Geomechanical Analysis of the Harvey Area: Review and Recommendations

A Report by ODIN Reservoir Consultants

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Declaration

ODIN Reservoir Consultants has been commissioned to undertake to provide a reservoir modelling study for the South West Hub CO_2 Sequestration Project on behalf of The Department of Mines, Industry Regulation and Safety, (DMIRS).

The evaluation of Carbon Capture and Storage is subject to uncertainty because it involves judgments on many variables that cannot be precisely assessed, including CO_2 sequestration rates and capture, the costs associated with storing these volumes, sequestration gas distribution and potential impact of fiscal/regulatory changes.

The statements and opinions attributable to us are given in good faith and in the belief that such statements are neither false nor misleading. In carrying out our tasks, we have considered and relied upon information supplied by the DMIRS and available in the public domain. Whilst every effort has been made to verify data and resolve apparent inconsistencies, neither ODIN Reservoir Consultants nor its servants accept any liability for its accuracy, nor do we warrant that our enquiries have revealed all of the matters, which an extensive examination should disclose.

We believe our review and conclusions are sound but no warranty of accuracy or reliability is given to our conclusions.

Neither ODIN Reservoir Consultants nor its employees has any pecuniary interest or other interest in the assets evaluated other than to the extent of the professional fees receivable for the preparation of this report

Note:

ODIN has conducted the attached independent technical evaluation with the following internationally recognised specialists:

Mark Tingay *is a globally-recognised expert in geomechanics and pore pressure prediction with a proven track record of improving drilling safety and efficiency, increasing hydrocarbon extraction, developing new exploration plays and planning CO_2 sequestration projects. Mark has a wide-ranging experience in geomechanics and pore pressure for both well planning and reservoir engineering applications. He has worked with over 20 companies worldwide, with extensive experience throughout Australia and Asia. Mark is in the 'Top 10' most published and cited experts in petroleum geomechanics and pore pressure in the world, and his work has received over a dozen awards, including the AAPG JC Cam Sproule Award, EAGE Louis Cagniard Award and ASEG Early Achievement Award. He is the current Asia-Pacific Vice President of AAPG, former federal Vice-President of ASEG, has held numerous committee and leadership roles in AAPG, SPE, SEG, ASEG, and is a 2017 PESA Distinguished Lecturer and Course Instructor.*

1.   EXECUTIVE SUMMARY

Geomechanical analysis is essential for estimating the risk of fault reactivation, determining maximum safe injection pressure and for planning future injection wells in the SW Hub project. Geomechanical studies involve calculating and predicting the present-day in-situ stress tensor (magnitudes and directions) and the conditions required for rock failure to occur (rock strengths and elastic rock properties).

This study has undertaken a detailed and careful review of all available rock mechanical testing and in-situ stress analysis for the SW Hub Project, in order to assess where this work can be considered complete, and to identify any key areas where further analysis may be required.

This review identified three key aspects of geomechanical modelling for which further analysis is recommended, namely the:

- careful review of existing rock mechanics tests and the undertaking of additional rock mechanics testing;
- collection of additional fracture test data for calibration of minimum horizontal stress magnitude estimates, through review of offset well information and testing in any future Harvey wells, and;
- re-analysis of maximum horizontal stress magnitudes utilising updated and improved rock mechanical properties and minimum horizontal stress magnitude estimates.

The first key outcome of this review is that the Yalgorup and Wonnerup Members of the Lesueur formation display unusual compactive/ductile rock mechanical properties and behaviours. In particular, recently available rock mechanical tests indicate that rock strengths were over-estimated in prior geomechanical studies. The overestimation of rock strengths has likely resulted in an overestimation of horizontal stress magnitudes. A basic sensitivity analysis herein suggests that present-day stress regimes in the Harvey region may be normal to strike-slip, rather than the thrust to strike-slip stress regime estimated in prior studies. Lower horizontal stress magnitudes are predicted to result in a lower risk of fault reactivation during CO_2 injection.

2.   INTRODUCTION

Geomechanical analysis is an essential component of the SW Hub project. Understanding of present-day stress state, and rock mechanical properties and strengths, is necessary for the assessment of the mechanical sealing capacity of rocks, determination of injection pressure thresholds, risking of induced seismicity, and the planning of any future appraisal or development wells.

Figure 2.1 illustrates how each element or stage of the modelling workflow interacts. Geomechanics is part of the "Data Analysis" with the outcomes being fed into the modelling and simulation phase of the work and acting as a guide to the limits applied to the simulation models.
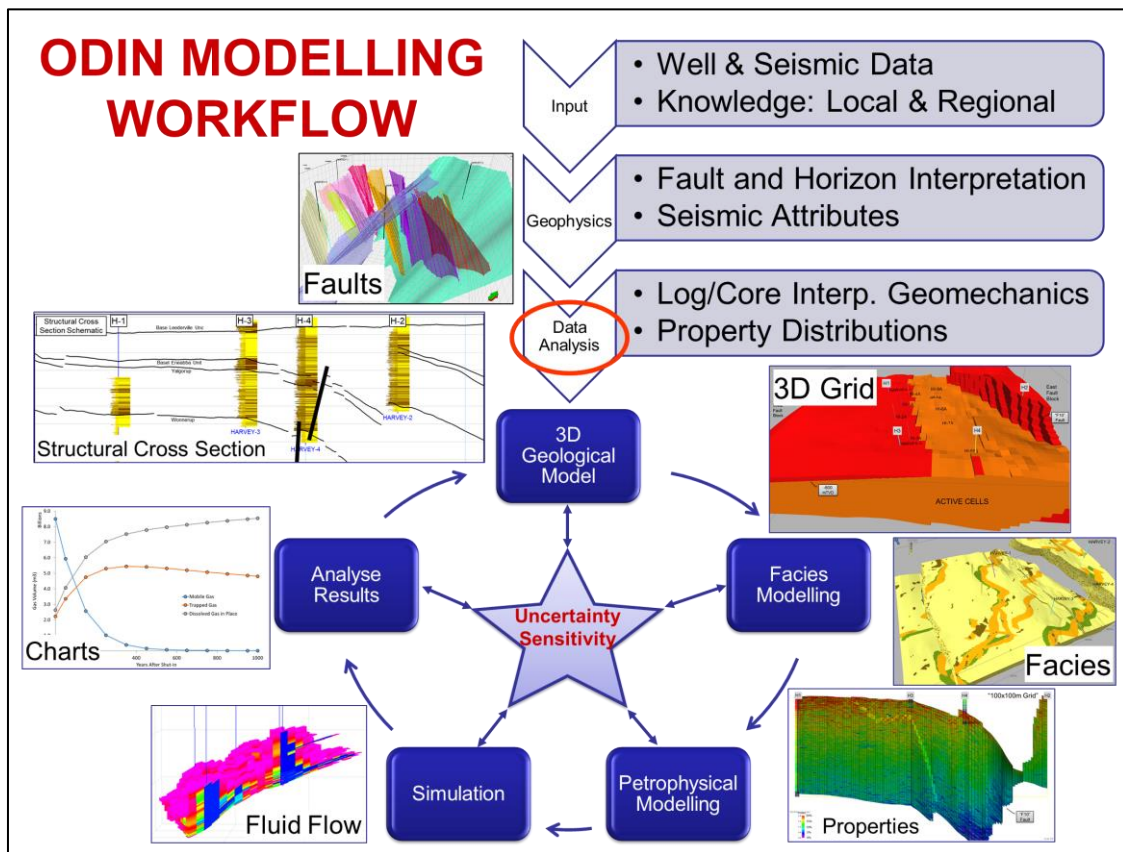

Figure 2.1: ODIN Modelling Workflow.

The aim of this study is to review all available geomechanical analyses that have been conducted, and to assess the implications of recent data or alternate methodologies on existing interpretations. Hence, the purpose of this report is to make recommendations for further studies and analysis to characterise the geomechanical aspects of the Harvey area. Please note that this report is not intended to provide any detailed interpretations or new geomechanical analysis.

A total of six geomechanical reports have been reviewed herein, which broadly fall into two categories: rock mechanical testing and in-situ stress analysis. Both categories are essential for geomechanical analysis of the SW Hub project. In-situ stress analysis uses borehole and other data to estimate and constrain the state of stress in the project region, and to estimate how stresses and pressures may change due to fluid injection. Rock mechanical testing involves laboratory testing of core samples in order to determine static elastic rock properties (e.g. Young's modulus and Poisson's ratio) and estimate rock failure criteria.

