faults with characteristic fault-bend folding. Most of the early Permian rift faults inverted during this time.

The final deformation event of the Hunter-Bowen Orogeny was a focussed ENE-WSW compression that resulted in over 1 km of uplift along narrow, 300 km long, fold-thrust belt. This belt runs along the current eastern margin of the basin and has a major impact on the coal fields in the study area. Along strike, the fold-thrust belt contains between 2 and 8 significant thrust faults across a 20–30 km wide zone. Individual faults are between 30 and 140 km long and have up to 1000 m throw. Deformation increases to the east, where tight folding becomes dominant.

After the Hunter-Bowen Orogeny, the Mesozoic to Cenozoic history of eastern Australia was relatively quiet. Subduction stepped out to the east, allowing the intracratonic Surat Basin to develop above the Bowen Basin. Widespread siliciclastic volcanism and uplift during the Cretaceous was associated with rifting and later the opening of the Tasman Sea. Several small intrusions and numerous dykes within the northern Bowen Basin are correlated with this event. Later the Duaringa Basin developed as a half-graben associated with the opening of the Coral Sea that is superimposed on the Bowen Basin, probably inverting one of the late Hunter-Bowen thrust faults. Cenozoic hot-spot related volcanism was associated with widespread basalt lava flows across the Bowen Basin, several sheet volcanoes, and abundant dykes. Since the late Cenozoic, Australia’s drift to the north led to a collision with Papua New Guinea, setting up the present-day stress field.

### 3. Materials and methods

In this study, a comprehensive analysis of various borehole image logs, such as Acoustic Televiewer (ATV), Optical Televiewer (OTV), Fullbore Formation MicroImager (FMI), Compact Micro Imager (CMI), and Slim-hole CMI (SCMI), was conducted to interpret BOs and DIFs. In addition, a thorough literature review was undertaken, and stress data from 29 other boreholes in the northern Bowen Basin were compiled. Hence, this paper presents the horizontal stress orientations from 709 boreholes (i.e., 680 our own analysis and 29 boreholes from the literature) for the northern Bowen Basin (Fig. 2).

Table 1 summarize the database and the sources of data for stress analysis in this paper. A brief introduction on the tools and methods that have been used in this study is explained below.

### Table 1

<table>
<thead>
<tr>
<th>Data sources</th>
<th>No. of boreholes</th>
<th>No. of data records for the $S_{max}$ orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine boreholes</td>
<td>537</td>
<td>644</td>
</tr>
<tr>
<td>Coal Seam Gas wells</td>
<td>143</td>
<td>216</td>
</tr>
<tr>
<td>Published literature</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>Sum</td>
<td>709</td>
<td>890</td>
</tr>
</tbody>
</table>

Fig. 3. Structural history of the Permo-Triassic Bowen Basin from its inception to the present-day.
3.1. Stress mapping approach

In geomechanics, the state of the stress is explained by the concept of the Cauchy stress tensor.\(^{51-53}\) Assuming that the overburden stress (i.e., vertical stress; \(S_v\)) is one of the three principal stresses, the minimum and maximum horizontal stresses (\(S_{\text{hmin}}\) and \(S_{\text{hmax}}\) respectively) are principal stresses as well. Hence, the 3D stress tensor is described with the magnitudes of \(S_v, S_{\text{hmax}}, S_{\text{hmin}}\) and the orientation of \(S_{\text{hmax}}\).\(^{52}\)

Stress mapping is a visual representation for any of the stress tensor parameters that can visualise stress magnitudes,\(^{46}\) stress orientations and stress regimes;\(^{53-57}\) and even pore pressure, which is an important parameter to understand effective stresses.\(^{56}\) The use of stress maps has a long history and it has been used as a well-established approach to understand the stress pattern of a region and investigate the stress sources at different scales such as mine, field and basin,\(^{10-15,14,15,36-37}\) and even continental and global scales.\(^{56,60-69}\) Most of previous basin-scale stress orientation maps were primarily derived from petroleum borehole data, which were limited to specific intervals, such as reservoirs. In addition, conventional petroleum wells are usually having long borehole spacing that can cause significant uncertainty regarding the spatial and depth-related patterns of horizontal stress orientations. This study, however, employs mine borehole image log data, spanning from the near surface to a depth of 1.6 km. Notably, mine boreholes have close borehole spacing (sometimes <30 m), facilitating the creation of a high-resolution stress map both spatially and in terms of depth, ranging from the near surface to 1.6 km depth.

