Report

Stimulation Risk Assessment - Santos Southwest Queensland Tenements

Site Setting and Stimulation Process

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127666004-011-R-Rev0

June 2020

Distribution List

Golder Associates - 1 electronic copy

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Executive Summary

Introduction

Santos Ltd (Santos) engaged Golder Associates Pty Ltd (Golder) to prepare a desktop risk assessment of stimulation (previously referred to as hydraulic fracturing) activities for conventional oil and gas production in their Southwest Queensland (SWQ) tenements. This Stimulation Risk Assessment (SRA) is undertaken to meet Department of Environment and Science (DES; formerly Department of Environment and Heritage Protection (DEHP)) Environmental Authority (EA) consent conditions.

This version of the SRA report updates a 2012 version of the report (127666004-011-R-Rev0, December 2012). Updated content includes reference to the updated Environmental Authority (EA) Blueprint conditions (updated December 2019), updated tenements (as of January 2020), historical well stimulation events and potential dates for future stimulation events. Background information, such as the geological setting, hydrogeology, environmental values and stimulation process, etc has largely not changed in this version of the SRA.

This desktop SRA is presented in two report volumes, as follows:

- Volume One (this report) discusses the environmental and geological settings within which Santos' stimulation activities take place and the general techniques for the drilling, completion and stimulation of wells. The report also discusses why stimulation is essential in SWQ and outlines Santos' current forward programme for fracture-stimulation, although it should be noted that for a variety of reasons (including but not limited to future production performance and / or access-related issues such as the flooding of the Cooper Creek system), the forward programme is frequently reviewed and is subject to change.
- Volume Two relates specifically to the stimulation fluids proposed to be used by *Stimulation Service Providers*[1] on Santos wells in the SWQ conventional oil and gas fields. The report considers the ecological and human health toxicity of the chemical constituents in the stimulation fluids and includes an exposure pathway assessment and risk characterisation based on a review of complete exposure pathways and controls to mitigate exposure.

In the future, specific data relating to the stimulation fluids used by other Stimulation Service Providers may be submitted as a subsequent Volume Two of this report, to allow Department of Environment and Science (DES) approval for fracture-stimulation operations by these contractors.

Golder previously prepared an Underground Water Impact Report (UWIR) for the SWQ conventional oil and gas operations, which was prepared for Santos in accordance with the requirements of the Water Act 2000 (Golder, 2012a; updated January 2020). This SRA report considers the geological and hydrogeological conceptual model developed in the UWIR, any updates to the UWIR (January 2020), additional information provided by Santos, and the requirements of DES to provide a formal risk assessment of stimulation activities in the SWQ Project Areas.

Comparison of Conventional Oil and Gas Operations to Coal Seam Gas (CSG) Operations

There are key differences between CSG and conventional oil and gas production, both in the geographic and geological setting of the resource and the methodology for accessing the resource, that have a substantial bearing on the risk profile presented by stimulation activities. These include:

[1] At the time of reporting (January 2020) 31 Haliburton products only were in use in SWQ hydraulic fracturing operations. No Schlumberger fracturing products were in use.

- Santos' conventional oil and gas operations in SWQ are located in an arid, sparsely populated area of central Australia. Whilst groundwater is an important water supply to support the rural land uses, the extent of water supply development is limited (commensurate with the small population base).
- In Santos' SWQ operations, the hydrocarbon reservoirs generally occur in anticlines capped with thick, laterally-extensive, low permeability formations that isolate the reservoirs from overlying water-bearing formations.
- The oil and gas reservoirs in the SWQ study area are very deep, of the order of 1500 to 3000 m below ground level, which provides hundreds to over a thousand metres vertical separation between the formations in which stimulation activities are proposed and the shallow groundwater resources. There is also no requirement to remove formation water in order to facilitate gas flow, with the possible exception of well blow downs on a case by case frequency.

Environmental Setting

Santos operates conventional gas and oil fields across petroleum tenements within an approximately 30,000 km^2 portion of SWQ. The terrain in the study area is generally characterised by low undulating topography (hills and ridges) between the drainage channel systems of the Cooper Creek. The area is sparsely developed, and generally comprises rural communities and homesteads that are largely engaged in pastoralism.

The stratigraphy primarily comprises the Eromanga and underlying Cooper Basins, where the oil and gas reservoirs are respectively located. These Basins contain the proposed target formations for stimulation activities. A detailed description of key geological and hydrogeological features is provided in the text, including geological models for the study area, identification of the target hydrocarbon-bearing sandstone formations (oil in the Eromanga Basin formations at depths ranging from 700 to 1,200 m below ground level (mbgl); and gas in the Cooper Basin formations at depths of 1,500 to greater than 2,000 mbgl), their hydraulic characteristics, adjacent aquifers and aquitards, structural features including faults and fracture characteristics (and their potential to behave as barriers or conduits), regional and local seismicity characteristics, aquifer environmental values and the location of groundwater users.

In terms of the environmental setting, this document has provided specific information that addresses the requirements anticipated of the EA conditions regarding stimulation that will apply to new areas proposed for development.

These specific inclusions are located within the logical flow of the description of the existing environment in the SWQ study area.

Key Environmental Values

Based on an understanding of the environmental setting, this risk assessment considered the following key environmental values:

Groundwater Environmental Values:

- Town water supply;
- Stock and domestic water supply;
- Sandstone aquifers of the GAB; and
- Groundwater Dependant Ecosystems (GDEs).

Surface Water Environmental Values:

- Protection of aquatic ecosystems;
- Recreation and aesthetics: primary recreation with direct contact, and visual appreciation with no contact; and
- Cultural and spiritual values.

Terrestrial Environmental Values:

- Protection of flora and fauna, particularly small mammals, reptiles and birds.

The report considers the applicable environmental values in the context of the proposed stimulation activities within the study area.

Stimulation Process Description Summary

With regard to the process of stimulation, the requirements of the EA approval conditions are considered within the stimulation description as they are proposed to be employed in the SWQ study area, with the specific information included as follows:

- Practices and procedures to ensure that the stimulation activities are designed to be contained within the target gas producing formation;
- Details of where, when and how often stimulation is to be undertaken on the tenures covered by this environmental authority;
- A description of Santos' well mechanical integrity testing program;
- Process control and assessment techniques to be applied for determining extent of stimulation activity(ies) (e.g. microseismic measurements, modelling etc); and
- A process description of the stimulation activity to be applied, including equipment and a comparison to best international practice.

Conclusions

Based on the available geological information for the study area, the following key points are noted:

- The DEHP database[2] and the interim results of the WBBA program (WBBA 2012; UWIR 2020) indicate that groundwater supply development in the vicinity of Santos' tenements is limited to the Glendower and Winton Formations, and to a lesser extent the Hooray Sandstone. The minimum vertical offset between the Glendowner and Winton Formations and the shallowest hydrocarbon reservoirs (oil reservoirs of the Cadna-Owie Formation) is 400 to 800 m, which includes the low permeability formations of the Wallumbilla Formation and Allaru Mudstone, which form a thick, competent and regionally extensive seal between the Cadna-Owie Formation and the shallower aquifers. The vertical offset to gas reservoirs is much greater (1,000 m to 1,800 m).
- Within formations that host both aquifers and hydrocarbon reservoirs (e.g. Hooray Sandstone), the water-bearing zones are separated from hydrocarbon reservoirs by intra-formational seals. However, there is not enough information available to discretise the internal stratigraphy of these formations. Where petroleum activities (including stimulation) occur within a formation that hosts both aquifers and hydrocarbon reservoirs, the lateral distance of the water supply bores accessing the aquifer to Santos' tenements was considered.
- Based on information from 2012, and information provided by Santos (January 2020), the closest functioning beneficial use bore to the Santos tenements targeting the Hooray Sandstone in the DEHP database records is the Coothero Bore, which is located at least 25 km from the closest tenement

[2] DEHP database accessed in 2012

proposed for stimulation and more than 80 km from the closest tenement with activities proposed at a similar depth. The Coothero Bore is monitored by Santos as part of the UWIR monitoring program.

Based on the available site setting information for the study area, the following key points are noted:

- Cooper Creek is largely influenced by surface water flows and evaporation, with negligible contribution from groundwater. Waterholes and billabongs occur throughout the Cooper Creek floodplain and channel complex, some of which coincide directly with Santos tenements. Cooper Creek resides within the Channel Country Strategic Environmental Area under the Regional Planning Interests Act.
- Three of the identified wetlands (Cooper Creek – Wilson River Junction, Bulloo Lake and Cooper Creek Swamps – Nappa Merrie) are within the boundaries of Santos' tenements. It should be noted that stimulation activities may be completed within any tenement boundary over the life of the Project.
- The Cooper Creek catchment and downstream Lake Eyre are popular recreational fishing destinations. Popular fishing spots include Bulloo River at Thargomindah, Wilson River at Nockatunga and Cooper Creek flows (episodically).

Based on the stimulation process information provided by Santos, the following key points are noted:

- Buffers are assigned during establishment of well leases between petroleum operations and potential "environmentally sensitive areas" identified though database review and site-specific ecological assessment where warranted.
- The procedures employed by Santos' and its contractors follow a design philosophy predicated on the guidance, specifications and recommended practices of the American Petroleum Institute (API), considered to represent international best practice.
- The procedures employed by Santos' and its contractors for mechanical integrity and surveillance follow a design philosophy with international best practice. Practices for ensuring well mechanical integrity consist of a robust surveillance plan.
- OH&S procedures are implemented during stimulation operations to prevent workers from direct contact with chemicals during spills and when handling flowback water or sediments. Golder understands that there has not been a recordable spill since stimulation commenced in 1987.
- Santos operational procedures monitor fracture/stimulation design to stay within the target formation.
- Santos implement spill containment procedures during operations to prevent migration of and exposure to chemicals.

Hence, the combination of the remote project location, sparse local population density (and limited water supply development), different production methods and the substantial vertical separation of oil and gas reservoirs from primary groundwater supply aquifers results in an inherently low risk profile with regard to stimulation activities. In addition, Santos procedures and operational controls are design to mitigate residual risk.

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APPENDICES

1.0 INTRODUCTION

1.1 Preamble

Santos Ltd (Santos) is a holder of numerous existing Environmental Authorities (EAs) for activities and operations throughout Southwest Queensland (SWQ), collectively referred to as “SWQ”. To meet EA consent conditions, a formal risk assessment of stimulation activities is required and subsequently, Golder Associates Pty Ltd (Golder) has been engaged by Santos to prepare this Stimulation Risk Assessment (SRA).