Rock mechanical testing data is a crucial input parameter for in-situ stress analysis, as the rock mechanical properties are used to make log-based predictions of rock properties throughout the study area and these are, in turn, used as the key control for the determination of in-situ stress magnitudes and all associated implications. However, the key observation of this review is that the majority of in-situ stress analysis was undertaken prior to rock mechanical testing data being available or used only a very limited amount of rock mechanical data. A review of predicted rock mechanical properties and failure criteria versus measured data highlights that there are potentially significant uncertainty in the inputs and constraints on in-situ stress analysis, and that stress magnitudes are potentially over-estimated.

This report will first review the rock mechanical testing results from the SW Hub wells, including undertaking a quality-check of all tests, as well as providing recommendations for further testing and methodology improvements. In-situ stress analysis is then reviewed, with focus on where analysis has been done appropriately, and where potential improvements or updated analysis may be required, especially with regards to the inclusion of rock mechanical testing results. Finally, this report summarises key recommended follow-up analysis or testing for the SW Hub project.

3.   REVIEW OF ROCK MECHANICAL TESTING

Rock mechanical testing is primarily undertaken in this study to determine elastic rock properties (such as Young's modulus and Poisson's ratio) and to determine rock failure criteria (also known as failure envelopes). Four rock mechanical testing reports have been obtained for this study and are reviewed herein.

1. Curtin University testing of GSWA Harvey 1 core material conducted in 2012 (ANLEC 3-1110-0122).
2. CSIRO Testing of GSWA Harvey 1 core material, conducted in 2013 (Delle Paine et al., 2013).
3. CSIRO Testing of DMP Harvey 3 and DMP Harvey 4 core material conducted in 2017 (ANLEC 240 report, in review).
4. Core Laboratories testing of DMP Harvey 3 core material conducted in 2016 (HOU-150878).

3.1   Review of Rock Mechanical Testing Method

Almost all rock mechanical testing provided for this study has been conducted using multi-stage triaxial testing, with only the samples tested by Core Lab using conventional triaxial testing. Conventional triaxial testing involves one cycle of destructive testing for each core plug, in which the sample is placed under a specific lateral confining stress and then has an increasing axial stress applied until failure occurs (typically shear fracturing). Under conventional triaxial testing, failure tests are conducted on a set of multiple plugs from approximately the same depth, with the combined results then being used to determine elastic rock properties (and how they vary under different confining stress) and to estimate brittle failure criteria/envelope parameters (for example, cohesion, friction angle and unconfined compressive strength).

Multi-stage triaxial testing differs from conventional testing in that all tests are conducted using a single core plug. Rather than undertake multiple destructive failure tests, multi-stage triaxial testing involves several loading stages/cycles (each under different confining stress values) in which the sample is stressed but is not brought fully to failure. Typically, loading cycles in multi-stage triaxial testing will stress the sample to beyond the elastic yield point, and approximately 90% of the estimated peak (failure) stress.

Multi-stage triaxial testing commonly involves four or five loading cycles to above the yield point, followed by one final 'failure cycle', in which an axial load is applied until the sample undergoes failure (typically shear fracturing).

Multi-stage triaxial testing is a relatively common method for rock mechanical testing, and has the advantages of being quick, requiring less core samples, and of avoiding possible variations that may occur between the samples as part of a conventional triaxial 'set'. The key disadvantage of multi-stage triaxial testing is that samples are not brought fully to failure multiple times which potentially weakens the sample due to pushing it beyond yield point multiple times prior to failure. As such, multi-stage triaxial testing is considered by the author to be more prone to potential errors or uncertainties than conventional triaxial testing.

All rock mechanics tests analysed herein were conducted in sands, or relatively permeable (predominately >1 mD) clastics. As such, all tests were conducted in drained conditions (fluid able to freely flow out of test chamber so pore fluid pressure stays constant). No mechanics tests have been provided for shales or low permeability sealing lithologies.

3.2 2012 Curtin University GSWA Harvey 1 Rock Mechanical Testing

Geomechanical testing was undertaken on two samples from GSWA Harvey 1 as part of a larger Curtin University study on the effects of CO_2 injection on rock properties at four potential carbon capture and storage sites in Australia. Both samples (55H and 54H) were from the Wonnerup Member at 1935m depth. Multi-stage triaxial testing was undertaken on sister core plugs, with the 55H sample tested after CO_2 flooding and compared against sample 54H that had been tested prior to CO_2 flooding. The Curtin University rock mechanics testing apparatus allows flow of different fluid types, including CO_2, under controlled pressure and high temperature (up to 200°C) conditions.

Multistage triaxial tests on GSWA Harvey 1 Wonnerup material were conducted using three loading cycles (at 5, 12.5 and 20 MPa confining pressure) followed by a final fracture test stage at 30 MPa confining pressure. Loading cycles indicated that the samples initially behaved in a highly compactive manner, with clear non-linear stress-strain behaviour. The samples showed typical elastic behaviour in the final failure stage,

with clear linear stress-strain relationships. Whilst the linear elastic behaviour in the final test stage suggests reliable results, it is important to note that these samples are likely strengthened due to the loading stage compaction, and thus final test results should be considered as possible over-estimates, and of moderate quality. Furthermore, any elastic properties or failure criteria from these tests should have an estimated uncertainty.

The post-flood sample was generally observed to be slightly weaker than the pre-flooding sample, with lower cohesion, friction angle and UCS (unconfined compressive strength). This slight weakening is believed to be the result of material being flushed out of the sample by the flooding, rather than any chemical interaction from the CO_2.

Curtin University also undertook rock mechanics testing on core material from the Lesueur Sandstone in Pinjarra 1 located in the Perth Basin. Two samples (both simply identified as being from Core 3) were tested, with one sample tested after CO_2 flooding and one prior to flooding. Precise depths for the samples are not provided, and it is only noted that they come from ~3000m depth. The pre-flooding sample showed higher cohesion and UCS. However, the post-flooding sample appeared slightly stronger than the pre-flooding sample, with respect to the observed higher friction angle and lower Young's modulus. It is likely that changes in rock mechanical properties are the result of material being flushed from the sample, rather than any chemical changes in the rock related to CO_2 interaction.

It should be noted that the Lesueur Formation samples displayed highly compactive behaviour, typical of porous rocks (samples were ~16.5% porosity). This behaviour included non-linear stress-strain paths and highly variable failure conditions that indicate failure via ductile deformation, rather than brittle failure. The Lesueur Sandstone results suggest that any elastic properties or failure criteria obtained from the tests must be carefully recalculated for specific stress conditions, and that uncertainty estimates should be made on any parameters used. These tests are classified as being of moderate quality.

A summary of the published results from the testing is provided in Table 1 in section 3.6.

3.3 2013 CSIRO GSWA Harvey 1 Rock Mechanical Testing

Geomechanical testing was undertaken by CSIRO on 11 samples from GSWA Harvey 1 as part of a larger 2013 CSIRO and Curtin University study titled 'Facies-based rock properties distribution along the GSWA Harvey 1 stratigraphic well'. All samples were taken from the Yalgorup and Wonnerup members. An additional three Yalgorup samples were intended for geomechanical testing but failed prior to testing due to weakening from brine saturation. Detailed test data was provided for ten out of the eleven multi-stage triaxial tests undertaken and have been QC'd herein below. A summary of the published test results for all samples is provided in **Error! Reference source not found.** in Section 3.6.

Sample 206616 (AKA #827) is from the Yalgorup member at 920.56m depth. Multi-stage testing involved five preliminary loading stages and a sixth and final loading stage that failed the sample. Stress and strain data indicate good quality tests, with relatively good linear elastic behaviour and clear brittle failure. Core plug photos do not show any visible failure, but stress-strain data clearly indicates shear failure. The linear fitted failure envelope shows a significant difference between the preliminary loading and final failure stress conditions, and thus failure envelope parameters (cohesion, friction angle and UCS) should be considered uncertain.

Sample 206628 (AKA #831) is from the Yalgorup member at 1273.89m depth. Multi-stage testing involved five preliminary loading stages and a sixth and final loading stage that failed the sample. Stress and strain data indicate that failure started to occur almost instantly under applied axial loading, with the samples undergoing extensive compactive behaviour (negative volumetric strains and highly different radial strains throughout axial loading). Plug photos indicate that shear failure occurred, but deformation appears to be primarily ductile. Mohr circle plots confirm ductile compactive behaviour. Test results are low quality and should not be used for determining elastic properties or failure criteria.

Sample 206635 (AKA #832) is from the Yalgorup member at 1323.93m depth. Multi-stage testing involved five preliminary loading stages and a sixth and final loading stage that failed the sample. Stress and strain data indicate that failure started to occur almost instantly under applied axial loading, with the samples undergoing extensive compactive behaviour (zero to negative volumetric strains and highly different radial strains

throughout all axial loading). Plug photos show one clear break, perpendicular to the applied load (across entire core plug), and further indicating ductile compactive behaviour. Mohr circle plots confirm ductile compactive behaviour. Test results are low quality and should not be used for determining elastic properties or failure criteria.

