Appendix F8

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Review of Reports on possible Subsidence at Scott Reef: Torosa Field

BROWSE FLNG DEVELOPMENT
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REVIEW OF REPORTS ON POSSIBLE SUBSIDENCE AT SCOTT REEF: TOROSA FIELD

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CONTENTS

1 EXECUTIVE SUMMARY **1**

2 SCOPE **2**

2.1 DOCUMENTATION PROVIDED 2

3 OVERVIEW **2**

4 DETAILED COMMENTS **3**

4.1 OTHER FIELD COMPARISONS 4

5 REPORT INCONSISTENCIES **5**

6 ONGOING APPRAISAL **6**

7 APPROACHES FOR MONITORING AND OBSERVING GROUND DEFORMATION **6**

7.1 GPS AND TILTMETERS 7
7.2 INSAR 7
7.3 DOWNHOLE INSTRUMENTS 8
7.4 OTHER OPTIONS 8
7.5 LIMITATIONS 8

8 OPTIONS TO MANAGE GROUND DEFORMATION **9**

8.1 PRESSURE MAINTENANCE 9

9 SUMMARY **10**

10 REFERENCES **11**

LIST OF TABLES

Table 1 Simple Estimates of pore volume compressibility (c_{pp}) from reported Cz and sample porosity.......... 4

1 EXECUTIVE SUMMARY

This report provides a review of two reports provided to CO_2 Geological Storage Solutions (CGSS) by the Department of Sustainability Environment, Water, Population and Communities as regards to potential subsidence at Scott Reef associated with future gas production in the Torosa field by Woodside.

Overall the report and methods documented by Woodside are appropriate for the current phase of the project and the conclusions are reasonable. A range of further details that could be provided have been recommended. A few inconsistencies in the report have been noted, but they do not alter the overall nature of the report.

The high level analysis of the estimate of subsidence is, at a preliminary level, of a low magnitude; less than is reported in other regions of the world. The reason for this may in part be due to the geological settings and rock types at the Torosa field. Given that the quantitative estimates are based on a relatively small core sample dataset, further information on the nature of the laboratory testing would assist a further analysis of this difference. The current laboratory data provides for compaction coefficients at the very low end of offshore gas field analogues. Should further appraisal wells be drilled at Torosa, obtaining more sample points, and or using additional techniques to estimate in-situ compressibility, may be of value. A range of potential monitoring technologies have been suggested, but will need to be analysed in detail taking into account the specific location factors in the Scott Reef area and the field production plans. Management of the potential subsidence can also be achieved through normal oil and gas industry operations, such as reservoir pressure management through fluid injection. Potential monitoring and management options need to be considered on both a commercial and technical basis.

2 SCOPE

The Department of Sustainability Environment, Water, Population and Communities requested CO_2 Geological Storage Solutions (CGSS) to review two reports provided by Woodside as part of the assessment documentation for the Browse Upstream Development (EPBC 2008/4111) regarding the possible subsidence of Scott Reef associated with future gas production in the Torosa field.

The deliverables included;

1. An assessment of the
   a. conservativeness of any calculations
   b. confidence in the predictions, and
   c. include a comparison of the predicted ground deformation against other observed ground deformation levels for comparable scenarios.
2. Advise whether any additional information is required and, if so, the nature of that information,
3. Recommendations regarding possible monitoring approaches to observe ground deformation, including the level of confidence in the effectiveness and sensitivity of these approaches.
4. Recommendations regarding possible management options to manage subsidence so as to not subside below a prescribed level, including the level of confidence in the effectiveness of these management options.
5. Review additional material(s) and amend any assessment of the confidence of the prediction or recommendations regarding monitoring and management options, if required.

2.1 DOCUMENTATION PROVIDED

CGSS were provided with two reports, being;

1. First Order Analytical Estimates of Scott Reef Subsidence as a result of Reservoir Compaction in the Torosa Field, Browse Basin (van Ruth, 2012) – pp25.
2. A Review of Analytical Compaction and Subsidence Modelling (Rahman, 2012) – pp17.

3 OVERVIEW

The approach adopted by Woodside in estimation of ground deformation is an appropriate methodology for the late appraisal phase of reservoir development. In terms of the reliability of the analysis, most of the uncertainty will depend on the quality of the limited laboratory data that has been analysed and calculated. Of significance are the levels of effective stress conditions applied to the samples during the course of the laboratory tests.