This version of the SRA updates a 2012 version (127666004-011-R-Rev0, December 2012 previously referred to as a Hydraulic Fracturing Risk Assessment (HFRA)). Updated content includes reference to the updated Environment Authority (EA) Blueprint conditions (updated December 2019), updated tenements (as of January 2020), historical well stimulation events and potential future stimulation dates. Background information, such as the geological setting, hydrogeology, environmental values and stimulation process, etc has not changed in this version of the SRA.

This desktop SRA is presented in two volumes, as follows:

- Volume One discusses the environmental and geological settings within which Santos’ stimulation operations take place and the general techniques for the drilling, completion and stimulation of wells. The report also discusses why stimulation is essential in SWQ and outlines Santos’ current forward programme for fracture-stimulation, although it should be noted that for a variety of reasons (including but not limited to future production performance and / or access-related issues such as the flooding of the Cooper Creek system), the forward programme is frequently reviewed and is subject to change.
- Volume Two relates specifically to the stimulation fluids proposed to be used by *Stimulation Service Providers*[3] on Santos wells in the SWQ conventional oil and gas fields. The report considers the ecological and human health toxicity of the chemical constituents in the stimulation fluids and includes an exposure pathway assessment and risk characterisation based on a review of complete exposure pathways and controls to mitigate exposure.

In the future, specific data relating to the stimulation fluids used by other Stimulation Service Providers may be submitted as a subsequent Volume Two of this report, to allow DES approval for fracture-stimulation operations by these contractors.

Golder previously prepared an Underground Water Impact Report (UWIR) for the SWQ conventional oil and gas operations, which was prepared for Santos in accordance with the requirements of the Water Act 2000 (Golder, 2012a; updated January 2020). The current report considered the geological and hydrogeological conceptual model developed in the UWIR, any updates to the UWIR (January 2020), additional information provided by Santos, and the requirements of DES to provide a formal risk assessment of stimulation activities for the future development of the SWQ Project Areas.

1.2 Limitations

Your attention is drawn to the document - “Limitations”, which is included in APPENDIX A of this report. The statements presented in this document are intended to advise you of what your realistic expectations of this report should be. The document is not intended to reduce the level of responsibility accepted by Golder, but rather to ensure that all parties who may rely on this report are aware of the responsibilities each assumes in so doing.

[3] At the time of reporting (January 2020) 31 Haliburton products only were in use in SWQ hydraulic fracturing operations. No Schlumberger fracturing products were in use.

1.3 Santos SWQ Project – Overview

Santos currently operates a significant number of conventional gas and oil fields within SWQ (Figure 1). The area covered by the petroleum tenements within which these fields encompass is approximately 30,000 km^2 of largely semi-arid agricultural land and was first developed for petroleum operations in the early 1970's. Within the Cooper-Eromanga Basin as a whole (including that part which lies in South Australia), Santos operates approximately 114 gas fields and 87 oil fields, the majority of which are currently in production (Figure 2).

- *Conventional oil* is produced from the formations of the Eromanga Basin (a sub-basin within the Great Artesian Basin (GAB)). The oil is present in discontinuous oil reservoirs within interbedded sandstones beds or larger sandstone formations. There are several types of oil reservoirs resulting from the process of "trapping" of the oil (Section 2.4.3.4).
- *Conventional gas production* is undertaken from porous sandstone formations and as such does not require the depressurisation of the target beds (with respect to groundwater). Some water is produced as a by-product however the volumes are limited (refer to the UWIR (2020) for detailed discussion). The conventional gas production is typically associated with the deeply-buried formations of the Cooper Basin (separate from and underlying the GAB). Very limited volumes of gas have also been produced from within the Eromanga Basin Production Areas.

For the purposes of this assessment, the term "*study area*" refers to the area applicable to this assessment: all SWQ tenements operated by S*antos* and the land immediately surrounding the Santos tenement boundaries (Figure 2).

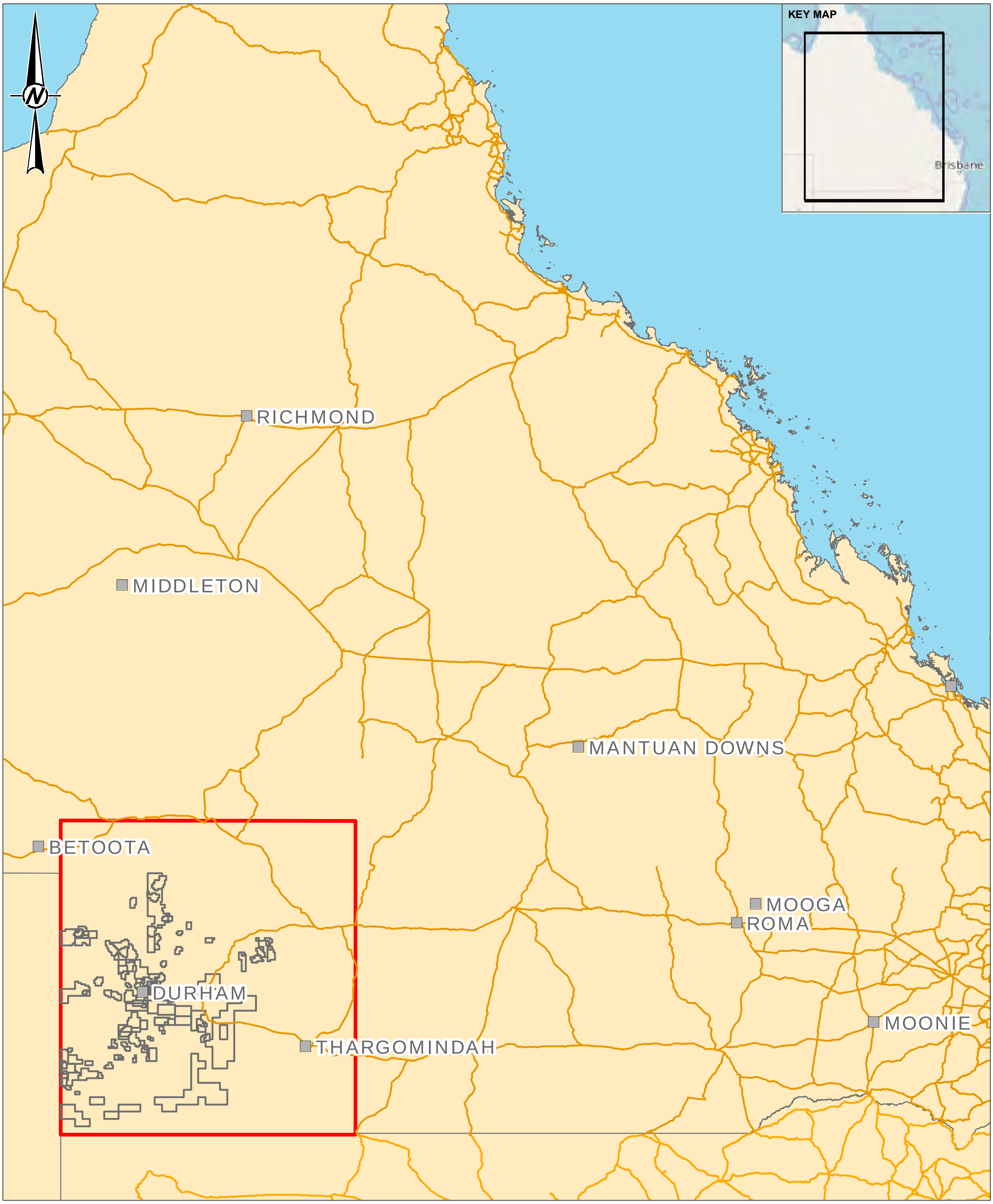
1.3.1 Proposed Stimulation Operations

The use of stimulation is essential in order to achieve economically-viable flow-rates and recoverable volumes from the majority of the production wells that are drilled in SWQ.

Between March 2013 and May 2019, 101 oil and gas wells underwent stimulation activities with another 67 oil and gas wells potentially undergoing stimulation activities between 2020 and 2022.

It should be noted that for a variety of reasons (including but not limited to future production performance and / or access-related issues such as the flooding of the Cooper Creek system), the forward drilling and stimulation programme is frequently reviewed and is subject to change.

The oil and gas production field and lease areas are further discussed in Section 1.5.



LEGEND

- Town/Locality
- Highway/Major Road
- Santos Tenements
- Study Area

0 KILOMETERS 250

1:7,000,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019

CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
SANTOS SWQ STUDY AREA

CONSULTANT

GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
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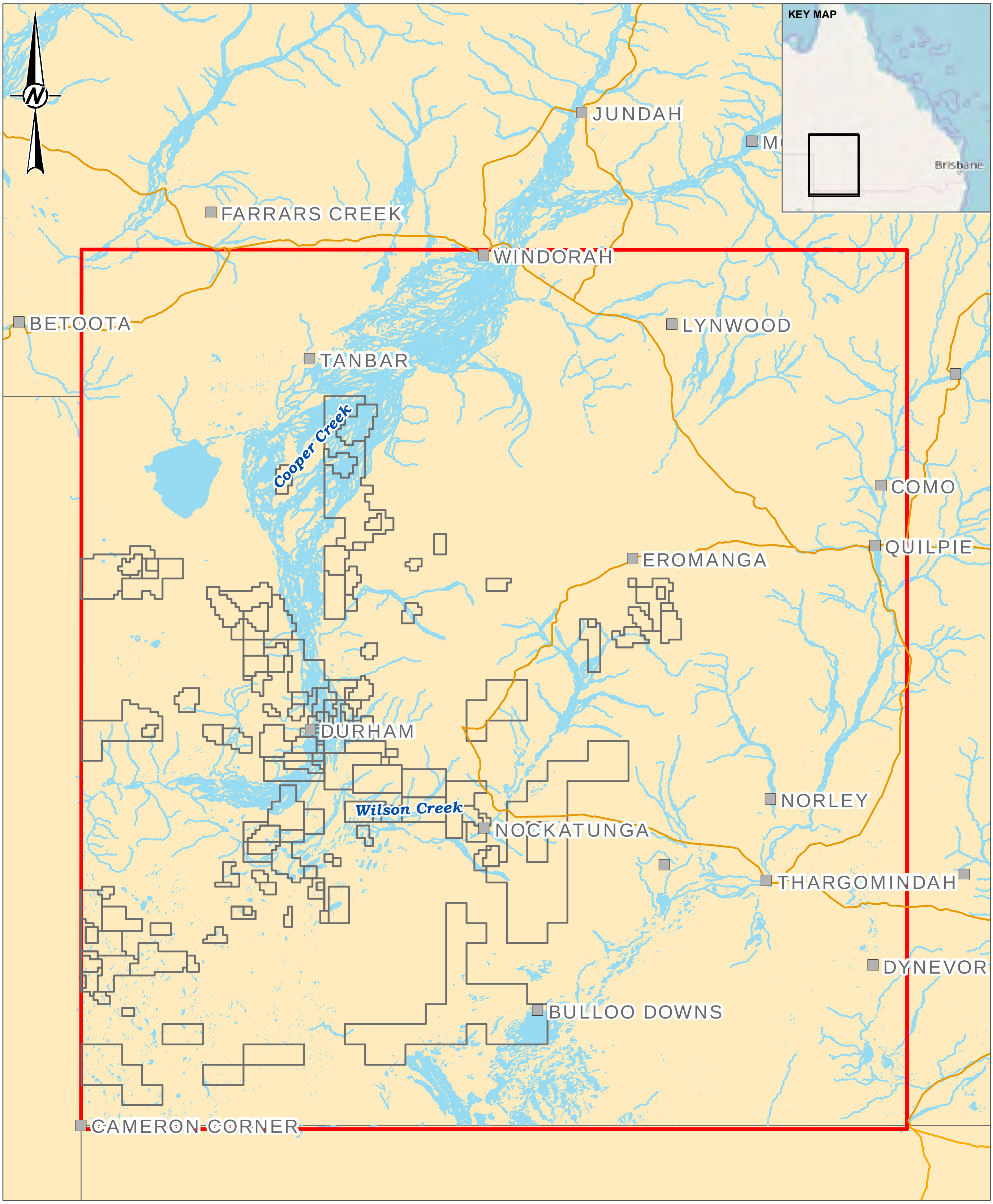