Sample 206644 (AKA #837) is from the Yalgorup member at 1343.61m depth. Multi-stage testing involved five preliminary loading stages and a sixth and final loading stage that failed the sample. The stress and strain data suggests some possible concerns. Volumetric strain undergoes unusual "s-shaped" behaviour, and radial strains show divergence immediately upon commencement of final axial loading, indicating compactive failure or ductile deformation very early in the loading process. Plug photos do not exhibit any signs of shear failure, with all deformation appearing to be compactive/ductile. Mohr circle plots indicate that the sample may have been significantly damaged/fatigued during the fourth and fifth preliminary loading stages. Test results are of moderate quality, and it is recommended that test results not be used, especially the failure criteria (cohesion, friction angle, UCS), but results (particularly elastic rock properties) may possibly be used with caution, and with a significant uncertainty range placed upon values.

Sample 206645 (AKA #838) is from the Wonnerup member at 1897.66m depth. Note that there is a discrepancy in sample number labelling on the provided stress-strain charts, and this sample is incorrectly labelled as 206646 therein. Multi-stage testing involved five preliminary loading stages and a sixth and final loading stage that failed the sample. Stress and strain data indicate that this test is of moderate quality. Volumetric strains are as expected, but radial strains show immediate divergence shortly after the onset of main axial loading, suggesting some component of ductile shear failure. Core plug photos exhibit a clear shear failure plane. The Mohr circle plot indicates a very consistent linear failure envelope. Overall, this test is considered of moderate quality, but elastic rock properties and failure parameters require uncertainty estimates.

Sample 206646 (AKA #839) is from the Wonnerup member at 1897.91m depth. Multi-stage testing involved four preliminary loading stages and a fifth and final loading stage that failed the sample. Stress and strain data indicate that this test is of good quality. Volumetric strains are as expected, though radial strains show some divergence shortly after the onset of main axial loading, suggesting at least some component of ductile

failure. Core plug photos exhibit a clear shear failure plane. The Mohr circle plot indicates a reasonably linear failure envelope, though the final failure stage is noticeably stronger than loading stages, highlighting the need for uncertainty estimates on failure parameters. Overall, this test is considered good quality, but elastic rock properties and failure parameters require uncertainty estimates. However, please note that there is uncertainty regarding the data for this test, as the stress-strain chart indicates only five loading cycles (including the final failure cycle), yet the associated Mohr circle plot for this test indicates six cycles of loading (this is the only test in Delle Paine et al. (2013) with only 5 clear loading cycles). Recommend CSIRO undertake re-check of raw original data and test records.

Sample 206648 (AKA #841) is from the Wonnerup member at 1902.92m depth. Multi-stage testing involved five preliminary loading stages and a sixth and final loading stage that failed the sample. Stress and strain data indicate that this test is of good quality. Volumetric strains are as expected, though radial strains show some divergence shortly after the onset of main axial loading, a component of ductile failure. Core plug photos exhibit a clear shear failure plane. The Mohr circle plot indicates a good linear failure envelope. Overall, this test is considered good quality, but elastic rock properties and failure parameters require uncertainty estimates.

Sample 206662 (AKA #844) is from the Wonnerup member at 1940.58m depth. Multi-stage testing involved five preliminary loading stages and a sixth and final loading stage that failed the sample. Stress and strain data indicate that this test is of moderate quality. Volumetric strains are reasonable, but radial strains show unusual behaviour on the final loading stage, suggesting that the plug failed early (prematurely?) and via some degree of ductile behaviour. Core plug photos exhibit a clear shear failure plane, but also visible compactional deformation/bulging. The Mohr circle plot is either missing or mislabelled for this test, as no Mohr circle plot is provided for this sample number, but rather for a sample titled '206649' for which no information is provided. Assuming that the Mohr circle plot titled '206649' is mislabelled and comes from sample 206662, the plot provides a reasonable linear failure envelope. However, the final failure stage is significantly stronger than loading stages, highlighting the need for uncertainty estimates on failure parameters. Overall, this test is considered moderate quality, but elastic rock properties and failure parameters require uncertainty estimates, and efforts should be made by CSIRO to check that provided data is from the correct test/plug sample.

Sample 206672 (AKA #848) is from the Wonnerup member at 2496.22m depth. Multi-stage testing involved five preliminary loading stages and a sixth loading stage that failed the sample. Stress and strain data indicate that this test is of good quality. Both radial and volumetric strains are as expected and indicate brittle shear failure. Core plug photos exhibit a clear shear failure plane. The Mohr circle plot indicates a good linear failure envelope. Overall, this test is considered good quality, but elastic rock properties and failure parameters require uncertainty estimates.

Sample 206675 (AKA #849) is from the Wonnerup member at 2503.46m depth. Multi-stage testing involved five preliminary loading stages and a sixth and final loading stage that failed the sample. Stress and strain data indicate that this test is of reasonable quality. There appeared to be a equipment issue during the final axial loading stage, related to the axial stress. However, despite this issue, both radial and volumetric strains look reasonable and indicate brittle shear failure. Core plug photos exhibit a clear shear failure plane. The Mohr circle plot indicates a reasonable linear failure envelope, though the final failure stage is clearly stronger than loading stages, highlighting the need for uncertainty estimates on failure parameters. Overall, this test is considered good quality, but elastic rock properties and failure parameters require uncertainty estimates.

Sample 206683 is from the Wonnerup member at an undisclosed depth. No stress-strain data or general test information is provided for this sample. However, there is a Mohr circle plot for this sample, which indicates that the sample underwent a six cycle multi-stage triaxial test, with five loading cycles and one final failure cycle. The Mohr circle plot shows an extreme discrepancy between the final failure strength and the loading cycles. The inability to QC this sample, and the high degree of uncertainty on failure properties from the Mohr circle plot, indicates that this test should be considered as low quality and not utilised.

Only seven, out of eleven, multi-stage triaxial tests conducted by CSIRO in Harvey 1 are considered valid herein for use in geomechanics analysis. However, there are three issues;

1. the observations of significant ductile compactive behaviour in many samples,
2. the chemically-induced failure of three samples during brine saturation, and

3. no uncertainty estimates on elastic rock properties and rock failure criteria.

These issues are not unique to just the CSIRO GSWA Harvey 1 rock mechanics testing, and hence will be discussed in more detail in section 3.6 below.

3.4   2017 CSIRO DMP Harvey 3 and DMP Harvey 4 Rock Mechanical Testing

Geomechanical testing was undertaken by CSIRO on four samples from DMP Harvey 3 and DMP Harvey 4, which were extracted for review herein from a larger, in review, 2017 ANLEC 240 study. All samples were taken from the Yalgorup member. All samples were used for multi-stage triaxial testing that involved three preliminary loading stages to approximately 90% of estimated peak stress, followed by a fourth and final full failure stage. Detailed stress and strain data were provided for all four samples for quality checking herein and are reviewed below. The results for all samples, as extracted from the report, are compiled in **Error! Reference source not found.** in Section 3.6

Sample 2481 is from the Yalgorup member in DMP Harvey 4 at 907.55m depth. Stress and strain data indicates that the samples undergo yielding at very low differential stresses in the three initial loading stages, with the stress required to cause yielding decreasing with each stage (at increasing confining pressures). The final failure loading stage shows highly curved stress-strain behaviour, before clear shear failure occurs. The test data indicates that the sample has undergone significant compactant ductile deformation prior to fracturing, and that failure is a mixture of ductile-brittle failure and not pure brittle failure. Core plug photos show multiple fractures, including clear shear failure, but also failure parallel and perpendicular to the applied axial load. The failure envelope is highly curved, with required shear stress for failure decreasing at the highest confining pressures, which further indicates that failure is not brittle, and dominated by ductile deformation. This test is considered to have moderate reliability. Elastic properties and failure envelope parameters (cohesion, friction angle and UCS) should not be obtained using a linear relationship and must be considered highly uncertain.

Sample 2483 is from the Yalgorup member in DMP Harvey 4 at 900.05m depth. All samples undergo yielding at approximately 6 MPa differential stress and 1% strain, regardless of confining pressure, during all three preliminary loading stages. Sample shows extensive compactional/ductile behaviour after yield in the final loading stage, with no indication of any brittle-failure related stress drop. Post-test sample exhibited a

compactional shear band, with no evidence for brittle failure. The failure envelope is highly curved, with required shear stress for failure decreasing at the highest confining pressures, which further confirms that failure is not brittle, and dominated by ductile deformation. This test is considered to have low reliability. Elastic properties should not be calculated from this data, given the highly non-linear stress-strain behaviour observed. Failure envelope parameters (cohesion, friction angle and UCS) should not be estimated for this sample.