The compaction coefficient estimates that have been reported would, at a preliminary level of analysis, appear to be on the low side of what has been observed in other industry applications. An outcome of the preliminary overview is that the results should perhaps prompt Woodside to consider some further work to formally benchmark their input values for Cz (and the derived pore volume compressibility c_{pp} ~Cz/phi) against other industry correlations and analogue data so as to document how much the values may, or might not be, on the low side of normal industry experience.

It may be prudent for Woodside to consider committing to surveillance & monitoring information in regards compaction as well as obtaining some additional data and analysis associated with future appraisal wells at the field location.

4 DETAILED COMMENTS

The Woodside methods, to estimate average levels of subsidence, are based on use of Geertsma (1973) methods and that publication is considered as an industry norm and is 'best practice'. The methodology used is therefore considered to be both robust and acceptable. The method does however rely on accurate estimates of the uniaxial compressibility coefficient, and the stress conditions under which to run these measurements

For Woodside these estimates were obtained from laboratory measurements conducted in the United Kingdom. In the work reviewed here, CGSS only have had access to the Woodside report and its descriptions of the tests. CGSS have not seen the corresponding data for bulk compressibility mentioned by the Baker Hughes review (Rahman, 2012). CGSS note that the reported laboratory tests indicated that the samples displayed reasonably low values of compaction coefficient. This is the prime reason why the estimates of subsidence are also reasonably low (around the 7cm mark for lifetime depletion at a 95% confidence level). A compaction of 7cm is considered to represent relatively minor, even insignificant, levels of compaction. Therefore, the key question, in the review by CGSS, concerns whether the low uniaxial compaction coefficients can be considered meaningful and reliable. CGSS further note from information provided by Woodside that at initial pore pressure conditions, the effective overburden pressure was some 4800 to 5000 psia. This is a relatively large stress condition and, is in large part responsible for the resulting low compaction coefficients. The logic and reasoning behind the choice of initial effective stress appears sound and consistent with both measured formation pressures and estimates for overburden stress. We note that had the initial effective overburden stress been some 3500 psia, then higher compaction coefficients would have resulted (on the same rock samples).

We conclude therefore that the low reported compaction coefficients, while low by analogy to other offshore gas reservoirs, is a reasonable outcome given the consolidated rock quality and net stress conditions.

To that extent CGSS feel that there are some questions for clarification that can be asked, namely;

- Were the samples tested in a 'wet' restored state?
  - What fluid was used to fill the pore space in the laboratory tests?
  - Were any particular steps taken to prevent clays drying out in samples prior to testing?
- What comparison to industry ranges, for the derived parameter pore volume compressibility - cpp ~ Cz/phi) have been made?
  - What rationalizations are offered for any significant differences?
    - CGSS note that industry correlations (for cpp or Cz) are not exact or perfect, due to the geological differences that occur between sites, however CGSS feel that a comparison would be appropriate
- What are the longer term surveillance plans and mitigations for compaction?
  - What happens if compaction turns out to be different from that predicted?
    - How and when will that be known?
- What is the scope to acquire more data in the event of further appraisal at the field?
  - e.g. making use of in-situ tidal pressure fluctuations to estimate compaction coefficients
- What are the possible sources of error in determining the initial effective stress conditions? While we believe the effective stress conditions applied by Woodside to the laboratory samples appear

reasonable, we also believe that if they were to be substantially lower, for whatever reason, then very different measurements would have been obtained.

  - The net axial effective stress for Torosa-1 would appear to be 13,400-6526=6874 psi, while that reported for Calliance-3 was 5511 psia (after conversion from 77-39Mpa). The magnitude of the effective stress for Torosa-1 seems large, and the difference in effective stress between the sample sets also seem quite large. Can Woodside confirm these effective stress levels are appropriate?

- What levels of applied effective stress have historically been applied by Woodside in other Torosa, Calliance and/or Brecknock core tests? If they are substantially different (i.e. lower), then why?
- There should be comparison to published correlations for consolidated sandstone
  - These may show that the laboratory measurements are well on the low side
  - We note that while Woodside present a benchmark plot attributed to Shell, the Torosa data falls on the lower most boundary of the benchmark data.
- When expressed as cpp (Pore volume compressibility), the low values of Torosa cpp are very clear. CGSS have estimated (uniaxial) pore volume compressibility (by neglecting grain compressibility) in the following table. The estimated pore volume compressibility by this approach (which are numbers that CGSS are more familiar with) seems quite small compared to other gas reservoirs in the North West Shelf area. Are these estimates for cpp consistent with current Woodside reservoir forecasting methods?