LEGEND

- Town/Locality
- Highway/Major Road
- River/Creek
- Santos Tenements
- Study Area

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1:2,500,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
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CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
OIL AND GAS FIELDS FOR THE SWQ PROJECT

CONSULTANT

GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
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1.3.2 EA Conditions

The Environmental Authority (EA) approval requirements for the Santos' SWQ operations necessitate the collection and provision of information on stimulation. Detailed regulatory requirements contained in these approvals and the sections of this risk assessment where the conditions are met are provided in Table 1. Conditions related to stimulation risk assessments can vary between Santos SWQ EAs and can also vary to those included within DES' Streamlined model conditions for petroleum activities Guideline (ESR/2016/1989).

Table 1: Summary of Consent Conditions*

Condition	Report Volume	Report Section
(a) a process description of the **stimulation** activity to be applied, including equipment	One	3.3
(b) provide details of where, when and how often **stimulation** is to be undertaken on the tenures covered by this environmental authority	One	3.4.1
(c) a geological model of the field to be stimulated including geological names, descriptions and depths of the target gas producing formation(s)	One	2.4 and 2.5
(d) naturally occurring geological faults	One	2.4.3.5 and 2.4.5
(e) seismic history of the region (e.g. earth tremors, earthquakes)	One	2.4.5
(f) proximity of overlying and underlying aquifers	One	2.6
(g) description of the depths that aquifers with environmental values occur, both above and below the target formation	One	2.6
(h) identification and proximity of **landholders' active groundwater bores** in the area where **stimulation** activities are to be carried out	One	2.5.7
(i) the environmental values of groundwater in the area	One	2.6
(j) an assessment of the appropriate **limits of reporting** for all water quality indicators relevant to **stimulation** monitoring in order to accurately assess the risks to environmental values of groundwater	Refer Stimulation Impact Monitoring Program	-
(k) description of overlying and underlying formations in respect of porosity, permeability, hydraulic conductivity, faulting and fracture propensity	One	2.4.4 and 2.5.5
(l) consideration of barriers or known direct connections between the target formation and the overlying and underlying aquifers	One	2.5.2.3, 3.3.4 and 3.3.7
(m) a description of the well mechanical integrity testing program	One	3.2.2

Condition		Report Volume	Report Section
(n)	process control and assessment techniques to be applied for determining extent of **stimulation** activities (e.g. microseismic measurements, modelling etc.)	One	3.3.4 and 3.3.7
(o)	practices and procedures to ensure that the **stimulation** activities are designed to be contained within the target formation	One	3.3.4 and 3.3.7
(p)	groundwater transmissivity, flow rate, hydraulic conductivity and direction(s) of flow	One	2.5.3, 2.5.4 and 2.5.5
(q)	a description of the chemicals used in **stimulation** activities (including estimated total mass, estimated composition, chemical abstract service numbers and properties), their mixtures and the resultant compounds that are formed after **stimulation**	Two	3.0
(r)	a mass balance estimating the concentrations and absolute masses of chemicals that will be reacted, returned to the surface or left in the target formation subsequent to **stimulation**	Two	3.2
(s)	an environmental hazard assessment of the chemicals used including their mixtures and the resultant chemicals that are formed after **stimulation** including: (i). toxicological and ecotoxicological information of chemical compounds used (ii). information on the persistence and bioaccumulation potential of the chemical compounds used (iii). identification of the chemicals of potential concern in stimulation fluids derived from the risk assessment	Two	4.0, 5.0, 6.0 and 7.3.2
(t)	an environmental hazard assessment of the chemicals used including mixtures and the resultant chemicals that are formed after stimulation	Two	4.0, 5.0, 6.0 and 7.3.2
(u)	identification and an environmental hazard assessment of using radioactive tracer beads in **stimulation** activities where such beads have been used or are proposed to be used	One	3.3.7.10
(v)	an environmental hazard assessment of leaving chemical compounds in **stimulation fluids** in the target formation for extended periods subsequent to **stimulation**	Two	
(w)	human health exposure pathways to operators and the regional population	Two	6.0
(x)	risk characterisation of environmental impacts based on the environmental hazard assessment	Two	7.0
(y)	potential impacts to landholder bores as a result of **stimulation** activities	Two	2.2.3.1

Condition		Report Volume	Report Section
(z)	an assessment of cumulative impacts, spatially and temporally of the **stimulation** activities to be carried out on the tenures covered by this environmental authority	Two	7.5
(aa)	potential environmental or health impacts which may result from **stimulation** activities including but not limited to water quality, air quality (including suppression of dust and other airborne contaminants), noise and vibration	One and Two	1.3 (Report Version One) 4.0, 5.0, 6.0 and 7.3.2 (Report Version 2)

*Consent conditions from Schedule K (Well Construction, Maintenance and Stimulation), subsection K6, 21 December 2019

1.4 Risk Assessment Process

Risk assessment provides a systematic framework for characterising the nature and magnitude of risks from stressors (in this case, stimulation chemicals). Risk assessment is an important tool for decision-making. Australian risk assessment guidance has been used in the preparation of this report, namely draft guidance for ecological risk assessment provided by the Environment Protection Authority (EPA) Victoria (Gibson *et al.*, 1997) and enHealth-Environmental Health Risk Assessment, "Guidelines for Assessing Human Health Risks from Environmental Hazards", June 2004 (enHealth, 2004).

The scope of the qualitative risk assessment comprises of:

- **Issue Identification** (Volume One) - A description of the current environmental setting (including a description of potential receiving environments and the various factors which act upon them, including climatic influences), detailed geological and hydrogeological information, gas well integrity and a description of the stimulation process including an identification of the constituents of the stimulation fluid(s);
- **Exposure Assessment** (Volume Two) – The exposure assessment comprises an evaluation of surface and subsurface exposure pathway assessment;
- **Hazard Assessment** (Volume Two) – An evaluation of the environmental hazard of relevant chemical additives in the stimulation fluid based on aquatic toxicity, environmental persistence and bioaccumulation. The environmental hazard assessment provides a relative ranking of the chemical additives and those chemicals considered to represent a high hazard are identified as chemicals of potential concern (COPC) for further assessment. An evaluation of terrestrial and human health toxicity will also be presented;
- **Risk Characterisation** (Volume Two) – A qualitative evaluation of environmental and human health risk associated with the stimulation activities based on the identification of complete exposure pathways and hazard identification.

The evaluation of exposure pathways includes both *subsurface* and *surface* processes. The principles for ecological and human health risk assessment consist of the following steps: issue identification, hazard (or toxicity) assessment, exposure assessment, and risk characterisation. Human health risk assessment is limited to assessment of effects on one receptor: *humans*. Ecological risk assessment is concerned with assessment of effects on the ecosystem (populations and communities) and therefore is not limited to one receptor. The guidance framework for ecological risk assessment in Australia is the "Guideline on Ecological Risk Assessment" (NEPM, Schedule B(5), 1999; updated 2013) which refers to draft guidance prepared by EPA Victoria (Gibson *et al.*, 1997). These guidance documents focus on risks to terrestrial environments although the overall approach for assessment or risk is the same. The risk assessment was undertaken in general accordance with these guidelines and national guidelines for risk assessment recommended by enHealth (enHealth-Environmental Health Risk Assessment, “Guidelines for Assessing Human Health Risks from Environmental Hazards”, June 2012).

If, in the future, conditions, stimulation methodologies and/or regulatory requirements change, and/or additional exposure pathways to additional receiving environments are identified, further evaluation of the associated risks *may* be warranted.

1.5 Study Area

Santos’ Production Licences in SWQ cover an area of over 17,000 km^2. The development of petroleum fields in SWQ started in the early 1970s. Santos currently produces conventional gas and oil from approximately 212 gas wells from 53 fields and 250 oil wells from 47 fields in SWQ.

The land is generally characterised by low undulating topography (hills, ridges and valleys) between the various fluvial systems (e.g. the Cooper Creek). The areas occupied by these creek systems are regionally referred to as “Channel Country” and consist of a system of braided or anastomosing channels and associated inter-channel areas and floodplains. Surrounding the floodplains are gravel plains, dunefields and low ranges. The area is sparsely developed, and generally comprises rural communities and homesteads that are largely engaged in pastoralism.

The Cooper Basin underlies, but is considered to be geologically separate from, the Eromanga Basin, which is the largest sub-basin within the Great Artesian Basin (GAB). Some of the sedimentary formations associated with the GAB are recognised as regionally significant aquifers (Figure 3). There are no outcrops of the GAB formations within the study area, which is overlain by quaternary alluvium. With a couple of localised exceptions, conventional gas is produced from formations within the Cooper Basin, at depths exceeding 2000 m, while oil is mainly produced from formations within the Eromanga Basin at depths of approximately 700 to 1,200 m below ground level.

Santos activities are described in the SWQ *Project Areas* Environmental Management Plans (Santos, 2014). The summary information on activities and infrastructure reported below has been extracted from these environmental management plans.

As a summary, the SWQ study area includes a combination of gas and oil production, associated transport, storage and processing infrastructure and ongoing exploratory, appraisal and development drilling. The operations are grouped in “processing satellites” or centres where Santos has developed all the facilities necessary to the operations of the fields. Santos has developed the following infrastructure within the Cooper-Eromanga Basin as a whole (including that part which lies in South Australia):

- Approximately 29 Oil and Gas Processing Satellites, the main ones for SWQ are discussed in Section 1.5.1; and
- Approximately 212 producing gas wells and 250 producing oil wells in SWQ.