In this study, we map 890 \(S_{\text{hmax}}\) orientation data records inferred from 709 boreholes to understand the stress pattern of this mining region. To be consistent with previous stress mapping projects, we calculate the mean \(S_{\text{hmax}}\) azimuth for each borehole based on directional statistics.\(^{60,61}\) We then assign a quality (from A to E) to these \(S_{\text{hmax}}\) orientations following the World Stress Map Quality ranking scheme.\(^{40}A\)-quality is the most reliable data (the uncertainty of \(S_{\text{hmax}}\) is believed to be within \(\pm 15^\circ\)), \(B\) (\(S_{\text{hmax}}\) is believed to be within \(\pm 20^\circ\)), \(C\) (\(S_{\text{hmax}}\) is believed to be within \(\pm 25^\circ\)), \(D\) (\(S_{\text{hmax}}\) is believed to be within \(\pm 40^\circ\)) and \(E\) (\(S_{\text{hmax}}\) in that borehole is not reliable as the standard deviation is >\(\pm 40^\circ\) or the required information is incomplete). This quality ranking scheme enables us to compare \(S_{\text{hmax}}\) orientations inferred from different methods.\(^{40}\)

3.2. Borehole image log analysis

Borehole images logs are 360\(^\circ\) representation of borehole wall and are widely used in petroleum industry and more recently in mining sector for the analysis of subsurface structures.\(^{62-65}\) These logs come in various types, each tailored to different borehole environments.\(^{55}\) Typically, these tools capture borehole images either directly, through optical methods like video or photography, or indirectly, based on physical properties of the surrounding rock and fluid, such as density, resistivity, and acoustics.\(^{56}\) In this study, we utilized a range of image logs including acoustic-based (ATV), resistivity-based (FMI, CMI and SCMI) and optical-based (OTV) in 680 boreholes (Fig. 2). Image logs that sometimes are referred to as “optical cores” are considered as invaluable tool for characterisation of subsurface structures such as faults, fractures, and stress-related indicators in boreholes. Analysis of BOs and DIFs using image logs are considered as well-established methods for crustal stress analysis.\(^{76}\)

When a borehole is drilled, it removes a cylinder of rock that was originally providing support to the surrounding materials, which were under compression by far-field stresses. Consequently, the drilling operation leads to a re-distribution of stress on the borehole wall, potentially resulting in the formation of breakouts (BOs) and drilling induced fractures (DIFs) depending on the tensile and compressive strength of the drilled rock (Fig. 4).\(^{66}\) DIFs appear on the borehole wall when the tangential stress is less than tensile strength of the rock. These features, which align with the \(S_{\text{hmax}}\) orientation, can be interpreted as two vertical fractures on both side (~ separated by 180\(^\circ\)) of a vertical borehole, either as low amplitude fractures in ATV or conductive fractures in FMI/CMI logs (Fig. 4). However, it is crucial to note that in coal basins, there exists a significant risk of misinterpreting these features and cleats, which are natural vertical fractures in coal seams.\(^{57,63}\) In this study, we took precautions to avoid misinterpretations by cross-referencing the borehole image logs with core photos. This approach helped us ensure more accurate and reliable results, reducing the risk of misidentifications. Breakouts initiate when the circumferential (or hoop) stress exceeds the compressive strength of rock on the borehole wall.\(^{60}\) This results in the circular cross-section of a vertical borehole transforming into an oval shape, with the long axis indicating the orientation of \(S_{\text{hmin}}\) (Fig. 4).\(^{50}\) In borehole image logs, BOs are identified as poorly resolved (either low amplitudes zones in ATV or