Sample 2485 is from the Yalgorup member in DMP Harvey 3 at 888.075m depth. All samples undergo yielding at approximately 8-9 MPa differential stress, regardless of confining pressure, during all three preliminary loading stages. Failure of the sample jacket prevented the final stage from being completed, and thus the sample did not undergo a final failure test. All loading stages displayed highly non-linear behaviour, indicating extensive compaction or ductile deformation. The failure envelope is highly curved, with required shear stress for failure decreasing at the highest confining pressures, which further confirms that failure is not brittle, and dominated by ductile deformation. This test is considered to have low reliability. Elastic properties should not be calculated from this data, given the highly non-linear stress-strain behaviour observed. Failure envelope parameters (cohesion, friction angle and UCS) should not be obtained for this sample.

Sample 2490 is from the Yalgorup member in DMP Harvey 3 at 1226.45m depth. All samples underwent yielding at approximately 15-17 MPa differential stress, regardless of confining pressure, during all three preliminary loading stages. All stages showed highly non-linear stress-strain curves, aside from the first loading cycle at 5 MPa confining pressure. The final failure loading stage reached a peak differential stress of ~23 MPa and then this stress remained staying approximately constant (or slightly increasing) with further axial strain, without any sign of the stress drop associated with brittle failure. The post-test sample displayed a clear compactional shear band that confirms the sample primarily deformed through compaction and ductile shearing, with likely strain hardening behaviour. This test is considered to have low reliability. Elastic properties should not be calculated from this data, given the highly non-linear stress-strain behaviour observed. Failure envelope parameters (cohesion, friction angle and UCS) should not be estimated for this sample.

All four samples analysed in the 2017 study exhibited non-linear stress-strain behaviour and significant compactional ductile deformation. Furthermore, all samples have failure envelopes that are concave downwards in shape, which is contrary to that assumed in elastic brittle-failure geomechanical models. The implications of the observed ductile behaviour of these samples, and those in other reports, will be discussed in detail in section 3.6.

3.5   2016 Core Laboratories DMP Harvey 3 Rock Mechanical Testing

Core Laboratories, using conventional triaxial testing, undertook rock mechanical testing on 9 samples from DMP Harvey 3 (Report code HOU-150878). The rock mechanics tests used three sets of plugs, from three depths in the Wonnerup member (1420.65m, ~1471.6m and ~1511.8m), with each set comprised of three sister plugs. This group of tests was the only rock mechanics testing using the conventional triaxial method, in which individual samples undergo only one full loading cycle (that fails the sample), and failure criteria and elastic properties are determined by combining several single-stage tests conducted on plugs from approximately the same depth. This is in contrast to multi-stage triaxial testing, in which the same sample is loaded to yield (but not failure) multiple times before undergoing a final failure loading cycle. Detailed data is available for all nine samples from each of the three triaxial test sets. The reported test results are included in **Error! Reference source not found.** in section 3.6 below.

Triaxial Set 1 tested three plugs, labelled as 1VA (confining pressure, P_c=435psi), 1VB (P_c=725psi) and 1VC (P_c=1165psi), from the Wonnerup member at 1420.65m depth. Stress and strain data indicate that all three single-stage tests were of good quality, with approximately linear stress-strain behaviour at low applied stresses, with clear transition to yield and then brittle shear failure. Core plug photos confirm shear failure. Overall, this test is considered good quality, but elastic rock properties and failure parameters require uncertainty estimates.

Triaxial Set 2 tested three plugs, labelled as 2VA (1471.45m, P_c=435psi), 2VB (1471.63m, P_c=725psi) and 2VC (1471.73m, P_c=1165psi), from the Wonnerup member. Stress and strain data indicate that all three single-stage tests were of good quality, with approximately linear stress-strain behaviour at low applied stresses, with clear transition to yield and then brittle shear failure. However, sample 2VC, tested at the highest

confining pressure, exhibited stress-strain behaviour that indicates a significant degree of compactive/ductile deformation, in addition to brittle shear failure. Core plug photos confirm shear failure. Overall, this test is considered good quality, but elastic rock properties and failure parameters require uncertainty estimates.

Triaxial Set 3 tested three plugs, labelled as 3VA (1511.71m, P_c=435psi), 3VB (1511.79m, P_c=725psi) and 3VC (1511.86m, P_c=1165psi), from the Wonnerup member. Stress and strain data indicate that all three single-stage tests were of good quality, with approximately linear stress-strain behaviour at low applied stresses, with clear transition to yield and then brittle shear failure. However, sample 2VC, tested at the highest confining pressure, exhibited stress-strain behaviour that indicates a significant degree of compactive ductile deformation, in addition to brittle shear failure. Core plug photos confirm shear failure. Overall, this test is considered good quality, but elastic rock properties and failure parameters require uncertainty estimates.

Overall, the three sets of conventional triaxial tests yielded good quality results and are suitable for use in geomechanical models and analyses. However, it should be noted that these tests were conducted at relatively low confining pressures (<8 MPa), and over a relatively small range of confining pressures (2.9-8.0 MPa), and thus does not yield results over as wide a range of potential stresses as conducted in the three studies using multi-stage triaxial testing (which was over confining pressure ranges from 5 MPa up to 20 or 40 MPa). The results of the Core Laboratory testing indicate that the Wonnerup member may show reasonably linear elastic behaviour at low confining pressures, but this should be verified with further rock mechanics testing.

3.6   Summary and Recommendations

Geomechanical testing has been undertaken on a total of 26 samples from Harvey wells, plus two samples from Pinjarra 1, all of which have been reviewed in detail herein. These samples have resulted in elastic rock property (primarily Young's modulus and Poisson's ratio) estimates, as well as failure envelope estimates for 19 multi-stage triaxial tests and three conventional triaxial test sets. The published results from these tests are presented in **Error! Reference source not found.**, along with the quality level (low, moderate, high) determined herein.

Table 1: Summary of geomechanical testing and published results for the SW Hub region[i].

Well	Sample	Depth	Formation	φ	YM	PR	S₀	FA	UCS	Qual	Source
Harvey-1	55H	1935	Wonnerup	14.3	20.6	0.32	10	36.9	40	Mod	Curtin, post-flood
Harvey-1	54H	1935	Wonnerup	14.3	21	0.3	12.4	39.1	52	Mod	Curtin, pre-flood
Harvey-1	206616	920.56	Yalgorup	-	10.2	0.17	7.79	14.6	20.1	High	CSIRO 2013
Harvey-1	206628	1273.9	Yalgorup	12.8	2.2	-	-	-	-	Low	CSIRO 2013
Harvey-1	206635	1323.9	Yalgorup	15.9	1.8	0.25	-	-	-	Low	CSIRO 2013
Harvey-1	206644	1343.6	Yalgorup	12	7.9	0.23	5.82	10.8	14.2	Mod	CSIRO 2013
Harvey-1	206645	1897.7	Wonnerup	14.2	16.1	0.21	15.5	26.6	50.3	Mod	CSIRO 2013
Harvey-1	206646	1897.9	Wonnerup	15.6	21.6	0.18	7.93	35.4	28.9	High	CSIRO 2013
Harvey-1	206648	1902.6	Wonnerup	12.9	19.3	0.21	20.6	31	72.6	High	CSIRO 2013
Harvey-1	206662	1940.6	Wonnerup	11.5	20	0.19	10.6	31.4	37.6	Mod	CSIRO 2013
Harvey-1	206672	2496.2	Wonnerup	11.4	20.3	0.22	18.9	33	69.2	High	CSIRO 2013
Harvey-1	206675	2503.5	Wonnerup	12.7	23.3	0.17	14.2	35.8	55.3	High	CSIRO 2013
Harvey-1	206683	2516	Wonnerup	-	-	-	-	-	-	Low	CSIRO 2013
Harvey-4	2481	907.55	Yalgorup	-	3	0.37	5.54	2.6	11.6	Mod	CSIRO 2017
Harvey-4	2483	900.05	Yalgorup	-	3.6	0.42	2.9	8.7	6.75	Low	CSIRO 2017
Harvey-3A	2485	888.08	Yalgorup	-	2.8	0.33	5.9	2.2	12.3	Low	CSIRO 2017
Harvey-3A	2490	1226.5	Yalgorup	-	4.1	0.38	8.21	4.3	17.7	Low	CSIRO 2017
Harvey-3	Set 1	1420.7	Wonnerup	-	13.2	0.26	2.98	41.4	13.2	High	Core Laboratories
Harvey-3	Set 2	1471.6	Wonnerup	-	18.2	0.19	3.95	37	15.9	High	Core Laboratories
Harvey-3	Set 3	1511.8	Wonnerup	-	13.3	0.18	3.39	42.1	15.2	High	Core Laboratories
Pinjarra-1	Core 3	~3000	Lesueur	16.5	20	0.33	14	34.2	46	Mod	Curtin, pre-flood
Pinjarra-1	Core 3	~3000	Lesueur	16.5	18.1	0.33	6.5	43.7	26.8	Mod	Curtin, post-flood