1.5.1 Oil and Gas Occurrences and Production

A consequence of the geological setting of the Cooper and Eromanga Basins is the location of *gas* fields within the centre of the basin system (Figure 2) and the *oil* fields mainly around the edges of the study area (mainly in the centre and the east of Santos tenements in SWQ).

The petroleum fields proposed for production, the corresponding lease areas and infrastructures are discussed in the following sections.

1.5.1.1 Target Gas Formations

Gas is primarily extracted from the formations of the Cooper Basin. The geology of the Cooper Basin is presented in Section 2.4.3.1. The main consequence of the geological setting is the very deep location of the target gas reservoirs at depths of 2,000 m or more. The gas fields are located in the centre of Santos tenements in SWQ and in SA (Figure 2).

The primary gas reservoirs (discussed in Section 2.4.3.4) targeted for stimulation are sandstones within:

- The Paning and Doonmulla Members (Nappamerri Group);
- The Toolachee Formation (Gidgealpa Group);
- The Epsilon Formation (Gidgealpa Group); and
- The Patchawarra Formation (Gidgealpa Group).

These reservoirs are stacked porous sandstones, separated by coals and / or finer-grained siltstones mudstones (refer to detailed stratigraphy in Section 2.5.2). These impermeable layers are typically referred to as the seal or cap rock beds where they are located immediately above the reservoirs. The sandstone reservoirs often have low porosities and permeabilities (usually of the order of 1-10 milliDarcies), such that fracture-stimulation is essential in order to achieve economic flow-rates and production volumes.

In addition, other sediments may become targets for stimulation if encountered in future wells.

Operation of tenements is likely to change in the future and assessment of additional tenements will be considered prior to stimulation being undertaken following due consultation with DES and the Department of Natural Resources, Mines and Energy (DNRME).

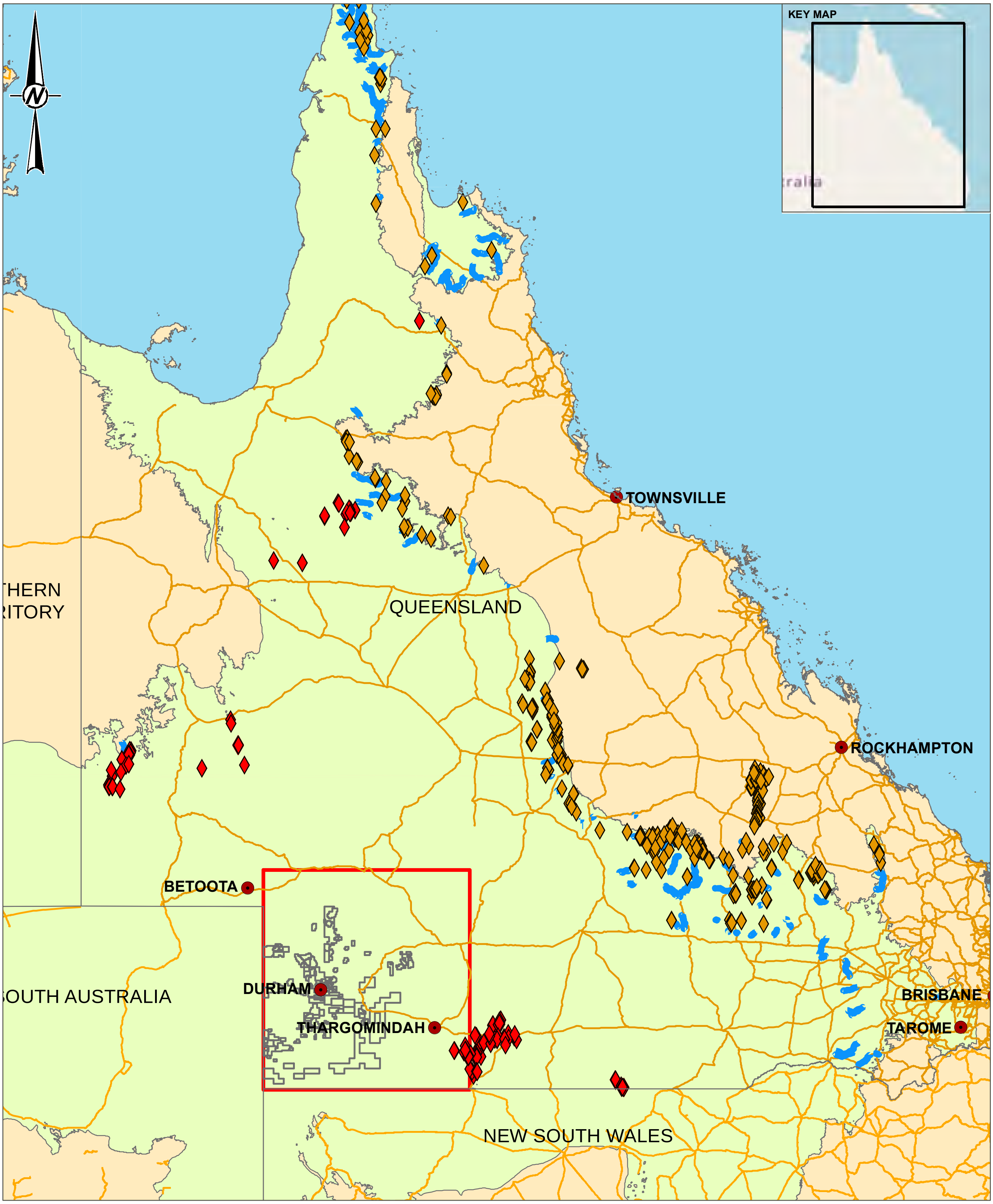
1.5.1.2 Target Oil Formations

Oil is produced from sediments within the formations of the Eromanga Basin (part of the Great Artesian Basin), at depth of approximately 700 to 1,200 m below ground level. There are 227producing oil wells within Santos tenements in SWQ.

The oil reservoirs (discussed in Section 2.4.3.4) targeted for stimulation are:

- The Murta Formation (Upper Hooray Sandstone). Oil reservoirs are abundant in the Murta Formation (interbedded mudstones, siltstones and fine grained sandstones);
- The Birkhead Formation, comprising interbedded siltstone, mudstone and fine sandstone. Oil reservoirs are present mostly in the Lower Birkhead unit, scattered oil reservoirs also occur in the Middle Birkhead unit; and
- The Wyandra Sandstone Member (upper unit of the Cadna-Owie Formation), oil occurrence is less frequent.

Operation of tenements is likely to change in the future and assessment of additional tenements will be considered prior to stimulation being undertaken following due consultation with DES and DNRME.



LEGEND

- Town
- GAB ROP Discharge Spring
- GAB ROP Recharge Spring
- GAB ROP Water Course Spring
- Highway/Major Road
- Santos Tenements
- Study Area

0 KILOMETERS 250

1:10,000,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. GAB BOUNDARY, SOURCED FROM HTTPS://DATA.GOV.AU, SOURCED 18.12.2019

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PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
LOCATION OF THE GREAT ARTESIAN BASIN

CONSULTANT

GOLDER

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1.6 Comparison of Conventional Oil and Gas Operations to Coal Seam Gas Operations

HFRA (now referred to as SRA) reports have previously been prepared to address stimulation activities related to Santos' coal seam gas (CSG) developments as part of the Gladstone Liquefied Natural Gas (GLNG) Project. There are key differences between CSG and conventional oil and gas production, both in the geological setting of the resource and the methodology for access, that have a substantial bearing on the risk profile presented by stimulation activities.

Santos' conventional oil and gas operations in SWQ are located in an arid, sparsely populated area of central Australia. Whilst groundwater is an important water supply to support the rural land uses, the extent of water supply development of the productive aquifers is limited (commensurate with the low population base) and is almost entirely within the upper sedimentary formations of the Eromanga Basin. The lateral equivalents of the GAB aquifers in Eastern Queensland that support substantial beneficial uses have little or no water supply development in in the study area.

The nature of the hydrocarbon resources in SWQ is also fundamentally different from CSG targets. Conventional oil and gas reservoirs are formed when hydrocarbons in a porous (typically sandstone) formation are "trapped" and accumulate as a result of encountering a low permeability sedimentary or structural "seal". In Santos' SWQ operations, the hydrocarbon reservoirs generally occur in anticlines capped with thick, laterally-extensive, low permeability formations that isolate the reservoirs from overlying water-bearing formations. The nature of the geological and hydrogeological setting provides for substantial separation of fracturing and production activities from the shallower groundwater resources that support the majority of water supply development in the region. There is also no requirement to remove formation water in order to facilitate gas flow, with the possible exception of well blow downs on a case by case frequency. In addition, the oil and gas reservoirs in the SWQ study area are very deep, in the order of 1500 to 3000 m bgl, which provides hundreds to over a thousand metres vertical separation between the formations in which stimulation activities are proposed and the shallow aquifers that provide the majority of private groundwater supply.

Hence, the combination of the remote project location, sparse local population density (and limited water supply development), different production methods and the substantial vertical separation of oil and gas reservoirs from primary groundwater supply aquifers results in an inherently low risk profile with regard to stimulation activities.

2.0 SITE SETTING AND ISSUE IDENTIFICATION

The description of the site setting, and issue identification is covered under the following headings:

- Description of the climate in SWQ;
- Description of the topography;
- Description of the hydrology;
- Description of the continental geological setting and basin stress regime;
- Description of the regional geology and stratigraphy of the GAB;
- Description of the local geology and oil and gas field models;
- Seismic history of the region;
- Description of the GAB hydrogeological setting and hydrostratigraphy;
- Description of the hydrogeological context of oil and gas production;
- Groundwater quality and use in the study area;
- Environmental values of groundwater and surface water in the study area, which comprise the potential receptors considered in the exposure analysis for stimulation activities; and
- Proximity of overlying and underlying aquifers to the target oil or gas formations, and proximity of surface operations to sensitive receptors.

2.1 Climate

The Cooper Basin of SWQ is an isolated arid to semi-arid region of central Australia where the average rainfall is low (<300 mm per year) and is significantly exceeded by the pan evaporation potential (approximately 3,000 mm per year). The seasons are generally characterised by hot summers with significant thunderstorm activity and mild dry winters. December to February are the wettest and hottest months where temperatures generally exceed 35°C. The Bureau of Meteorology (BOM) provides monthly average data for temperature and rainfall for anywhere in Australia. For a more detailed description please refer to http://www.bom.gov.au/.