![Fig. 4. Examples of drilling induced fractures (DIF) and borehole breakouts (BO) in different types of image logs in the studied boreholes. Schematic diagram (right) is a cross section of a borehole that illustrates the relationship between BO, DIF and minimum and maximum horizontal stresses (\(S_{\text{hmin}}\) and \(S_{\text{hmax}}\) respectively).](image-url)
high conductive zones in FMI/CMI logs) forming on both sides of the borehole, separated approximately by 180° (Fig. 4). Not that all the boreholes studied in this study are vertical boreholes (<10° deviation), eliminating the need for additional corrections when determining horizontal stress orientations. It should be noted that all the image log data have undergone through a strict quality control (QC) including borehole location and its magnetic declination, inclinometry QC to orient the image log (i.e., use True North as the reference of the image), applying different filters and corrections to improve the quality of image logs and make them interpretable for BOs and DIFs analysis. Although various methods such as automatic picking of features for image logs have been introduced, we interpreted and analysed all the image logs manually because some studies have shown that automatic picking occasionally fail to recognize certain features and often misinterpret and misclassify them. More recently, Roshan et al., has introduced a new methodology to determine in-situ stresses using ATV logs without the requirements of borehole breakout analysis. However, in this study we analysed BOs and DIFs to be able to rank the mean S\text{Hmax} orientation according to the World Stress Map guidelines.

3.3. Statistical analysis: stress province and search-radii stress analysis

In order to comprehend the basin-wide stress pattern of the study area, we employ two statistical methodologies: the stress province and search-radii technique. These approaches rely on directional statistics to calculate both the mean orientation of S\text{Hmax} and its standard deviation, as explained below.

3.3.1. Stress province

The stress province is a method utilized in various releases of the Australian Stress Map project to assess the mean orientation of S\text{Hmax}, standard deviation, and significance of stress orientations within a specific region. To apply this method, at least four S\text{Hmax} data records should be available within close geographical proximity. High-quality data (i.e., data with higher quality according to the World Stress Map quality ranking), are given more weight in the statistical analysis. The next step involves calculating the mean orientation of S\text{Hmax} and the resultant vector length (R-value) for the Rayleigh Test, which assesses the randomness of the S\text{Hmax} azimuth. In this process, a null hypothesis is defined, assuming that the S\text{Hmax} azimuth in the region is random. Based on the null hypothesis and the R-value, six types of stress provinces can be classified: type 6 when the null hypothesis cannot be rejected at the 90% confidence level, type 5 when it can be rejected at the 90%, type 4 at the 95%, type 3 at the 97.5%, type 2 at the 99%, and type 1 at the 99.9%. Further details about this method can be found in Hillis and Reynolds, and Rajabi et al.

3.3.2. Search-radii stress analysis: mean S\text{Hmax} orientation on a regular grid

As mentioned earlier, stress maps offer pointwise and sparse information about the stress tensor’s parameters. However, this approach lacks the ability to provide stress information beyond the measurement domain, resulting in stress data gaps. To address this limitation, various methods have been employed, including statistical analysis, and geomechanical stress modelling to predict the stress pattern in regions where there is limited or (no) stress data.

In this study, we employ the search-radii approach, a statistical method that is used to determine reliable mean S\text{Hmax} orientations within a given standard deviation on regular grids. This method involves calculating the mean S\text{Hmax}, considering the quality of the S\text{Hmax} data records, as well as the distance to the grid point as weights. To implement this method, our criteria are that we expect a minimum of three S\text{Hmax} data records with A-C quality are available in the variable search radii. The method starts with a search radius of 1000 km, decreasing by 100 km in each step. Then we plot the mean S\text{Hmax} orientation on each grid point when the standard deviation is below 25° in the associated search radius. The search radius component of this method is termed as the wavelength of the S\text{Hmax} orientation, which is shown as background of the map. Hence, the final map shows the mean S\text{Hmax} orientation with standard deviations <25° on regular grids along with the wavelength.

4. Results

We developed the stress orientation map of the northern Bowen Basin by analysing 128 km of image logs in 680 vertical boreholes (Fig. 5 and Table 1). In addition, we conducted a comprehensive literature review, gathering 30 S\text{Hmax} data records from 29 other boreholes. This compilation included 20 data records from hydraulic fracturing measurements, 7 from overcoring tests, and 3 from image log analysis. Hence, our stress analysis and data compilation yielded a total of 890 quality-ranked S\text{Hmax} data records (Fig. 5, Table 2 and supplementary data). As a result, the Bowen Basin stress map stands as the most comprehensive, quality-ranked, basin-scale stress orientation map based on the World Stress Map database. Throughout our analysis, we interpreted a total of 9046 stress-related indicators, which included 8311 BOs and 735 DIFs across a depth range of 8 m–1600 m in the strata of the northern Bowen Basin.