Field	Depth	Interval	Porosity	Cz		cpp ~ Cz/phi	
	Metres	Unit	%	x10^-6/bar	x10^-6/psi	x10^-6/psi	x10^-5 /bar
Torosa-1	4302.29	J22.3	13.4	2.48	0.171	1.28	1.85
	4307.00	J22.3	15.2	3.30	0.228	1.50	2.17
	4319.32	J22.3	6.8	2.75	0.190	2.79	4.04
	4324.05	J22.3	14.2	3.01	0.208	1.46	2.12
	4375.57	J22.3	18.7	2.91	0.201	1.07	1.56
	4389.36	J22.3	15.7	2.68	0.185	1.18	1.71
	4395.3	J18	17.3	2.68	0.185	1.07	1.55
	4413.76	J18	17.3	2.80	0.193	1.12	1.62
	4439.26	J18	18.6	2.54	0.175	0.94	1.37
Torosa-6	4469.50	J28.3	14.5	3.27	0.225	1.55	2.26
	4481.89	J28.3	16.2	4.21	0.290	1.79	2.60
	4492.17	J28.3	0.5	1.72	0.119	23.72	34.40
Calliance-3	3820.67	J29.5	11.4	4.64	0.320	2.81	4.07
	3852.25	J28.4	21.16	4.34	0.299	1.41	2.05
	3906.52	J28.1	21.64	3.22	0.222	1.03	1.49
	3937.47	J28.1	9.2	2.63	0.181	1.97	2.86

Table 1 Simple Estimates of pore volume compressibility (c_{pp}) from reported Cz and sample porosity

4.1 OTHER FIELD COMPARISONS

Comparison with deformation in other fields in Australia by CGSS has not been done due to the lack of public information of case studies on this type of work, due in part to the lack of large gas fields in Australia that are pressure depleted and in suitable locations for deformation analysis to have been performed. To establish a meaningful comparison with subsidence in gas fields outside Australia would require proper analysis of the geological settings and development processes that were deployed at the other sites and those planned at the Torosa field; such work is possible but would require a considerable time investment to ensure meaningful comparisons were drawn. As the Torosa field estimates only relatively low subsidence levels, finding suitable comparison could be difficult as normally only the more extreme ranges are publicly reported; i.e. highly compactable geological settings.

Woodside made a comparison with the North Rankin gas field uniaxial compaction trend (van Ruth, 2012: Page 13 and 14 and Figure 5) and notes that it equates to the upper bound J28.3 (+60%) trend. The comment is made that this trend is "almost certainly an overestimate of uniaxial strain compaction in Torosa". CGSS would note that given the shallower depths and higher reservoir quality that exists in the Rankin trend, compared with the deeper and poorer quality reservoirs in the Torosa field, then it follows that the statement (van Ruth, 2012: Page 13) that " .. is almost certainly an overestimate of uniaxial strain compaction in Torosa.", is a reasonable statement to be made.

CGSS would however note a degree of caution in that none of the large gas fields on the North West Shelf have reached pressure depletion, and most are a long way from that occurrence. As such, whilst uniaxial strain compaction factors can be calculated based on individual samples and fields, how this data and these fields respond to the pressure depletion and compaction in terms of ground deformation, is largely a result driven by modelling; and analogues to other fields overseas. Each field's ground deformation will be a factor of reservoir pressure change, the thickness of the reservoir that the pressure change occurs over, and the uniaxial strain compaction factor for that reservoir. As always is the case in the geological sciences, actual responses are site specific, and whilst using such analogues and modelling is appropriate, they will need to be updated when actual experience is obtained from North West Shelf examples of full gas field depletion.

Thus the comparison to Groningen, whilst being of interest, and appropriate (given the history of that site and the original work performed at that location), the geological conditions will not be completely analogous. More discussion by Woodside of the other fields they have experience with, or have access to in terms of data, would be beneficial to future planning and assessments.