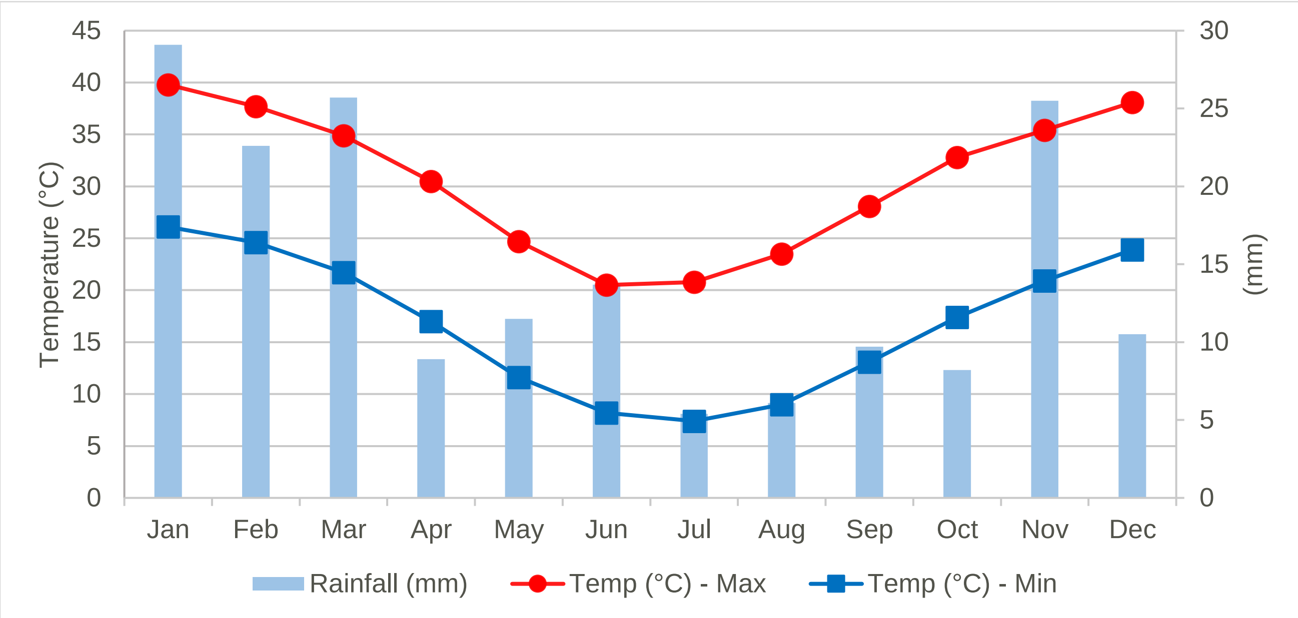
Table 2 and Figure 4 present the average minimum and maximum monthly temperatures and average monthly total rainfall from Ballera Gas Field, the closest BOM facility to Durham (approximately 16 km to the west). These data are averages for number of years. Annual average values are presented for temperature while average annual total amount of rainfall are presented in the same table. Maximum values are in red and minimum values in blue. No data on evaporation for the Ballera Gas Field site was available. However, data for evaporation was available for Windorah Evaporation Station located approximately 220 km to the north of Durham. Evaporation for Windorah ranged from 3.7 mm daily evaporation in June to 12.4 mm daily evaporation in December (data collected from 1969 to 2019). It should be noted that for this location the mean rainfall was higher than for Ballera and ranged from 10.0 mm mean monthly rainfall in August to 48.3 mm mean monthly rainfall in February approximately double that seen for Ballera in the same months.

Table 2: Mean Climate Characteristics within the Cooper Basin Operations Area – Ballera Gas Field

Mean	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Years
Temp (°C) - Max	39.8	37.7	34.9	30.5	24.7	20.5	20.8	23.5	28.1	32.8	35.4	38.1	30.6	2002-2019
Temp (°C) - Min	26.1	24.6	21.7	17.0	11.6	8.2	7.4	9.0	13.1	17.4	20.9	23.9	16.7	2002-2019
Rainfall (mm)	29.1	22.6	25.7	8.9	11.5	13.7	5.4	6.1	9.7	8.2	25.5	10.5	181.8	2000-2019

* Estimated from the average *daily* pan evaporation as reported by BOM.

Figure 4: Rainfall and Temperature Diagram - Monthly Averages from 1931-2012 for Ballera Gas Field



Source: BOM, 2012

2.2 Topography

The study area is situated across a large, relatively flat drainage area of the Cooper Creek river system referred to as the 'Channel Country' of far south-western Queensland (extending into South Australia).

The topography of the study area comprises low undulating hills and ridges between the drainage channel systems. The Channel Country is characterised by extensive alluvial plains with braided channel networks of the Diamantina and Coopers Plains. Surrounding the floodplains are gravel or gibber plains, dune fields and low ranges. The low resistant hills and tablelands present in the study area are remnants of the flat-lying Cretaceous (65 to 140 million years ago) sediments.

The drainage system of the study area is dominated by the Cooper Creek Basin and is discussed further in Section 2.3.

2.3 Surface Water

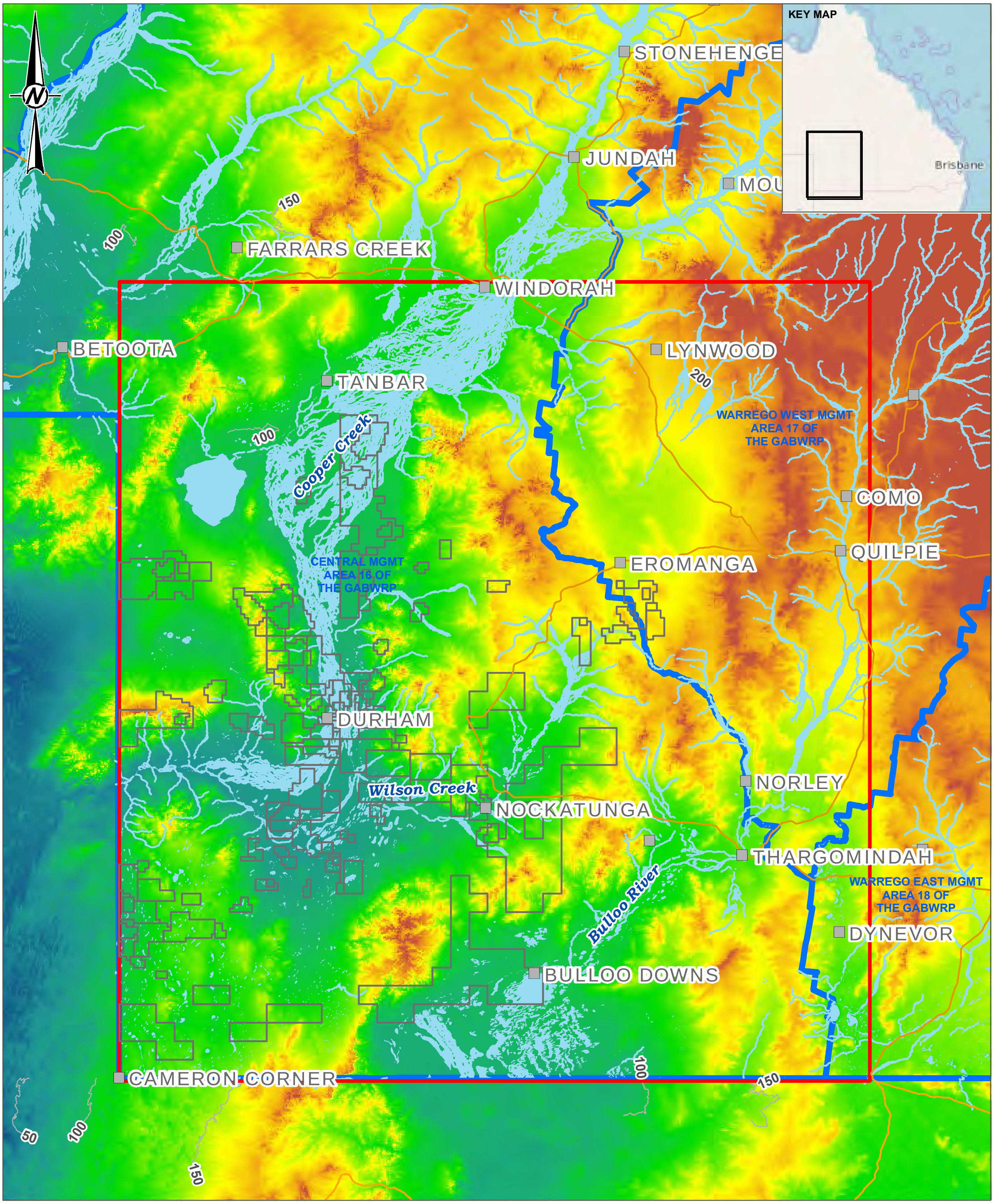
The surface water drainage system within the study area (Figure 5) is dominated by Cooper Creek Basin, which drains southwest towards Lake Eyre. This Basin comprises almost a quarter of the overall Lake Eyre Basin catchment. During periods of monsoonal rainfall in its headwaters, the flat topography and drainage channel system forms a large floodplain. The surface water flow bottlenecks where Cooper Creek crosses the Queensland-South Australia border.

Cooper Creek is an internal (i.e. no outlet to the ocean) ephemeral river of 1,500 km in length and covering a catchment area of 306,000 km^2. Water flows vary greatly over time and are predominantly controlled by the occurrence of monsoonal rains in the headwaters of the Cooper Creek drainage system (Kotwicki and Allen, 1998).

Generally, Cooper Creek stream flows are confined to the main channels, but every three to four years flows are sufficient to inundate parts of the Cooper Creek floodplain, via a network of tributary channels. The cyclic nature of flows in Cooper Creek has been reported to correlate with La Nina events, which result in monsoon rains penetrating further into inland Australia (Kotwicki and Allen, 1998). During extended periods of no flow, the Cooper Creek drainage contracts to a series of disconnected, semi-permanent waterholes that form in deeper portions of the river channels, which provide drought refuges for a variety of flora and fauna. Two minor flood events were observed in 2019 and the latest large flood event was observed in early to mid 2010 (Figure 6).

Within the study area (largely confined to the Cooper Creek catchment basin), there are also intermittent surface water flows following storm events that cause ponding of surface water on interdune clay pans, predominantly in the dunefield regions and other areas.

There are only a handful of major water storages in the Cooper Creek Basin, with no in-stream dams. There are a number of small weirs for stock and domestic purposes, and a limited number of larger weirs that are mainly used for town water supply including at the northern margin of the study area at Wombunderry. Waterholes are the biggest storages in the basin with some entitlements to divert water to off-stream storages for domestic use. There is no supplemented water supply scheme in the Cooper Creek Basin.