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[i] Summary of geomechanical testing and published results for the SW Hub region (Table 1): φ is porosity (%), YM is Young's Modulus (GPa; static), PR is Poisson's ratio dimensionless; static), S0 is cohesion (MPa), FA is friction angle (degrees), UCS is unconfined compressive rock strength (MPa; 'intercept UCS' obtained from linear failure envelope fit used to estimate cohesion and friction angle), "Qual" indicates the assessed test quality based on quality check made in this report (low, moderate or high). All samples underwent multi-stage triaxial testing, other than those tested by Core Laboratories, which underwent conventional triaxial testing. Samples that failed prior to testing, or had incomplete testing, are not included herein. Note that these values should not be used directly in geomechanical modelling. Any required values should be specifically recalculated for the desired application and should include uncertainty estimates.

This review and quality check of Harvey rock mechanic tests raises several concerns that may have implications for all geomechanical analysis undertaken in the Harvey region. There are four issues resulting from this review.

1. Limited high-quality tests and no shale tests.
2. Compactive and ductile behaviour.
3. Chemical-induced weakening.
4. No uncertainty analysis.

1. Only eight, out of twenty-two, rock mechanics tests were ranked as high quality which have been interpreted to be reliable for use in this review, with a further eight tests having moderate quality and being potentially or partially useable. Furthermore, all the tests undertaken have been in sands, or relatively permeable clastics, without any samples being tested that are from more fine-grained sequences. The limited number of high-quality tests, combined with the limited lithological diversity in samples tested, suggests that rock mechanics remains uncertain in the Harvey region.

In my opinion, there is currently an insufficient dataset for developing reliable predictive models of rock mechanical properties. Hence, a recommendation is to undertake significantly more rock mechanics testing, with a focus on obtaining high quality tests and diversity of rock facies/lithology. It is noted that conventional rock mechanics testing seemed to produce more robust results than multi-stage testing, but this may also be a function of the relatively low confining pressures used in the testing conducted by Core Laboratories. Testing of clay-rich and silty material is recommended but is dependent on core quality and preservation. Clay-rich samples can be highly compromised, with regards to rock strengths and elastic properties, when exposed to water-based drilling mud, as well as to laboratory brines. Given the time-intensive requirements of shale rock mechanics testing (undrained testing), it is important to undertake a pre-assessment of the potential for samples having been already compromised from water exposure.

2. Almost all samples tested in the Harvey region were observed to exhibit some degree of compactive or ductile. Geomechanical analysis undertaken to date has assumed normal elastic rock behaviour that would result in typical brittle failure. However, the rock mechanics tests indicate that the rocks are able to be deformed at very low

strains, and thus will likely fail at significantly lower applied stresses than has been assumed in the geomechanical analyses used to estimate in-situ stresses. This suggests that in-situ stress magnitudes, and particularly the maximum horizontal stress magnitude, may have been overestimated previously, which will be discussed in section 4.5 below.

3. The third issue of concern from this testing is the observation of chemical-induced weakening and failure of several Yalgorup plug samples when saturated with brine. The most likely cause of this weakening, and that interpreted in the CSIRO report, is that brines are interacting with clays. The presence of water-responsive clays in the Yalgorup indicates that there was likely non-elastic stress induced failure, or weakening, of the Yalgorup member related to drilling mud interaction in all Harvey wells. This may have compromised Yalgorup core, making rock mechanics testing results less reliable. Furthermore, such weakening is not considered in the geomechanics modelling undertaken to date and may influence previously estimated in-situ stress magnitudes (see section 4.4 below).

4. The final issue from these rock mechanics testing results is the absence of any uncertainty analysis in estimated rock mechanical properties or failure criteria parameters. Elastic rock properties, such as Young's modulus and Poisson's ratio, are estimated from the slope of different stress and strain curves. However, the samples herein rarely displayed clearly linear stress-strain behaviour, and thus the estimated elastic rock properties depend highly upon 'where', with regards to applied stress or strain, these values are determined. Elastic rock properties for some samples will be significantly different if measured at low, high or over a wide range of strain values. Furthermore, each study appears to have used different parameters to estimate elastic rock properties, and thus values cannot be directly compared between studies.

    Failure envelope parameters, namely cohesion, friction angle and UCS, also have no uncertainty ranges applied. These parameters are determined from a straight-line fit of stress values from between 4-6 triaxial stages applied to each sample. As can be seen from examples herein, a straight-line is often not a good fit to the test measurements. Providing only single value estimates for rock failure criteria gives an exaggerated confidence in the reliability of the measurements. Whilst there is no

standard approach to estimating uncertainty in rock mechanical testing results, there are multiple methods that can be tested, and it should always be considered routine practice to place uncertainty ranges on laboratory-derived rock mechanical properties.

4.   REVIEW OF IN-SITU STRESS ANALYSIS

Geomechanical analysis primarily involves the determination of the in-situ stress tensor, namely the magnitudes of the vertical, minimum horizontal and maximum horizontal stress and the orientation of the maximum horizontal stress. This section reviews two prior studies that have used borehole data in Harvey to estimate the in-situ stress tensor.

1. Rasouli et al., 2013, In-situ stresses in the Southern Perth Basin at the GSWA Harvey 1 well site. Exploration Geophysics, 44, 289-298.
2. Castillo, 2015, GeoMechanical Assessment of the Harvey Area. Report DMIRS/2015/2.

Note that pore pressures have not been reviewed herein as all data collected to date indicates that pore pressures are hydrostatic. Furthermore, there is no geological reason to expect overpressures in the Harvey target member.

4.1 Review of Horizontal Stress Orientation Analysis

Image log data, including both acoustic and resistivity images, has been collected in GSWA Harvey 1 from 840m to 2890m depth (only acoustic image log is available above ~1265m depth). The image log is generally of good quality and has been analysed in detail in both Rasouli et al. (2013) and Castillo (2015). A review of the image log herein confirms that the interpretation of drilling induced features in both studies is essentially correct and does not need to be updated. Both studies, and the review as part of this study, confirm that extensive wellbore breakout was observed in the GSWA Harvey 1 well, particularly between 900-1380m in the Yalgorup member and ~2810-2890m in the Wonnerup member. Only breakouts are observed (no drilling-induced fractures), and all are oriented approximately North-South, indicating the present-day maximum horizontal stress is oriented East-West. However, it is noted that the small subset of breakouts observed between 2810-2890m depth have a slightly different North-Nor-East orientation (~015-020°N). The approximately East-West present-day maximum horizontal stress orientation is consistent with observations of wellbore breakouts in other wells throughout the Perth Basin, and with the regional stress orientation in the Australian Stress Map (Rajabi et al., 2017). Hence, it is the recommendation of this study that no further stress

orientation analysis is required for the existing Harvey wells, though further image logs should be acquired if any future wells are drilled.

4.2 Review of Vertical Stress Magnitude Analysis

Vertical stress magnitudes have been estimated in Rasouli et al. (2013) and Castillo (2015) by the standard method of integrating density log data. The most critical aspects of vertical stress magnitude determination, and largest source of errors, are the estimation of shallow densities (from the surface to the top of the density log) and artefacts in density log data (Tingay et al., 2003). Density logs are prone to spuriously low-density artefacts from logging conditions, especially in rugose borehole where the density-logging tool cannot maintain good contact with the borehole wall. Such artefacts could result in an underestimate of the vertical stress if not appropriately removed or corrected. Neither the Rasouli et al. (2015) nor Castillo (2015) study state whether artefacts had been removed from density logs, however, no such artefacts appear readily apparent in the available study data, and it is assumed that the density log used was in good condition. Rasouli et al. (2013) apply the industry-standard method of using vertical seismic profile velocities combined with a calibrated Gardner transform to estimate densities from the surface to the top of the density log (at ~820m depth). Castillo (2015) does not describe how the vertical stress was calculated, other than by using the density log. However, the vertical stress estimates from both studies are comparable, and the methodology used in Rasouli et al. (2013) is as per industry standard practice. Hence, the recommendation of this study is that further vertical stress analysis is not required, and calculations of both prior studies are reliable.