5 REPORT INCONSISTENCIES

In several locations, inconsistencies were noted in the Woodside report (van Ruth, 2012). These do not alter the overall conclusions, but should be corrected. They include:

1. On page 18 Section 6.2.1 (Geertsma Method) the surface subsidence values quoted in this section are not correct relative to the values shown in Figure 9, which is quoted. Figure 9 that is shown, relates more closely to the data quoted on page 22 Section 6.2.2 (Bruno Method), but not exactly. Figure 9 thus is likely based on a different run of the Monte Carlo simulations than is actually reported in the text. This error should be corrected.
2. On Page 23 Section 6.4 (Discussion) the averages quoted are ambiguously referred to, referring to the value of 4.21 as the highest recorded samples from the laboratory analysis, whereas they are actually 4.34 and 4.64; albeit from the nearby Calliance field and not Torosa. This ambiguity should be clarified and/or fixed.
3. On page 13, Section 5.5.1, the equation quoted is missing the exponential component (e) and thus in its present form is incorrectly reported and appears instead as a decaying exponential. It should approximately read $2 \times 10^{-6}\, e^{0.0528\phi}$. This should be corrected. CGSS replotted the primary data to derive this inconsistency, and note that Rahman (2012) do quote the exponential correctly (page 3 – equation 3) with an almost identical exponential to that derived by CGSS.

4. Figures 6, 7 and 8 lack units of measure.

6 ONGOING APPRAISAL

If any further appraisal is to take place at the field, CGSS would recommend that consideration be given to locating down-hole pressure gauges to be used to directly measure periodic pressure signals caused by tidal loading. Methods using this in-situ data can then be used to estimate cpp and Cz directly, and thus input this data into future models.

Comments from Woodside should be sought as to:

1. Preparation of samples prior to testing and what fluids were used during the test.
2. To compare and contrast against industry correlations for pore-volume compressibility.
3. To request some understanding of further more advanced modelling work that may follow these first order analytical estimates in regard to:
    a. Given that the methodology used of Geertsma (1973) method relies on an approximation of a disc for the reservoir distribution, and it is known that the reservoirs being considered comprise a regional distribution and two onlapping relationships (i.e. not a uniform series of overlying disc shapes), then what may be the individual and cumulative effect of these actual reservoir distributions on the potential surface subsidence, either;
        i. Potentially enhancing or diluting the subsidence magnitude?
        ii. Changing the location of the maximum subsidence (i.e. that subsidence may not be evenly distributed in a bowl shape but be an irregular shape based on the actual geometries and relative reservoir pressure changes in each reservoir system)?
    b. The potential impact on subsidence of either;
        i. a more compartmentalised reservoir system(s), or
        ii. a more hydrodynamically connected reservoir system(s)?
    c. The potential impact on subsidence of the permutations of 3(a) and 3(b)?

7 APPROACHES FOR MONITORING AND OBSERVING GROUND DEFORMATION

The selection of technologies for measuring ground deformation will be dependent on their suitability taking into account a range of factors such as; precision and repeatability of the technique, locational factors (water depth; stability of the surface or sea-bottom, remoteness), nature of infrastructure and facilities (fixed or floating), likely magnitude of deformation (versus accuracy of technique), commerciality, etc.

There are a variety of methods by which ground deformation has been traditionally monitored and measured, including the use of high resolution differential GPS and tilt-meters. These techniques are appropriate technologies with different levels of accuracy being achieved depending on the location; onshore, offshore and/or in isolated locations. Use of radar satellite data, with processing techniques known as InSAR (Interferometry Synthetic Aperture Radar) is also a possibility to consider. There are also techniques for monitoring compaction in the deep surface, in a well bore, using radioactive bullets/detectors and vertical seismic profiling. Detailed sea-bottom bathymetric profiling is also a technique to consider.

The applicability of direct ground deformation monitoring techniques will depend on the presence of surface features and facilities that are stable and can be considered as permanent fixtures. For the offshore environment associated with Scott Reef and development of the Torosa field, the suitability of the various technologies will depend on the field development plan and facilities that are implemented (i.e. fixed or floating platforms) and the nature of permanent and emergent Scott Reef surface areas (if any). CGSS has not made any significant assessment of such details in any detailed manner for Scott Reef or the Torosa field development plan. It is CGSS understanding that the platform facilities will be floating rather than fixed, thus negating most technologies to measure ground deformation.

Of concern for direct measurements of ground deformation will be how permanent any of the emergent parts of the reef are, and how much ground deformation occurs in the normal cycle of storms and cyclones and reef growth. It may be an option to have a permanently fixed structure constructed, that could be used for a range of technologies to use as a base for measurements. This option should be investigated.