LEGEND

- Town/Locality
- Highway/Major Road
- River/Creek
- Groundwater Management Area
- Santos Tenements
- Study Area

Elevation
High : 475
Low : 0

0 KILOMETERS 100
1:2,750,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)
1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. SRTM - NGA AND NASA

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PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
TOPOGRAPHY AND DRAINAGE OF THE STUDY AREA

CONSULTANT
GOLDER

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APPROVED	CB

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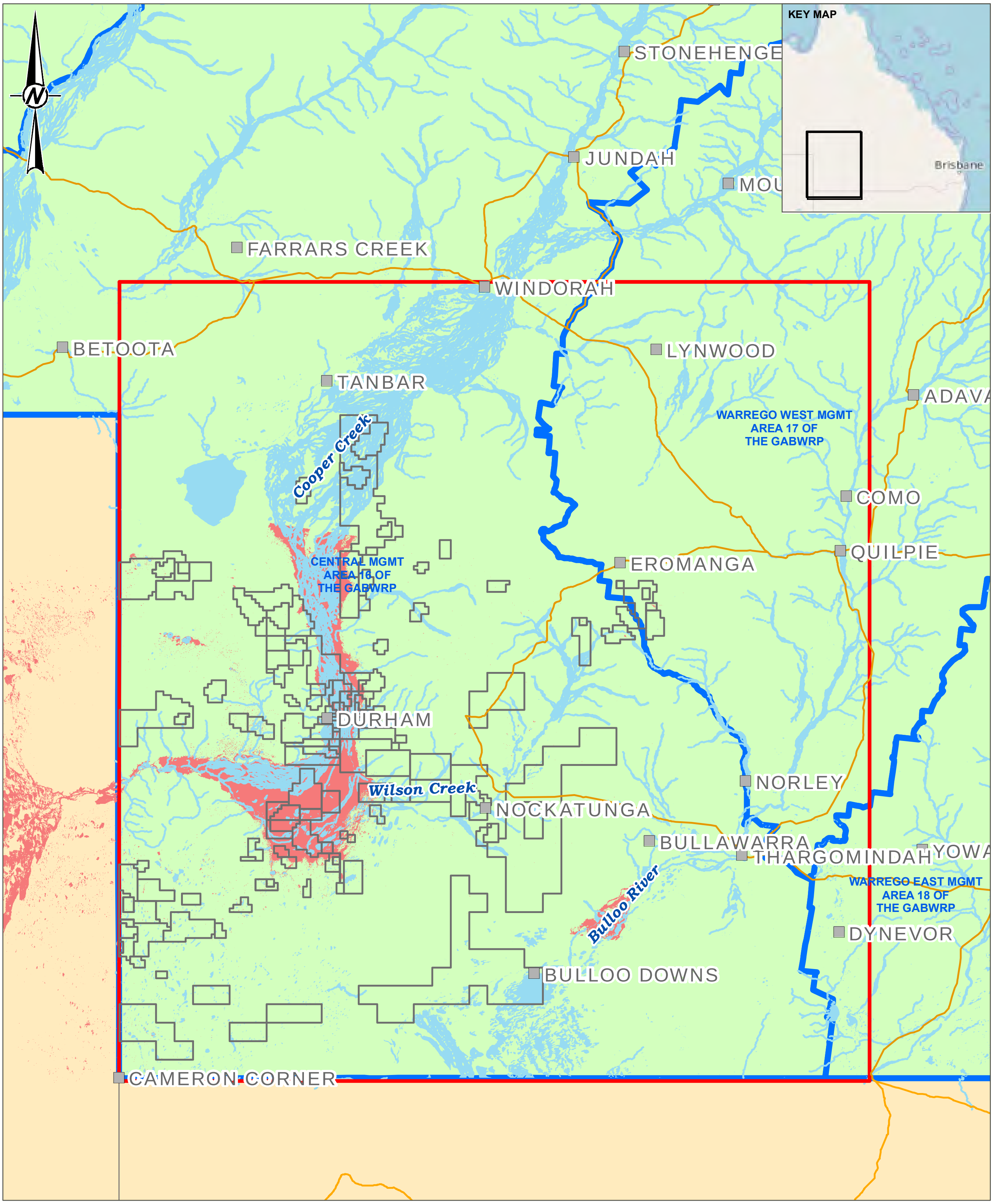

LEGEND

- Town/Locality
- Highway/Major Road
- River/Creek
- Flood Area 2010 Extent
- Groundwater Management Area
- Santos Tenements
- Study Area

0 KILOMETERS 100

1:2,750,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. FLOOD EXTENTS PROVIDED BY SANTOS, 2011

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PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
STUDY AREA DURING A FLOOD EVENT (2010)

CONSULTANT

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2.4 Geological Setting

2.4.1 Continental Setting

The study area is located in the south-western portion of the Great Artesian Basin (GAB). The GAB is a hydrogeological basin that underlies approximately one fifth of the Australian continental area and extends beneath a large portion of Queensland, South Australia, New South Wales and the Northern Territory; stretching between the Great Dividing Range to the Lake Eyre depression (Figure 3). The GAB consists of three large sedimentary basins (the Eromanga, Carpinteria and Surat Basins), comprising layered sedimentary sequences up to 3,000 m thick in the deepest portions of the basin. The sub-basins of the GAB unconformably overlay a number of older depositional basins including the Cooper Basin in SWQ (Figure 7).

It has been an historical convention in Queensland's groundwater management framework to include the upper sedimentary sequences of certain older basins underlying the GAB (specifically, the Bowen, Galilee and Cooper Basins) in the broader definition of the GAB groundwater resource. Whilst this convention was adopted for administrative convenience, in a strict geological sense these basins are considered to be distinct and separate from the sub-basins of the GAB.

2.4.2 Regional Geological Setting

The study area is situated over portions of the Eromanga and Cooper Basins in SWQ. The geology within the study area includes a late Carboniferous to Triassic age sequence of interbedded sandstones, coals and siltstones associated with the Cooper Basin, which is unconformably overlain by the Jurassic to Cretaceous sedimentary deposits of the Eromanga Basin (Figure 7).

The Eromanga Basin is the largest of the main sub-basins of the GAB. It contains two major centres of basin subsidence: the Central Eromanga depositional centre and the Poolowanna Trough separated by the Birdsville Track Ridge (Figure 7).

The Cooper Basin is entirely buried below the Eromanga Basin and they are vertically separated by a major unnamed unconformity. Although considered structurally separate sedimentary depositional centres, they are stratigraphically and, to a very limited extent, hydraulically connected. Formations of the Cooper Basin and the GAB have varying nomenclature in stratigraphic successions from one area to another. Habermehl (1986) and others have tried to provide basin-wide correlations between nomenclatures for the GAB. This section adopts the geological nomenclature defined for SWQ by Draper (2002). Reference to "equivalent naming" is required in order to link with the nomenclature used in the QLD GAB regulation.

At the surface, the regional geological maps indicate a predominance of consolidated sediments of the Glendower Formation (Tertiary) or Winton Formation (Cretaceous) on the higher ground structures and also Quaternary alluvial deposits (Figure 8 and Figure 9) associated with the Cooper Creek flood plains. The Quaternary surface sedimentation of the Cooper Creek catchment was described by Nanson et al. (2008) as comprising extensive late Quaternary fluvial and aeolian deposits, overlain by thick floodplain and channel mud deposits.

The general stratigraphic sequence for the study area is presented in Table 3.

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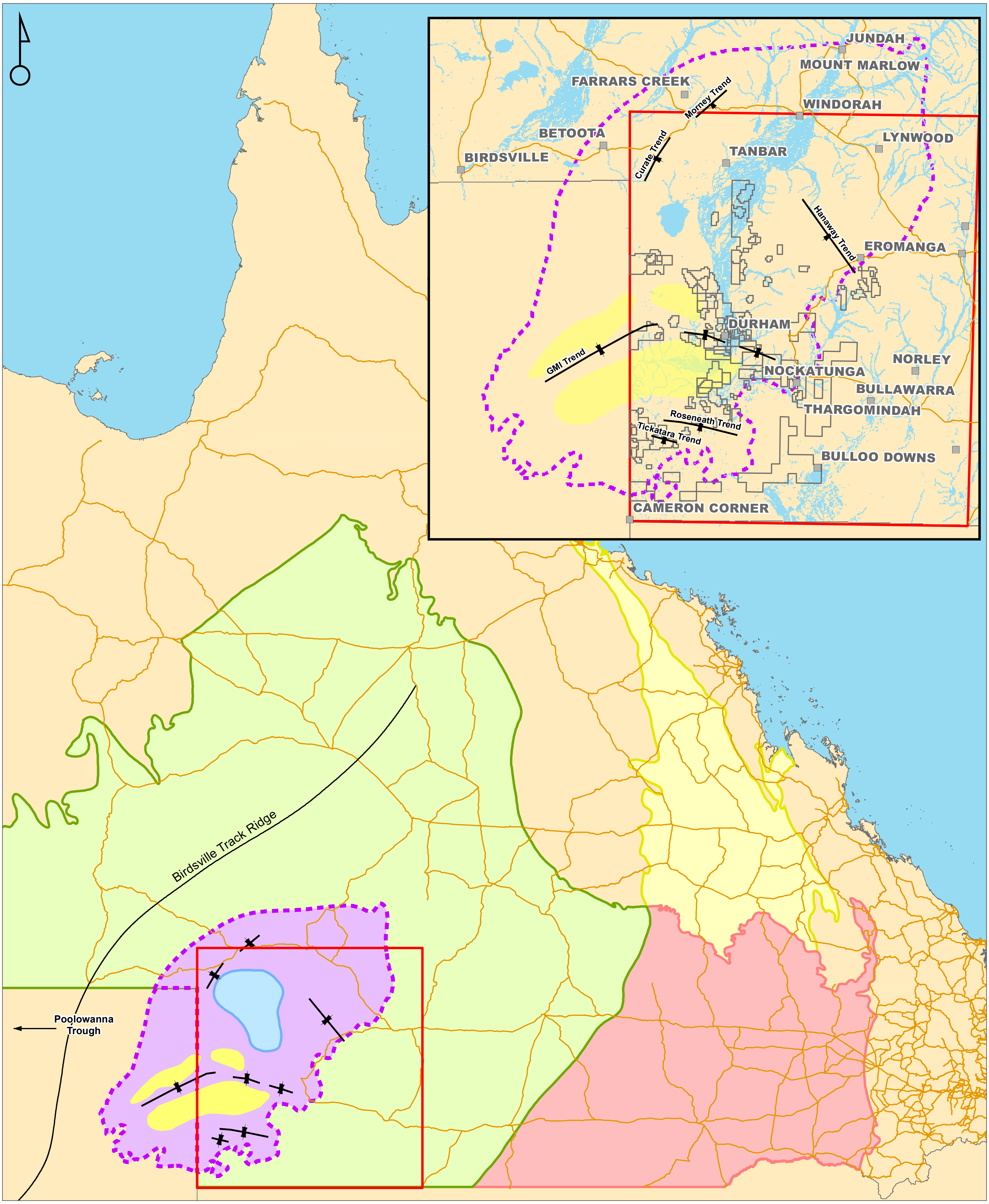