4.3 Review of Minimum Horizontal Stress Magnitude Analysis

Estimates of present-day minimum horizontal stress magnitude represent one of the major uncertainties of geomechanical analysis in the Harvey region. The minimum horizontal stress magnitude is most reliably estimated by analysis of fracture closure pressures in mini-fracture tests and extended leak-off tests. However, these tests were not undertaken in the Harvey wells, and the only tests available that can potentially be used to estimate the minimum horizontal stress magnitude are two formation integrity tests (one each in GSWA Harvey 1 and DMP Harvey 3) and a leak-off test in DMP Harvey 2. Formation integrity tests (FITs) are of little use for stress analysis, as they do not

involve fracturing the formation. Rasouli et al. (2013) incorrectly interpret this test as a leak-off test, however, the conclusion of this review agrees with Castillo (2015), and that the GSWA Harvey 1 test did not involve rock fracturing. Leak-off tests can provide an approximate minimum horizontal stress magnitude. However, the leak-off test performed in DMP Harvey 2 was undertaken at only ~200m depth, and such shallow leak-off tests are generally unreliable as they are within the zone of very high horizontal stresses, and often approximately isotropic stresses, near the Earth's surface.

The absence of reliable fracture test data for the Harvey area means that there is no information to calibrate geomechanical estimates of horizontal stresses and, thus, no means to assess the reliability or accuracy of geomechanical predictions.

However, it is possible herein to review the different methods used for horizontal stress magnitude analysis in Rasouli et al. (2013) and Castillo (2015). Castillo (2015) highlights the significant uncertainty of stress magnitude estimation and undertakes a simple effective stress ratio method for minimum horizontal stress magnitude estimation, based primarily on regional stress magnitude analysis undertaken by King et al. (2008). The methodology used by Castillo (2015) is appropriate given the lack of calibration data available for the region. However, this method does not attempt to assess the natural variation in stress magnitudes that occurs between units of different geomechanical properties.

Rasouli et al. (2013) built a one-dimensional poroelastic mechanical earth model for GSWA Harvey 1 in order to estimate smaller scale stress magnitude variations that may be related to lithology or facies variations. The poroelastic approach undertaken by Rasouli et al. (2013) is, in my experience, highly beneficial, and typically superior to simple effective stress ratio methods. However, the poroelastic method requires reliable static elastic rock property estimates, and these were not available for the Rasouli et al. (2013) study. Comparison with predicted static elastic rock properties and reliable measured dynamic elastic rock properties indicates that Rasouli et al. (2013) over-estimated Poisson's Ratio (especially in the Yalgorup) and slightly underestimated the Young's modulus. Use of elastic rock properties that are more in agreement with measured values would yield lower predicted horizontal stress magnitudes for the Harvey region.

The absence of reliable calibration data for minimum horizontal stress means that it is particularly important to use as many approaches as possible to estimate the minimum horizontal stress magnitude, and to analyse and collect data from relevant offset wells. Hence, a recommendation of this review is that further analysis should be undertaken to analyse regional offset wells for geomechanical information and stress measurements.

Furthermore, both the effective stress ratio (Castillo, 2015) and poroelastic method used in Rasouli et al. (2013) should be utilised in order to examine larger field-scale and very small-scale stress magnitude variations, and to assess uncertainties in horizontal stress magnitude estimates. However, this analysis requires reliable rock mechanical property information and, ideally, predictive models for elastic properties and failure criteria, which further highlights the critical importance of undertaking more rock mechanics testing.

4.4   Review of Maximum Horizontal Stress Magnitude Analysis

The in-situ maximum horizontal stress magnitude is the most difficult component of the stress tensor to determine. No method currently exists for directly measuring the maximum horizontal stress magnitude in petroleum wells. Hence, the maximum horizontal stress magnitude can only be constrained to within an appropriate range by means of identifying the maximum horizontal stress magnitudes that would agree with regional and local observations. For example, the Harvey region, particularly within the target reservoir sequences, is seismically inactive, and thus the maximum horizontal stress must be less than that which would cause slip on optimally oriented faults (also known as the frictional limit to stress).

Furthermore, the observation of borehole breakout in certain zones in GSWA Harvey 1 can be used to constrain the maximum horizontal stress magnitude. In particular, both Rasouli et al. (2013) and Castillo (2015) attempt to determine the range of maximum horizontal stress magnitudes that would generate wellbore breakout in the key observed zones of the Yalgorup and Wonnerup members. Both studies then attempt to further constrain the maximum horizontal stress magnitude range by examining the stresses required to cause breakouts of the observed ~60-80° angular width in GSWA Harvey 1.

Both the Rasolui et al. (2013) and Castillo (2015) studies primarily utilise the modelling of breakout occurrence and breakout width to estimate a maximum horizontal stress

magnitude that is well in excess of the vertical stress, and even suggest that the minimum horizontal stress may exceed the vertical stress. Thus, both studies predict a present-day in-situ stress regime that is either strike-slip or reverse. However, the estimation of maximum horizontal stress from breakout occurrence and, in particular, breakout width methods implicitly makes a number of key assumptions that this review indicates may be inappropriate, namely that:

- breakouts form instantly after drilling a section of rock;
- rocks are fully elastic;
- rocks undergo typical brittle failure and have linear Mohr-Coulomb failure envelopes;
- members are not susceptible to chemical weakening;
- wellbore failure occurs at the minimum static mud weight, and;
- the minimum horizontal stress magnitude and rock strength is well constrained.

The review of rock mechanical properties and stress determination herein indicates that all of these implicit assumptions are potentially not valid. For example, it is not known when, precisely, breakouts formed in Harvey 1, as the image log was not collected until several days to almost two weeks after sections experiencing wellbore failure were drilled. This absence of timing information on breakout development means that the mud weight conditions when failure occurred are uncertain, and it is not known if there may have been failure triggered by swab or surge effects.

Furthermore, the rock mechanics tests indicate that the Yalgorup and Wonnerup members display compactive and ductile behaviour, and both members displayed non-brittle and curved failure envelopes. The Yalgorup member also showed evidence for chemical weakening in response to aqueous fluids, and thus may have been weakened by water-based mud in the almost two weeks that the formation was open prior to logging.

The method for constraining maximum horizontal stress magnitudes by breakout occurrence and breakout width are used by some geomechanics practitioners, and can yield good results when all the fundamental assumptions that underlie the equations for stresses around wellbores are valid. However, in the case of the Harvey wells, almost none of the fundamental assumptions can be considered robust or clearly valid.

Furthermore, all of the key issues, such as lack of timing information on breakout development, the ductile/compactive behaviour, predicted overestimates of rock

strengths and long open-hole time will result in these methods overestimating the horizontal stress magnitudes. This is then further compounded by the lack of reliable minimum horizontal stress calibration data, as minimum horizontal stress magnitude is a key input to the methods used to constrain and estimate the maximum horizontal stress.

A very simplistic sensitivity test was made herein to examine the potential overestimates of the horizontal stress magnitudes that could result from the use of breakout width method with the estimated rock mechanical properties and strengths in Castillo (2015), and is summarised in Table 2 and Table 3. This sensitivity analysis suggests that significantly lower horizontal stress magnitudes are required to generate the observed 60-80 degree breakout in the Yalgorup member, if the rock failure criteria is updated from that predicted in Rasouli et al. (2013) and Castillo (2015) using the values from the recently available test results. Indeed, the potential influence of simply varying rock failure properties may even result in a complete change in the estimated stress regime, from a thrust or strike-slip stress regime to a possibly normal stress regime. This change could, in turn, have implications on fault reactivation risk and maximum bottom-hole injection pressures, as discussed in section 4.5 below.

Table 2: Simplistic comparison of the potential effect of rock strength properties on estimated horizontal stress magnitudes (in MPa) at 1300m in the Yalgorup member.

Study	UCS	FA	σ_v	σ_{hmin}	σ_{Hmax}	Regime
Rasouli	~24	~23°	28.5	~26.0	~32.0	Strike-slip
Castillo	25-33	30-35°	28.5	~29.0	~45.0	Strike-slip/Reverse
Estimated	5-15	25°	28.5	~25.0	~28.0	Normal/Strike-slip

Table 3: Simplistic comparison of the potential effect of rock strength properties on estimated horizontal stress magnitudes (in MPa) at 2800m in the Wonnerup member.