Since individual S\text{Hmax} indicators, inferred from BO and/or DIF, occur in different depth intervals of a borehole, a mean orientation of S\text{Hmax} needs to be calculated from these indicators to represent the S\text{Hmax} orientation in that borehole. Generally, there are two methods (i.e., number-weighted and length-weighted) for the calculation of the S\text{Hmax} orientation in boreholes. For our analysis, we opted for the length-weighted approach, which assigns greater weight to the longer features (BOs or DIFs) when calculating the overall S\text{Hmax} in each borehole. We then used the World Stress Map quality ranking scheme to rank all the S\text{Hmax} orientations from A to E quality. Note that if both BOs and DIFs were picked in a single borehole, we reported two S\text{Hmax} orientations in that particular borehole, as suggested by the World Stress Map quality ranking.

4.1. Statistical analyses of stress data: stress provinces

In the statistical analysis of stress province, we accorded greater weight to A-quality data, which is regarded as the most reliable S\text{Hmax} data records. Conversely, we excluded E-quality data due to their lack of reliability. Consequently, we assigned weights of 4, 3, 2, and 1 to A, B, C, and D-quality data, respectively. After conducting the statistical analysis using 659 A-D quality data points, we determined that the mean S\text{Hmax} orientation for the northern Bowen Basin is N020°E, with a standard deviation of ±19°. With an R-value of 0.81, the null hypothesis can be rejected at the 99.9% confidence level, signifying that the northern Bowen Basin is classified as a Type-1 stress province, based on the Australian Stress Map classification.

The stress map of the northern Bowen Basin represents a unique and comprehensive database of stress orientations. It includes stress data records derived from various stress indicators, such as borehole breakouts, drilling induced fractures, overcoring, and hydraulic fracturing measurements, each with different qualities. To investigate potential discrepancies between different datasets, we calculated the basin-wide mean S\text{Hmax} orientations based on different datasets (i.e., different qualities and different stress indicators). In Fig. 6, we summarize the results of the statistical analysis for the different datasets. Notably, the mean S\text{Hmax} orientations obtained from almost all the datasets exhibit a remarkable similarity, indicating a high level of agreement and consistency. This finding further highlights the reliability of the different stress indicators and qualities used to determine the basin-wide mean S\text{Hmax} orientations.

4.2. Statistical analyses of stress data: search-radii methods

To predict a reliable mean S\text{Hmax} orientation on a regular grid, we
employed the search-radii method (see section 3.3.2). We conducted this analysis separately for both A-C and A-D quality data to see if the inclusion of D-quality data significantly impacted the results or not. The outcomes of the search-radii analysis are displayed in Fig. 7, which highlights a consistent mean $S_{Hmax}$ orientation in the northern Bowen Basin for both A-C and A-D quality data. The wavelength analysis (background colour in Fig. 7a and c) appeared to be very long, exceeding 600 km in northern region, which then gradually decreased to shorter wavelengths (approximately $\leq 100$ km) in the southern region. This wavelength pattern provides valuable insights into the spatial consistency of the calculated mean $S_{Hmax}$ Orientation from each grid point. Shorter wavelengths indicate higher stress variability and local perturbations, suggesting regions with more localized stress variations. Conversely, longer wavelengths represent a more consistent pattern of stress orientations over long distances, implying greater regional stress homogeneity.

Fig. 5. Stress map of northern Bowen Basin using 890 quality-ranked orientation of maximum horizontal stresses. Azimuth of lines represent the orientation of $S_{Hmax}$ and length of the lines shows their quality (see legend). The background map shows the regional geology and geological structures of the area based on.\textsuperscript{34}
4.3. Stress orientations with depth

Large stress mapping projects have highlighted that, on average, there is no systematic or significant stress rotations with depths at large scales, such as tectonic plates and continental scales.\(^5\) These studies also show that there is no variation of the derived stress orientations derived from different methods. However, at smaller scales, various depth-wise systematic stress variabilities have been observed, primarily associated with the presence of mechanical detachment zones.\(^6\)–\(^8\)

In most basin-wide stress mapping projects, the focus is primarily on examining the spatial pattern of stress orientation and comparing \(S_{\max}\) orientations between individual boreholes. However, little attention has been given to the detailed analysis of stress orientation pattern from near surface to deeper intervals. A significant challenge in conducting a detailed depth analysis of stress data in basins is the lack of sufficient coverage of stress information from near-surface to deeper intervals.