LEGEND

- Town/Locality
- Birdsville Ridge (Approximate Location)
- Highway/Major Road
- Structural Trend
- Geological/Structural Trough
- Cooper Basin
- Barrolka Trough
- Bowen Basin
- Eromanga Basin
- Surat Basin
- Santos Tenements
- Study Area

0 KILOMETERS 400

1:6,000,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)
1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. STRUCTURAL GEOLOGY OF GAB, DERM
4. STRUCTURAL ELEMENTS OF THE COOPER AND EROMANGA BASINS DIGITISED FROM LOWE YOUNG ET AL 1997

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HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
GAB STRUCTURAL GEOLOGY OF THE STUDY AREA

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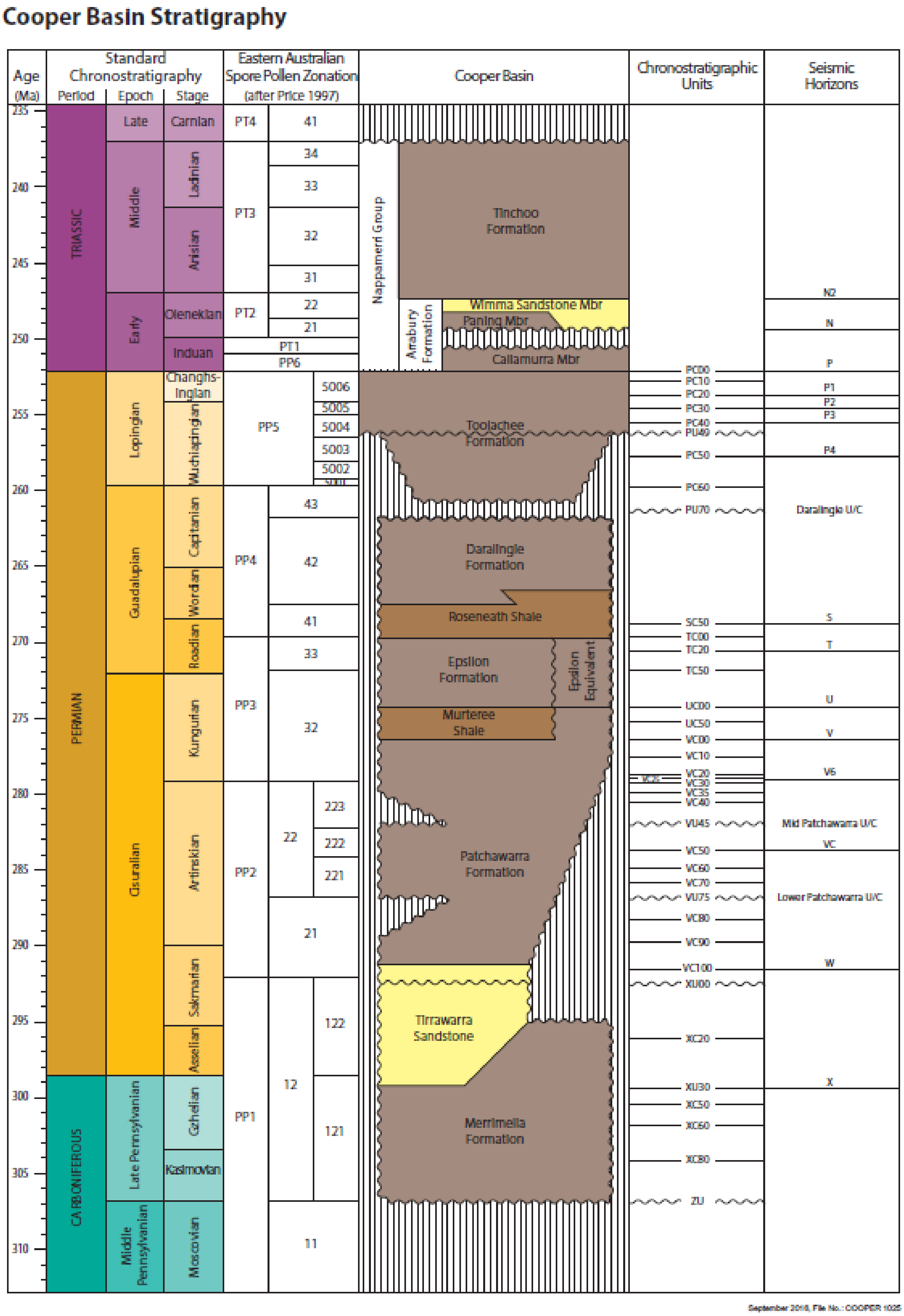
Table 3: Stratigraphic Sequence for the Study Area