Study	UCS	FA	σ_v	σ_{hmin}	σ_{Hmax}	Regime
Rasouli	~85	~33°	62	~51.0	~69.0	Strike-slip
Castillo	65-85	~41°	64	~53.5	~104.0	Strike-slip
Estimated	50-70	~34°	63	~50	~63	Normal/Strike-slip

Simplistic comparison of the potential effect of rock strength properties on estimated horizontal stress magnitudes(Table 2 and Table 3): These examples assume ~1300m and ~2800m depths in GSWA Harvey 1, biaxial failure conditions and assumes that observed width breakouts form instantly in response to a minimum mud weight of 1.25sg.

Stress magnitudes and UCS are given in MPa. Note that use of rock failure criteria that are more aligned to rock mechanical property tests may potentially result in estimation of significantly lower horizontal stresses, and possibly a change in in-situ stress regime.

Please note that the above basic sensitivity estimates in Table 2 and Table 3 is extremely simplistic. This estimate still does not consider the timing of breakouts, nor the potential chemical weakening effect of water-based mud on the Yalgorup member. The above sensitivity method still assumes a linear Mohr-Coulomb failure envelope (at low confining pressures only) and brittle failure, albeit with more appropriate rock mechanical properties. Furthermore, the above sensitivity analysis uses the 'mid-case' estimates from Castillo (2015) and does not incorporate the uncertainty on mechanical properties and stress magnitudes.

However, the potential significance of the uncertainty on rock mechanical properties, and minimum horizontal stress magnitudes, is hopefully clear from this simple example. The horizontal stress magnitudes, and thus the stress regime, is highly sensitive to changes in rock mechanical properties, so much so that the likely inadvertent overestimation of rock mechanical properties in prior studies (that did not have access to the rock mechanics tests available herein) may have resulted in significant overestimation of horizontal stress magnitudes, and potentially an incorrect present-day stress regime. The implications for this review of stress magnitudes is summarised in Section 4.5 and key recommendations for future stress magnitude analysis are outlined in Section 5.

4.5   Implications of In-Situ Stress Analysis Review

Based on the review of the existing geomechanics studies undertaken in the Harvey area, it is probable that horizontal stress magnitudes have been over-estimated because of the assumption of typical elastic rock behaviour and an over estimate of the rock mechanical strengths. An estimate of potential in-situ stress magnitudes using average rock mechanical properties for the Yalgorup member suggests that the present-day stress regime may be normal or borderline strike-slip, rather than the previously estimated strike-slip/thrust stress regime in earlier studies. The analysis herein is to highlight how sensitive geomechanical models are to key input parameters and demonstrates the need for more testing and stress magnitude analysis, as documented more extensively in Section 5.

The potential overestimate of horizontal stress magnitudes, and change in stress regime, has implications for geomechanical applications in the SW Hub project, particularly with regards to fault reactivation risk and maximum bottom-hole injection pressures. Bottom hole injection pressures are generally limited by either the minimum horizontal stress magnitude (injection pressure should not exceed the tensile fracture pressure) and the proximity of the stress regime to failure (injection pressure should not exceed that required to cause shear failure).

This review of geomechanical aspects herein suggests that the minimum horizontal stress magnitude may be in the lower part of the range of estimates in earlier studies. Though, it is important to note that FITs in GSWA Harvey 1 and DMP Harvey 3 failed to initiate tensile failure despite using high fluid pressures (>1.73sg). Hence, it is likely that this potential implication has relatively low significance for potential bottom-hole injection pressures. This is discussed in more detail in Section 4.6.

The risk of shear failure through injection of fluids (and increase in reservoir fluid pressures) is typically assessed by examining the magnitude of the differential stress (difference between the maximum and minimum principal stresses, or diameter of the Mohr circle) and by estimating the proximity of the Mohr circle to the failure envelope (e.g. via shear tendency, change in Coulomb Failure Stress or other methods). A potentially major implication of this review is that prior studies predicted high maximum horizontal stress magnitudes, and thus large differential stresses and a stress regime that is relatively close to, and well aligned for, shear failure (Figure 4.1). However, the review herein indicates that the maximum horizontal stress magnitude may be lower, even equal to or less than the vertical stress magnitude. Such a stress regime has a significantly smaller differential stress and is significantly 'further' (in terms of required fluid pressure changes) from shear failure. Furthermore, the pre-existing approximately North-South striking faults in the SW Hub region are approximately optimally aligned for reactivation in the thrust faulting stress regime predicted by Castillo (2015) but would be very poorly oriented for reactivation under a normal or strike-slip present-day stress regime (Figure 1). Hence, a broad implication of the geomechanical review undertaken herein is that the risk of fault reactivation, and shear failure, is likely to have been overestimated in prior studies. This is discussed in more detail in Section 4.6.

There is an additional implication for wellbore stability analysis from the review herein, which was not a key aim of the study. Any updated geomechanical models that may stem from the recommendations herein are also likely to result in drilling strategy changes in any future wells in the SW Hub project. For example, the observation of chemical weakening, and the potentially revised stress regime, may mean that well design could be modified to mitigate or minimise stability issues. It may be more suitable to drill unstable sections quickly, and with high mud weight and inhibition (e.g. KCl), and then quickly case these sections off. Early project wells had a necessary focus on the collection of core and wireline log data, which resulted in long open-hole sections and open-hole times. However, this requirement may not be necessary if sufficient data has been collected, or such data could potentially be supplanted by MWD/LWD log data and use of new large-diameter sidewall coring wireline tools.
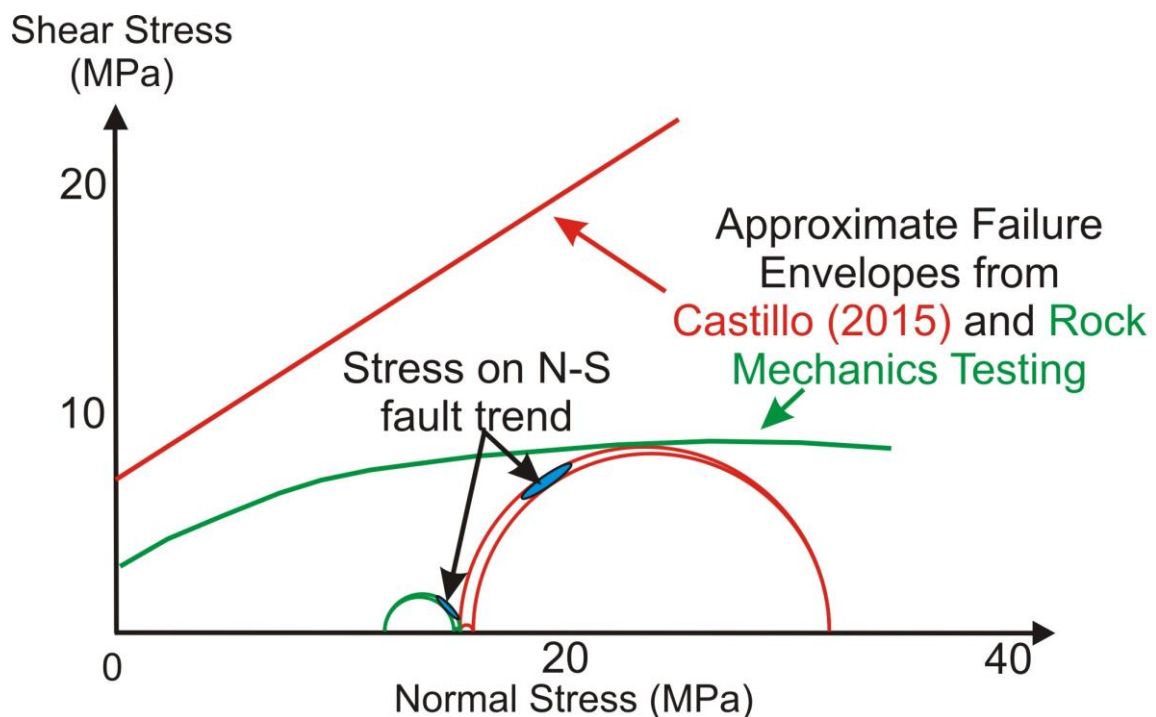

Figure 4.1: Approximate Mohr circles at ~1300m depth from Castillo (2015; in red) and as approximately estimated in this study (in green; see Table 1)

Figure 4.1 shows the approximate Mohr circles at ~1300m depth from Castillo (2015; in red) and as approximately estimated in this study (in green; see Table 1). The chart also highlights the difference in failure envelope as assumed in Castillo (2015; in red),

compared to a failure envelope used herein that is approximated from rock mechanics testing data (in green). The estimated shear and normal stress that would be applied on approximately North-South striking fault planes is plotted in the blue shaded regions. The implications of this review are that horizontal stress magnitudes may have been overestimated in prior studies and, as a result, the present-day stress state may be at a lower risk of fault reactivation due to CO_2 injection.