### Table 2

Type and quality of the maximum horizontal stress orientations in northern Bowen Basin stress map. Quality is based on the World Stress Map ranking scheme.\(^9\)

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Number of quality ranked data</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>A-quality</td>
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<tr>
<td>Borehole Breakout</td>
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</tr>
<tr>
<td>Drilling induced fractures</td>
<td>0</td>
</tr>
<tr>
<td>Hydraulic fracture</td>
<td>0</td>
</tr>
<tr>
<td>Overcoring</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
</tr>
</tbody>
</table>

**Fig. 6.** Statistical analysis of maximum horizontal stress (\(S_{\max}\)) orientations using various datasets with different quality and data types. The calculated mean \(S_{\max}\) orientations for most data sets exhibit a high level of consistency, demonstrating agreement among the results. The only exception is the D-quality hydraulic fracture test, which consists of a single measurement and shows some deviation from the other datasets.
This limitation arises because most image logs are typically run in specific intervals, such as reservoirs, and, hence, there is not enough coverage of stress information from near surface to do an extensive analysis.

In this study, the utilization of mine borehole data presented a unique opportunity to investigate the depth-wise pattern of stress orientation, spanning from near surface (approximately 8 m) to a depth of 1.6 km [Fig. 8]. For the depth analysis of $S_{\text{Hmax}}$ orientation, we plotted...
all pointwise data, which included 9046 of $S_{H\text{max}}$ orientation inferred from BOs and DIFs, 118 data records from HF and 7 data records from OC analysis. By calculating the mean $S_{H\text{max}}$ orientation and standard deviation in 100 m intervals, we examined the stress orientation patterns throughout the depth range (near surface to 1.6 km) in the study area. Fig. 8 reveals a remarkable and consistent mean $S_{H\text{max}}$ orientation in each interval and overall, despite the complex structural geology and tectonics of the basin, as well as the presence of coals with distinct mechanical properties relative to other strata in the basin. Note that in our study, most of the borehole are shallow boreholes (i.e., $<700$ m depth), and that resulted in more data in the shallower intervals (see last track in Fig. 8), meaning that the deeper intervals have been only covered by limited number of boreholes. For example, only 20 borehole data were available for deeper than 1 km, while there were hundreds of boreholes for shallower than 700 m (Fig. 8). Hence, the stress orientations look more scattered in the shallower intervals, which we believe it is due to the data density and the inherent uncertainty in stress data analysis. Note that the statistical analysis of mean $S_{H\text{max}}$ orientations shows small variations above and below 700 m (approximately $15^\circ$ to $25^\circ$), which is within the standard deviation. Hence, our analysis indicates the absence of any systematic basin-wide variability of stress orientation with respect to depth in the northern Bowen Basin (Fig. 8).

![Fig. 8. The depth analysis of stress data in the northern Bowen Basin was conducted using pointwise data of maximum horizontal stress ($S_{H\text{max}}$). The data were plotted against depth, and the mean orientation of $S_{H\text{max}}$ along with the standard deviation, was calculated for each 100-depth interval. No. of boreholes represent the number of boreholes with $S_{H\text{max}}$ indicators in each interval. The results show that the $S_{H\text{max}}$ orientation remains consistent across different depth intervals, with only small variations observed (approximately $15^\circ$ to $25^\circ$, which is within the standard deviation) above and below 700 m. These slight variations at shallower intervals can be attributed to data density (see the no. of datapoints and boreholes) and the inherent uncertainty in stress data analysis.](image-url)
5. Discussion

5.1. Stress orientation in northern Bowen Basin

This study resulted in a comprehensive stress orientation map for northern Bowen Basin (Fig. 5). Notably, Fig. 6 demonstrates a high degree of consistency in the mean $S_{\text{max}}$ orientation across various qualities and types of data throughout the study area. For example, based on 153 A-C quality data records, the mean $S_{\text{max}}$ orientation for the study area was determined to be N018° ± 16°. Remarkably, this value is similar to the mean $S_{\text{max}}$ orientation calculated using 659 A-D quality data, which resulted in N020° ± 19°. These outcomes highlight the robustness and reliability of the stress orientation data across different datasets, reaffirming the consistent stress pattern observed throughout the northern Bowen Basin.