7.1 GPS AND TILTMETERS

High resolution GPS is a technology that can be used for measuring ground deformation, and is often used with different levels of accuracy being available. In the isolated location of Scott Reef, and with the platform facilities that are planned as being floating rather than fixed, they will likely be of little value. Tiltmeters measure the change in angle of the instrument over time and can be used to document change in elevation. The use of both these technologies on any emergent and permanent land on Scott Reef should be investigated.

7.2 INSAR

More recent innovations in satellite based technologies include the use of Interferometry Synthetic Aperture Radar (InSAR). InSAR has been widely used in the onshore in the mining and to a lesser extent oil and gas industry. It is now also being applied in other applications where fluids are produced or injected into the deep subsurface (enhanced coal bed methane, groundwater, tar sands, geological storage of CO_2). However, it does have a limitation as a technology for the offshore, in that it needs to be able to acquire a series of coherent reflections from the area of interest over a period of satellite passes and time. Unstable areas such as snow, water and ploughed fields result in a loss of coherence and no calculation of potential deformation is possible. Thus in offshore locations it has limited applications.

However, CGSS is aware of new applications that are being applied to use InSAR with offshore platforms that are fixed to the sea bottom. One of the limitations will be the order of precision that can be determined. For onshore areas with good natural reflectors or artificial corner reflectors and high resolution radar data, then precision to 1mm can be achieved. However in isolated offshore locations on a platform, the precision may be at the centimetre scale, and thus may have error bars as large as the deformation that might be anticipated at some locations.

An option that should be considered for Scott Reef, is whether the emergent land components of Scott Reef itself may represent an opportunity to use InSAR, both for deformation on the emergent sections of the reef, but also as a tie point to increase the accuracy and precision of any measureable ground deformation associated with the offshore platform facilities (if they were fixed). However, it is CGSS's understanding that the offshore platforms to be used on the Torosa field will be floating, and thus not useable as a location for acquisition of coherent reflectors.

For the land surface area of Scott Reef, an artificial corner reflector (ACR) would likely be required to record any ground deformation. An ACR is a simple aluminium object abut 30cm across, that can be affixed to a concrete pad or existing infrastructure such as a marker buoy or trig station. CGSS has not been engaged to examine the potential on any land surface locations for InSAR associated with Scott Reef. An analysis would be required using locally derived knowledge to consider the viability of the land surface for any proposed location so as to estimate the likelihood of recording coherent reflectors using InSAR.

As noted above, for the option to monitor offshore facilities it will require them being permanently affixed to the sea-bottom, otherwise no reliable indication of ground deformation will be viable. If offshore facilities were affixed to the sea-bottom, then by referencing the land location (Scott Reef) with any platform location, precision at an order of magnitude below the expected deformation will likely be achievable, thus making this a potentially viable technology. Satellite passes can be obtained on demand (up to a few days) and can have repeat passes on a regular or on demand basis. Baseline information, prior to field production should be acquired and processed, and if required more regular satellite passes can be done. InSAR in some instances around Australia has been historically acquired, and thus if there are any natural reflectors on Scott Reef, or infrastructure (e.g. a trig station) that could produce coherent reflections, then a base line might be able to be established using this historical data. Such a historical baseline would be invaluable for establishing a benchmark for the field production.

7.3 DOWNHOLE INSTRUMENTS

A range of downhole technologies can be deployed to assist with measurement of ground deformation; i.e. compaction. One of the most promising for the Torosa field would be the implementation of radioactive bullets that are implanted into the deep subsurface well bore (into the rock formations) and that are then surveyed using specific tools to identify any differential displacement between the radioactive sources (Settari, 2002). In this way, compaction of the rock formations over specific intervals can be identified and monitored. Such data can then be used to more accurately determine models for overall ground deformation.

7.4 OTHER OPTIONS

Other options may exist for monitoring ground deformation, including repeat detailed bathymetric surveying and vertical seismic profiling in and between the well bores. The suitability of bathymetric surveying will depend on the precision of the technique relative to the ground deformation magnitude, the location (water depth), and the stability of the sea-bottom in the areas where ground deformation is likely to occur. For vertical seismic profiling, this technique can be used to measure any observable change in the seismically calculated velocities (or travel time of sound through the rock) in the geological formations over time, which can be an indication of compaction in those rock intervals.