4.6   Recommendations for Maximum Safe Reservoir Pressure

This study has been requested to provide an estimate of recommended maximum reservoir pressures that can be likely be achieved without triggering rock brittle failure. This maximum safe reservoir pressure can be used as a limit for CO_2 injection rates, pressures and volumes in the Harvey project, and is calculated by examining the fluid pressure required to generate either tensile failure (e.g. hydraulic fracturing) or shear failure (e.g. fault reactivation). This section will quantitatively examine each of tensile and shear fracture separately, before making a recommendation of maximum safe reservoir pressure in the Wonnerup member at 2000, 2500 and 3000 metres depth.

Tensile failure can potentially occur when fluid pressures exceed the magnitude of the minimum principal stress, which is considered to be the minimum horizontal stress in all geomechanical studies of the Harvey region (Rasouli et al., 2013; Castillo, 2015; Tables 2 and 3). The analysis herein indicates that minimum horizontal stress magnitudes have likely been slightly overestimated, due to the lack of reliable LOT/FIT data and rock mechanical properties from laboratory testing. The lower rock strengths estimated herein suggest that the minimum horizontal stress magnitude, and the pressure required to trigger tensile failure, are ~25.0 MPa at 1300m depth, and ~50.0 MPa at 2800 m depth. These values represent minimum horizontal stress gradients of >1.8 s.g., or extremely high reservoir pressures (in excess of the hydrostatic) of ~1650 psi at 1300m depth and ~3200 psi at 2800 m depth. This high minimum horizontal stress gradient has been somewhat validated by the failure of FITs to initiate fracturing at up to 1.73 s.g. in GSWA Harvey 1 and DMP Harvey 3. Hence, it is suggested herein that maximum safe reservoir pressure is unlikely to be constrained by the minimum horizontal stress, and that tensile fracturing due to CO_2 injection is unlikely in the Harvey field.

It is considered herein that the maximum safe reservoir pressure in Harvey is constrained by the shear fracture gradient, or the pressure that would trigger slip on fault planes. Castillo (2015) also highlighted that shear fracturing was the most likely restriction on maximum safe reservoir pressures. Castillo (2015) did not specifically recommend a maximum safe bottom hole injection pressure for the Harvey region, due to the lack of reliable data. However, his analysis proposed that shear fracturing, or fault reactivation, may be expected if fluid pressure in the reservoir is increased by more than ~500 psi (~3.5 MPa) above present-day hydrostatic values (in all models presented, ranging from 1300m to 2850m depth; Castillo, 2015). The analysis undertaken herein suggests that the allowable increase in reservoir pressure before the onset of shear failure may be greater than that suggested by Castillo (2015), due to a likely prior overestimation of horizontal stress magnitudes (Section 4.5). The estimates of in-situ stress herein indicate that shear failure may initiate if reservoir fluid pressures exceed the virgin hydrostatic pore fluid pressures by ~10 MPa (~1450 psi) at 1300m or ~15 MPa (~2175 psi) at 2800m (using the same coulomb failure criteria approach as undertaken in Castillo, 2015). However, standard industry practice is to undertake a conservative approach when dealing with different interpretations and uncertainty estimates, such as with geomechanical analysis in the Harvey region. Hence, the recommendation herein is to consider the lowest estimate of safe formation fluid pressure, from all studies, as the maximum safe allowable reservoir pressure. As such, it is recommended herein that Castillo (2015)'s suggested maximum safe reservoir pressure increase of 500 psi, at all depths in the Wonnerup, be used to calculate the maximum allowable reservoir pressure for the Harvey region.

Limiting the increase in reservoir pressure to less than 500 psi (~3.5 MPa) is considered herein to provide a conservative and robust maximum safe reservoir pressure threshold. The maximum allowable reservoir pressure for three requested depths is provided in Table 4. It is also noted that this pressure threshold was exceeded by wellbore mud weights of >1.3 sg at all depths from 2000-2900m in GSWA Harvey 1, providing some validation that a 500psi allowable reservoir pressure increase can be considered as a reliable safety threshold.

Table 4: Recommended maximum safe reservoir pressure thresholds in absolute pressures (in MPa and psi) and pressure gradients (in equivalent fluid densities in s.g.) at 2000m, 2500m and 3000m depth in the Wonnerup member.

Depth	Virgin Reservoir Pressure	Maximum Safe Pressure	Maximum Safe Pressure Gradient
2000	20 (2900)	23.5 (3400)	1.2
2500	25 (3625)	28.5 (4125)	1.16
3000	30 (4350)	33.5 (4850)	1.14

5.   RECOMMENDATIONS FOR FUTURE GEOMECHANICAL ANALYSIS

The review of rock mechanics tests and in-situ stress estimates herein has indicated that there is potentially a discrepancy in the current modelled estimates of rock mechanical properties and failure criteria, and in the minimum and maximum horizontal stress magnitudes. Newly available rock mechanics test results suggest the Yalgorup and Wonnerup members are potentially weaker than predicted in prior studies by Rasouli et al. (2013) and Castillo (2015).

Furthermore, these tests indicate that the Wonnerup and Yalgorup members commonly exhibit compactive and ductile deformation and failure, which is not considered in conventional geomechanical analysis. These assumptions, and over-estimates of rock strengths, likely result in an overestimation of horizontal stresses, and potentially a different stress regime than previously predicted. The prior studies undertook analysis using the data available at the time and used standard assumptions that are applicable in most sedimentary rocks. However, the more complete dataset that was available for this review indicates that some of these key assumptions and predictions can no longer be considered as valid in the SW Hub region. This highlights the need and importance of reliable and extensive rock mechanics information, as well as the need to re-address horizontal stress magnitude estimates in light of the newly available data.

The aim of this study was not to undertake any significant new, or detailed, geomechanical analysis. The estimated stress analysis herein is simplistic, and purely to highlight potential implications that stem from this geomechanical review. Hence, the stress and failure values herein are purely intended to illustrate the need for further analysis, rather than be used for key applications. However, the results of the review herein do highlight the need for significantly more study on rock mechanical properties. There are six key recommendations for rock mechanical testing suggested herein.

1. Conduct additional rock mechanics testing, both of sands and of other lithologies/facies. Sample selection needs to consider core quality and preservation.
2. Review the range of confining stresses required to be tested for different implications and tailor testing accordingly (e.g. low confining stresses for wellbore stability, but higher confining stresses for reservoir geomechanics).

3. Undertake more conventional triaxial testing (rather than multi-stage triaxial) if sufficient core material is available.

4. Quality-check all rock mechanics tests, and document when rocks are not displaying the typically assumed linear elastic and pure brittle failure behaviour.

5. Determine uncertainty estimates of laboratory rock mechanical test results. This will require development of a regionally specific uncertainty estimation method, which may utilise any of several different published approaches.

6. Undertake a detailed analysis of rock mechanical properties with sonic and other properties in order to develop more robust static-dynamic conversions and methods for predicting rock mechanical properties and failure criteria from log data. It is recommended that more complex prediction methods be tested, such as multi-variable statistics, intelligent methods or machine learning methods be tested, in addition to the simple single-variable predictions that are commonly utilised.

7. Assess the potential for additional types of rock mechanics tests to tackle future issues, such as prediction of potential injection-related pore pressure-stress coupling effects, which can be made through pore volume compressibility tests.

The geomechanical review undertaken in this study also highlights the need for further analysis of horizontal stress magnitudes and the stress regime, preferably following the availability of additional rock mechanics test results. Specific key recommendations for any future stress magnitude analysis are outlined below.

1. Regional analysis on leak-off tests and fracture tests data from offsets to further constrain possible range of minimum horizontal stress magnitudes.

2. Use of both effective stress ratio and poroelastic stress magnitude estimates to understand local versus regional stress magnitude variations, and to assess stress magnitude uncertainties.

3. Re-analysis of maximum horizontal stress magnitude (and its uncertainty range) using improved and updated rock mechanical properties, more applicable failure criteria and updated minimum horizontal stress magnitude. In particular, be careful of not breaching the many assumptions implicit in the breakout width method. Strongly recommend modelling both zones where breakouts are common, but also zones where breakouts are not present. For example, Castillo (2015) study modelled where breakouts occurred – but did validate model by checking whether estimated stresses would also predict no breakout formation in the large zones of the wellbore where failure was not observed.

4. Undertake a specific focus on the estimation of uncertainty bounds on stress magnitudes (and their implications). This should involve testing numerous potential uncertainty estimation methods, such as Monte Carlo simulations.

5. Review of key implications that arise from further stress and rock mechanics analysis, such as updated implications for fault reactivation risk, maximum bottom hole injection pressures and wellbore stability.

6.   REFERENCES

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