The majority of borehole data used in this study were obtained from open-pit mines (see Table 1), which are shallower with small coverage of borehole image logs. This resulted in a substantial number of D-quality data, which is considered as less reliable $S_{\text{max}}$ data records according to the World Stress Map ranking scheme. Previous studies in eastern Australian basins such as southern Bowen, Sydney, Surat, and Gunnedah have indicated that D-quality data records often represent a deviating local stress pattern. However, contrasting findings have been observed in other basins within Australia, as well as in the Moatize Basin in Mozambique, Taranaki Basin in New Zealand, Geothermal wells in Iceland, Western Canadian basins, and Southeast Asia. In these cases, D-quality data may not necessarily serve as indicators of localized stress and could instead represent regional stress patterns. Hence, extreme caution is required to work with D-quality data for basin stress analysis. Note that D-quality data can arise due to a high standard deviation of mean $S_{\text{max}}$ (i.e., between ±25° and ±40°) within a borehole or due to limited occurrences of BO/DIF (i.e., <4 distinct breakouts or <20 m combined length in a single borehole).

In our statistical analysis, we examined various sets of data with different qualities and found that the mean $S_{\text{max}}$ orientation of the study area did not show significant differences (Fig. 6). Even when considering only 506 D-quality data records, the calculated mean $S_{\text{max}}$ orientation for the study area was N022° ± 20°, which closely resembles the mean $S_{\text{max}}$ from A-C quality data (i.e., N018° ± 16°) and is well within the inherent uncertainties. This similarity is supported by the wavelength analysis of stress data for both A-C and A-D quality data, showing comparable results (Fig. 7a and c). Upon reviewing our database, it becomes evident that the majority of boreholes received a D-quality due to the limited occurrence of BO/DIF (i.e., <4 distinct breakouts or <20 m combined length in a single borehole), rather than a high standard deviation. Only 21 boreholes with D-quality exhibited a standard deviation of >25° (Fig. 9). Consequently, our findings reveal a consistent mean $S_{\text{max}}$ orientation in the northern Bowen Basin, regardless of the inclusion of D-quality data.

5.2. Observational stress data and large-scale geomechanical models’ predictions

The pattern of $S_{\text{max}}$ orientation in most Australian basins is well-documented in the published literature. However, there is a noticeable scarcity of stress information for some regions, such as northern Bowen Basin, despite it being recognized as a rich basin for energy and resources. Prior to this study, some researchers have worked on the stress state of northern Bowen Basin, however, the limited $S_{\text{max}}$ orientation, in the public domain, means that the stress pattern in this part of the Bowen Basin is poorly understood. Understanding the stress pattern in northern Bowen Basin is particularly significant given that detailed stress analyses in different Australian sedimentary basins have revealed various scenarios for stress pattern. For example, some basins, such as Darling, Cooper-Eromanga, Bonaparte, Gippsland, and Otway, display homogeneous $S_{\text{max}}$ orientations, while others, including Sydney, Gunnedah, Surat, Browse, and some parts of the Carnarvon basins, exhibit variable stress patterns. Hence, characterizing the stress pattern of the northern Bowen Basin becomes crucial to determine if it is affected by localized perturbations, similar to what has been observed in the southern Bowen and Surat basins. By shedding light on the stress pattern of this region, this study aims to contribute valuable insights to the overall understanding of the tectonics and geomechanical characteristics of the northern Bowen Basin.

Early studies on the stress pattern of northern Bowen Basin were conducted as part of larger investigations aimed at analysing the stress patterns of the entire Bowen Basin and eastern Australian basins. For instance, the analysis of hydraulic fracturing testing and overcoring measurements revealed that the mean $S_{\text{max}}$ orientation for the entire Bowen Basin is N16°E ± 27°. These studies revealed that the mean $S_{\text{max}}$ orientation in northern Bowen Basin is N007°E ± 23°. Further investigated the stress analysis of the Bowen Basin using detailed statistical analysis. It was suggested that although the $S_{\text{max}}$ orientation remains consistent over most of the Bowen Basin, there is a slight easterly rotation in the $S_{\text{max}}$ orientation between the northern and southern regions of the basin.

Tavener et al. examined 145 borehole data to explore the stress pattern of the Bowen and Surat basins. The findings of their investigation suggested significant variability in the $S_{\text{max}}$ orientation across their study area, leading to the identification of six sub-regions for the $S_{\text{max}}$ azimuth. According to Tavener et al., northern Bowen Basin shows N022°E ± 19° orientation for the $S_{\text{max}}$ that gradually rotates to N070°E.
± 34° in south-central Bowen and then N090°E ± 04° in southern Bowen Basin. It should be noted that Tavener et al.,11 defined their region for the northern Bowen Basin as approximately between latitudes of −24.00 and −25.00. In contrast, in our current study, we define the northern Bowen Basin as spanning from latitude −21.00 down to −24.36. Consequently, only two $S_{\text{max}}$ data records from Tavener et al.11 fall within the boundaries of our database for the northern Bowen Basin.