7.5 LIMITATIONS

Aside from the limitations to have an accurate measurement of ground deformation that are introduced due to the remote and offshore location with floating platform facilities, the limited number of measurement points on which to make assessments will be an issue. Ordinarily with many of the techniques described, they produce a large number of data points of coherent data from which maps of ground deformation can be determined. Many of the techniques described above will only, even if suitable permanent land locations exist on Scott Reef, produce a few discrete data points.

Some of the technologies described above have been applied in overseas oil and gas field developments, and have been successful. However, in some of these locations, the reservoirs and overburden have often been poorly consolidated and highly compresible, thus resulting in very large subsidence outcomes (10s of centimetres per year). Such large values are relatively easily detected with some of these techniques. For the Scott Reef location, a suitability analysis by Woodside of the technologies that exist, would be appropriate; considering commercial and technical factors as well as evolving field development plans.

Thus as is usual in the geosciences, it will likely be necessary to combine a range of technologies to produce a mosaic of measurements and technologies and thus achieve an estimate of the likely outcomes that are occurring. Much of this work then will rely upon modelling, combined with observations that in some instances may only be approximations.

8 OPTIONS TO MANAGE GROUND DEFORMATION

8.1 PRESSURE MAINTENANCE

As the principal cause of ground deformation associated with subsurface production of fluids (oil, gas, water) is due to the change in reservoir pressure, and its impacts on deformation of the reservoir system, then through maintenance or support of the reservoir pressure, any ground deformation can be managed. This is a normal oil and gas industry operation, and in some instances have been mandated by regulators to manage ground deformation.

Where fluids are injected into reservoirs, and results in pressure increase in the reservoirs, as occurs at some oil and gas production facilities around the world, then uplift can often occur; and has been measured and modelled quite accurately. Similarly, deformation is also observed associated with the extraction of fluids where there is significant pressure change in the reservoir.

Thus, if ground deformation does occur at any site, due to reservoir pressure decrease or increase, then either injection or extraction to maintain or support the pressure change to an acceptable level will normally reduce the magnitude of any ground deformation.

Oil and gas operators routinely inject fluids (water and gas (including methane (CH_4) or carbon dioxide (CO_2)) to enhance production of hydrocarbons, especially where there is a pressure drop in a reservoir[1]. They do this with the specific aim of maintaining the pressure in the reservoir as high as is technically and commercially viable, and thus increase the production rate of hydrocarbons as high as possible for as long as possible. At the Torosa field, the option to inject fluids into the depleting hydrocarbon reservoirs, and thus maintain reservoir pressure, will depend on a range of commercial and technical factors such as;

- Injectivity of the injection reservoir
    - i.e. the permeability and thickness of the injection reservoir
- Normal commercial and infrastructure costs for provision of compressors and the impact on the offshore facilities design
    - E.g. space on the platform
- Availability of well slots on the platform for injection wells
- The commercial viability of an adjoining platform if required just for injection

[1] Note: CO_2 also is used as an injection fluid to enhance oil production due to its property that alters the viscosity of the oil and assists the flow of oil, usually in poor reservoirs; i.e. not primarily for pressure maintenance.

- The likelihood of breakthrough of the fluids used for injection back at the producing wells (e.g. CO_2), and the commercial impact of dealing with those fluids and/or reinjecting them
- etc

CGSS has not assessed the technical or commercial suitability or viability of pressure maintenance via fluid injection for the Torosa field location.

9 SUMMARY

Overall, the Woodside report (van Ruth, 2012) is a reasonable approach to a high level or first-order analysis of the potential for ground deformation at Scott Reef associated with depletion of the Torosa gas field. More information could be provided as to the laboratory analysis (i.e. the laboratory report). The ground deformation amounts that have been modelled by Woodside, are at a high level analysis on the low level of what would ordinarily be expected for a gas field depletion. The geological conditions in the deep subsurface at the site, particularly effective stress levels, are likely the reason why a low estimate has been determined. More detailed modelling could be performed. There are a range of monitoring options that could potentially be performed to assist future ongoing assessment of the field depletion and impact on ground deformation. Mitigation options also exist in case ground deformation is at levels that are deemed to not be acceptable. CGSS make no comment as to the technical or commercial viability of the mitigation or monitoring options as these would need to be considered in more detail associated with an extensive consideration of the field production plans.

10 REFERENCES

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