Before this study, there was limited stress information available for the northern Bowen Basin, particularly in the far northern region, where it is an active mining area but has seen relatively limited exploration for deeper coal seam gas compared to the southern part of the basin (Fig. 1). In the absence of observational data, our understanding of the in-situ stress pattern in the region has mainly relied on geomechanical models of stress for the Australian tectonic plate. Several studies, as detailed by Rajabi et al., have attempted to investigate the regional stress pattern of Australia by constructing 2D and 3D geomechanical-numerical models at continental and tectonic plate scales. These published models have presented various patterns for the $S_{\text{max}}$ orientation in the northern Bowen Basin. For example, Reynolds et al.,18 utilized a 2D plate-scale model and predicted a regional pattern of NNE-SSW and NE-SW for northern Bowen Basin. Burbidge5 suggested a NE-SW orientation of the $S_{\text{max}}$ azimuth (in a normal faulting stress regime). On the other hand, 2D plate-scale models by Dyksterhuis et al.,66 and Müller et al.,67 proposed a NW-SE trend for the $S_{\text{max}}$ azimuth in the northern Bowen Basin. Given these divergent model predictions, this study contributes new observational data to evaluate the previously published models and gain insights into the factors influencing the stress pattern of northeastern Australia. By providing fresh observational data, this research allows for a more comprehensive assessment of the role of different forces on the stress pattern of the region.

5.3. Controls on the stress pattern of northern Bowen Basin

Over the past three decades, extensive analysis and modelling of the in-situ stress pattern in the Australian continent have revealed that the regional stress pattern (i.e., on scales greater than 500 km) is primarily controlled by tectonic plate boundary forces.5,18,86-88 However, when it comes to basin scales, detailed in-situ stress analysis has shown that the stress patterns of some basins cannot be solely described by plate tectonic forces, and additional forces at smaller scales (i.e., on scales less than 500 km) are required to explain the observed stress variability.5,9,11,49 Therefore, it is crucial to understand whether the stress pattern of the northern Bowen Basin is similar to basins that exhibit consistent $S_{\text{max}}$ orientation at the basin scale or if it displays significant stress variability.

As discussed earlier, this study has revealed a mean $S_{\text{max}}$ orientation of N020° ± 19°, which demonstrates a considerable level of consistency across the northern Bowen Basin (Figs. 5–7). Rajabi et al., conducted a comprehensive evaluation of various plate-scale geomechanical models of stress for Australia and found that the model developed by Reynolds et al.,18 exhibited the least deviation when compared to the observational mean $S_{\text{max}}$ orientation in the Australian stress provinces. Remarkably, the stress analysis conducted in this study also demonstrates a remarkable agreement between the $S_{\text{max}}$ orientation inferred from borehole data and the predictions provided by the 2D geomechanical-numerical model proposed by Reynolds et al.18

Our study area is situated in the northern part of the Australian plate, in close proximity to the Tonga Kermadec, Solomon Trench, New Hebrides, and Papua New Guinea regions (Fig. 1). The geographic proximity of the northern Bowen Basin to the boundaries of the Australian and Pacific tectonic plates underscores the potential impact of these plate boundaries on the stress pattern of northeastern Australia, including the Bowen Basin.19 The 2D plate-scale geomechanical model developed by Reynolds et al.,18 suggests that compression resulting from the interactions at the New Hebrides and Solomon boundaries leads to a prevailing NNE-SSW orientation for $S_{\text{max}}$ in the Bowen Basin region.19,20 Therefore, as proposed by Reynolds,19 the interplay between the Australian and Pacific plates at the boundaries of Hebrides and Solomon plays a crucial role in shaping the regional pattern of present-day stress in the northern Bowen Basin.

As outlined above, the stress orientation in the northern Bowen Basin exhibits no systematic rotation, and the regional stress pattern is primarily governed by plate tectonic forces. However, there are some variabilities in some regions both spatially and with depth. For example, Fig. 10 shows some perturbed $S_{\text{max}}$ orientation in the northern part of our study area, where the geology is more complex and variations in basement topography are observed.21 It is worth noting that geological and basement structures have been identified as key factors contributing to stress variabilities in eastern Australian sedimentary basins.5,9,11,49,69 In addition to spatial variations in stress patterns, we have also observed numerous depth-wise, small-scale rotation of stress (i.e., <500 m) in some of the boreholes, particularly in close proximity to faults, abrupt changes in lithology, and massive fracture zones (Fig. 11). These depth-wise stress variations suggest the influence of local geological features and structural complexities on stress distribution in the northern Bowen Basin. These findings underscore the significance of incorporating geological information and subsurface

![Fig. 10. Variable pattern of maximum horizontal stress ($S_{\text{max}}$) orientation, depicted by black lines, in northern part of the study area. As shown by Rajabi et al.,21 this part of the basin represents the changes in basement topography and also contains extensive swarms of dykes (purple lines). These stiff/hard materials could be a possible cause of stress variability in this region. Note that most of the stress azimuth data in this region are assigned as D-quality due to low number of breakouts in each borehole (see Fig. 9). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)](image-url)
One of the central inquiries addressed in this paper was whether the in-situ stress variability in the northern Bowen Basin resembles that of the southern Bowen and Surat basins. Through our detailed stress mapping efforts, which have resulted in the development of one of the most detailed and quality-ranked basin-scale stress maps worldwide, we have found a consistent $S_{\text{Hmax}}$ orientation across the entirety of the northern Bowen Basin. Furthermore, our study revealed the presence of stress variabilities at smaller scales, particularly in regions characterized by complex geology and significant changes in basement topography (Fig. 11). The remarkable consistency of $S_{\text{Hmax}}$ orientation in the northern Bowen Basin, when compared to the southern Bowen and Surat basins, is evident in our search-radii statistical analysis. As depicted in Fig. 7, there is a gradual decrease in the wavelength of $S_{\text{Hmax}}$ azimuth from north to south. This observation implies that $S_{\text{Hmax}}$ orientation exhibits a notably large wavelength in the northern parts of the basin, signifying a consistent stress orientation over substantial distance. As we move towards the southern part, the wavelength decreases, indicating that $S_{\text{Hmax}}$ orientation remains consistent over shorter distances in this region and more local perturbations occur.

6. Conclusions

Prior to undertaking this study, the Australian Stress Map database had a limited reliable open-file in-situ stress data records for the northern Bowen Basin. However, our comprehensive analysis of borehole data has led to a significant expansion of $S_{\text{Hmax}}$ data records, reaching a total of 890 records. These data were derived from an in-depth examination of 128 km of borehole image logs retrieved from 680 vertical boreholes. The statistical analysis of the $S_{\text{Hmax}}$ data demonstrated that the mean $S_{\text{Hmax}}$ orientation in the northern Bowen Basin is N020°E, with a standard deviation of ±19°. This mean $S_{\text{Hmax}}$ orientation displays strong spatial and depth consistency. Moreover, the agreement between the observed mean $S_{\text{Hmax}}$ orientation in this study and the predicted $S_{\text{Hmax}}$ orientation using a plate-scale geomechanical model emphasizes the significant influence of plate boundary forces on the stress pattern in the.
northern Bowen Basin. This pattern stands in contrast to most of the eastern Australian basins, such as the Surat, southern Bowen, Gunnedah, and Sydney basins, which display considerable stress variabilities at different scales due to the interaction of various forces. While the regional $S_{\text{max}}$ orientation in the northern Bowen Basin generally aligns with the NNE direction, small-scale stress rotations (ranging from 1 to 10 km) have been identified in regions with changes in basement topography and complex geology. Furthermore, detailed borehole image log analysis in this study uncovered very small-scale stress rotations (occurring between 1 and 10 m) in some boreholes. These rotations were attributed to stiffness contrasts caused by changes in lithology and the presence of geological structures.

CRediT authorship contribution statement

Mojtaha Rajabi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. Moritz Ziegler: Conceptualization, Formal analysis, Writing – review & editing. Oliver Heidbach: Conceptualization, Supervision, Writing – review & editing. Saswata Mukherjee: Conceptualization, Formal analysis, Writing – review & editing. Joan Esterle: Conceptualization, Data curation, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the results are available as online supplementary materials. However, the raw well log data are confidential.

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Appendix A. Supplementary data

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References