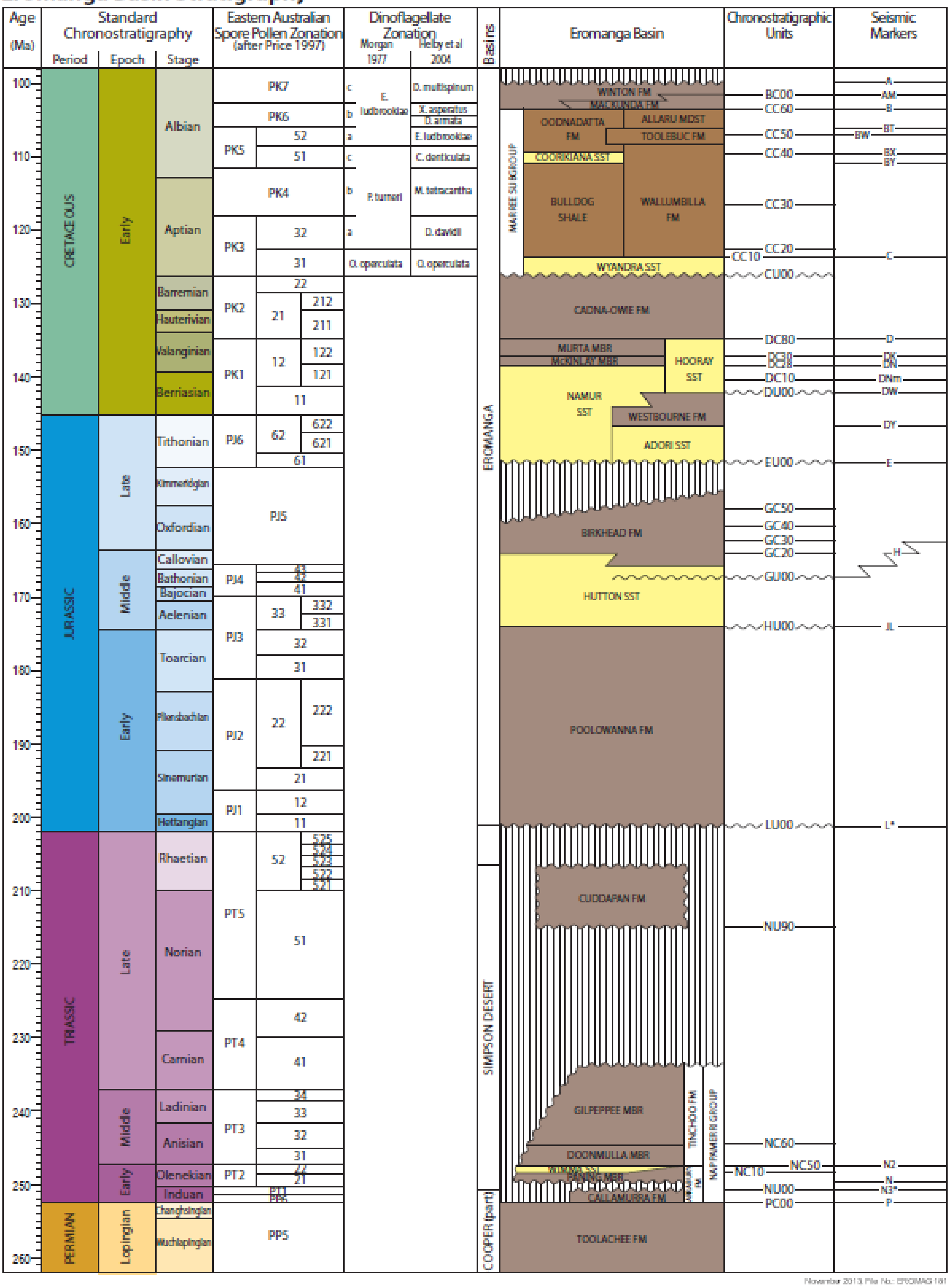
WRP Management Units		Litho-stratigraphy										
Central GMA16	Warrego West GMA 17			Unit name	Sub-unit	Equivalent Formation in GAB **	Deposits environment *	Lithology Description*	Geological Age	Thickness*	Santos Current Production Reservoir (Oil&Gas)	Hydrogeological Chracteristics
		Eromanga Basin		Tertiary sediments (Glendower Formation)			Fluvial deposits	Sandstone, silty silstone, conglomerate and minor mudstone	Tertiary	maximimum 145***	No	Aquifer
				Winton Formation			Terrestrial deposition environment. Fluviolacustrine.	Interbedded fine to coarse-grained sandstone, shale, siltstone and coal seams with intraclast conglomerates.	Cretaceous	Over 400 m in the Cooper region, maximum thickness of 1100 m in the northern Patchawarra Trough	No	Aquifer
				Mackunda Formation			Marine environment	Interbedded, partly calcareous very fine-grained sandstone, siltstone and shale in the basin centre.		60–120 m thick in the Cooper region	No	Aquifer
				Allaru Mudstone			Low-energy, shallow marine environment	Mudstone with thin calcareous siltstone and minor thin, very fine-grained sandstone interbeds		100–240 m thick in the Cooper region, but reaches thicknesses >600 m in the Patchawarra Trough.	No	Water bearing
Central 1	Warrego West 1			Toolebuc Formation		Surat Silstone	Marine environment	Mudstone		5 to 75 m **	No	Confining bed
				Wallumbilla Formation	Coreena Member Doncaster Member	Wallumbilla Formation	Marine environment	Mudstone and siltstone with minor interbeds of fine grained sandstone		maximum known of 260 m (Poolowanna Trough)	No	Aquifer
Central 2	Warrego West 2			Cadna-Owie Formation	Wyandra Sandstone Member	Cadwa-Owie Formation	Lowstand system infilling fluvial channels then transgressive systems	Medium to coarse-grained, quartzose to labile sandstone with scattered pebbles		From 3 to 18 m in Queensland	Oil (not frequent)	Aquifer
					Lower Cadna-Owie		Transition from terrestrial to marine deposition environment	Siltstone with very fine to fine-grained sandstone interbeds and minor carbonaceous claystone . Pebbly layers, diamictites and coarse breccia layers occur around the basin margin.		Typically 10–20 m thick around the basin margin, increasing to 75–100 m in the deeper parts of the basin. Maximum thickness of >115 m in the Nappamerri Trough.	No	Confining bed
Central 3	Warrego West 3			Hooray Sandstone	Murta Formation	Mooga-Gubberamunda Sandstone	meandering fluvial, floodplain and lacustrine environment	Thinly interbedded siltstone, shale, very fine to fine-grained sandstone and minor medium and coarse-grained sandstone. A basal siltstone is widespread in the Cooper region.		Maximum thickness of >90 m (incl. McKinlay Member) reached in the Nappamerri Trough.	Oil, some gas (not frequent) Seal	Aquifer
					McKinlay Member	Hooray Sandstone	lacustrine conditions	Fine to medium-grained sandstone interbedded with carbonaceous siltstone		Typically <30 m thick, and is often absent in the Cooper region	Oil (not frequent)	
					Namur Sandstone		meandering braided fluvial systems	Fine to coarse-grained sandstone with minor interbedded siltstone and mudstone. The basal Namur Sandstone, like the Adori Sandstone, has been strongly cemented with diagenetic calcite in places.		40 to 240 m thick in the Cooper region	Oil (not frequent)	
Central 4	Warrego West 4			Westbourne Formation		Injune Creek Group	lacustrine deposits (transgression)	Interbedded dark grey shale and siltstone with minor sandstone interbeds	Jurassic	30 to 140 m thick in the Cooper region	Oil (not frequent)	Confining bed
				Adori Sandstone			Amalgamated braided fluvial sandstone deposited in lowstand system tract.	Well-sorted, subrounded, cross-bedded, fine to coarse-grained sandstone. Calcite cemented zones up to 45 m thick are developed locally in the basal Adori and Namur sandstones		20 to 130 m thick in the Cooper region.	Oil (not frequent)	Aquifer
				Birkhead Formation	Upper Birkhead Middle Birkhead Lower Birkhead		Meandering to lacustral deposition. Birkhead "lake", largest	Interbedded siltstone, mudstone and fine to medium grained sandstone with thin, lenticular coal seams (<0.3 m thick)		A maximum thickness of >150 m occurs in the Patchawarra and Nappamerri troughs	oil - Basal Birkhead and Middle Birkhead (scattered)	Water bearing
Central 5	Warrego West 5			Hutton Sandstone			Erosion then lowstand system	Fine to coarse-grained quartzose sandstone with minor siltstone interbeds		From 40 m toover 360 m in the Patchawarra Trough.	Oil, some gas (not frequent)	Aquifer
Central 6	Warrego West 6			Poolowanna Formation	Upper Poolowanna	Precipice Sandstone	Transgression to highstand systems	Interbedded siltstone, sandstone and rare coal seams. Sandstone beds range from very fine to medium grained, and contain minor pebbles and granules of quartzite and reworked basement.		Maximum of 205 m in the Poolowanna Trough		Aquifer
					Lower Poolowanna		Lowstand (fluvial) and early transgressive system				Oil (not frequent)	
MAJOR UNCONFORMITY												
Central 7	Warrego West 7	Cooper Basin	Nappamerri Group	Tinchoo Formation	Gilpeppee Shale	Moolayember Formation		Interbedded siltstone and light grey sandstone	Triassic	Maximum of 109 m	Gas (not frequent)	Confining bed
					Doonmulla Member			Uniform dense siltstone, with minor coal seams (Gilpeppee Member) and intraclast conglomerate beds				
				Arraburry Formation	Wimma Sandstone Member	Clematis Sandstone		Fine to medium-grained quartzose sandstone with minor interbeds of siltstone and mudstone.		Maximum total thickness of 400 m in the Patchawarra Trough. Callamura Member: up to 150 m and more. Panning Member : up to 200 m and more. Wimma Sandstone : 115 m maximum	Gas (not frequent)	Aquifer
					Panning Member	Rewan Formation		Upward-fining cycles of fine to medium-grained sandstone grading into siliceous mudstone and siltstone units.			Oil (not frequent)	Confining bed
					Callamurra Member			Siltstone and mudstone, minor sandstone interbeds (Early Triassic).Siderite and cements have formed in siltstone and sandstone beds.				Confining bed
			Gidgealpa Group	Toolachee Formation			Channels deposits	Interbedded fine to coarse-grained sandstone, siltstone and carbonaceous shale, sometimes with thin coal seams (<3 m thick), and conglomerates.	Permian	Up to 175 m	Gas	Aquifer
				Daralingie Formation				Siltstone and mudstone with interbedded fine to very fine-grained sandstone. Minor coal seams and carbonaceous partings and streaks occur.				Confining bed
				Roseneath Shale				Siltstone, mudstone and minor sandstone.		Up to 100 m or plus in some throughs		Confining bed
				Epsilon Formation				Thinly bedded, fine to medium-grained sandstone with carbonaceous siltstone and shale, and thin to occasionally thick (<2-20 m) coal seams.		Maximum thickness of 156 m in the Nappamerri Trough.	Gas	Aquifer
				Murteree Shale				Argillaceous siltstone and fine-grained sandstone.		Relatively uniform in thickness, averaging 50 m. Maximum thickness of 80 m in the Nappamerri Trough.		Confining bed
				Patchawarra Formation			Individual and stacked channels	Interbedded fine to medium-grained, locally coarse-grained and pebbly sandstone, siltstone, shale and coal .		Up to 680 m thick in the Nappamerri Trough	Gas	Aquifer
				Tirrawarra Sandstone			Braided channel deposits	Fine to coarse-grained, moderately well sorted sandstone with minor shale interbeds and rare, thin coal seams and stringers. Conglomerate beds are locally well-developed, notably in Gidgealpa and Big Lake Fields.		Maximum 75 m total thickness	Gas (not frequent)	Aquifer
				Merrimelia Formation			Glacial sediments deposits, deep glacio-lacustrine sediments	Conglomerate, sandstone, conglomeratic mudstone, siltstone and shale	Late Carboniferous to Early Permian			Water bearing

Data sources:
*: Petroleum Geology of South Australia, Volume 2 and 4, http://www.pir.sa.gov.au/petroleum/access_to_data/petroleum_publications/petroleum_geology_of_south_australia
**: GAB WRP, 2007
***: Australian Stratigraphy Database

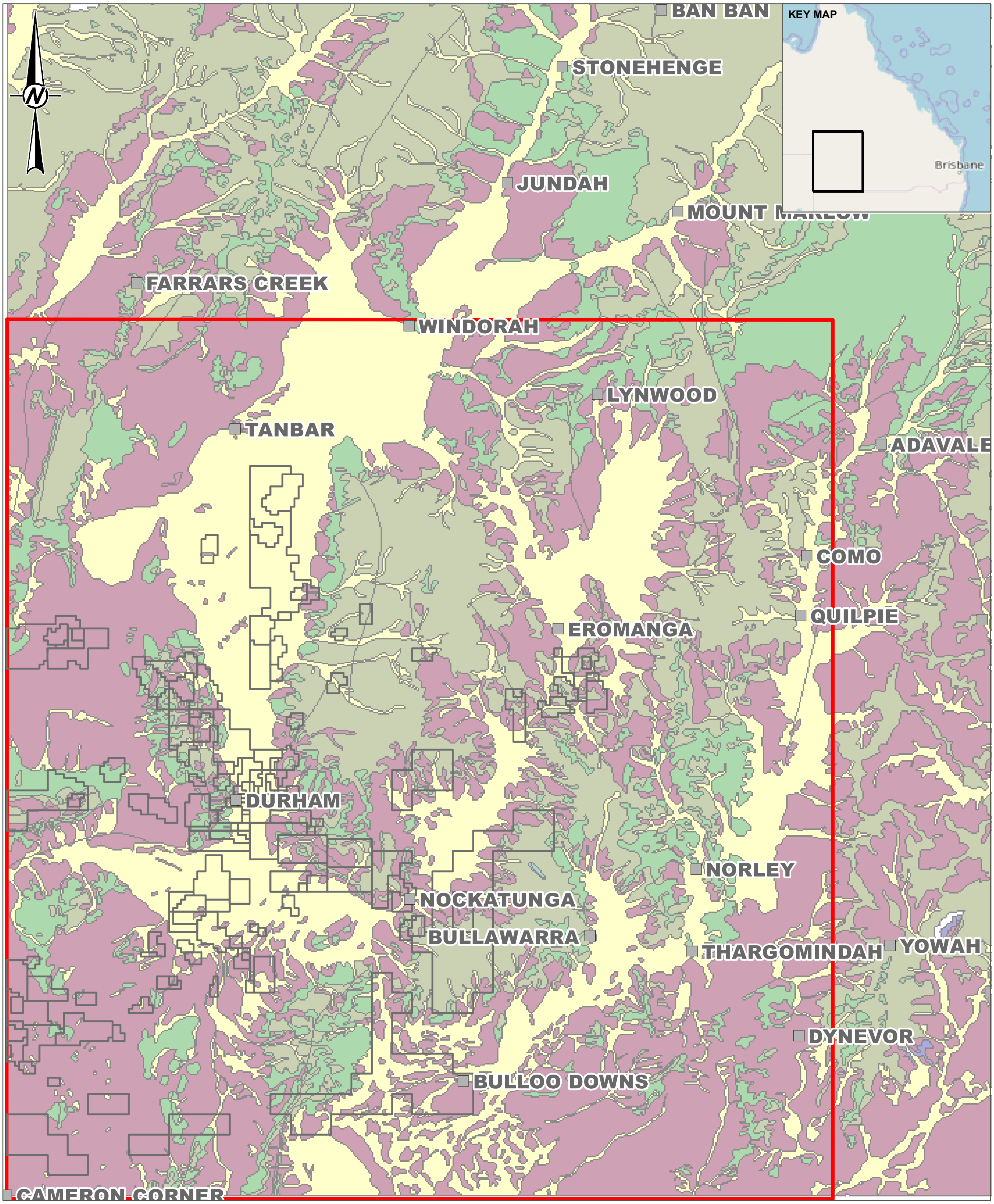
Figure 8: Chronology and Stratigraphy of the Cooper and Eromanga Basins (Queensland and South Australia)



Eromanga Basin Stratigraphy



Source: Draper, 2002



LEGEND

- Town/Locality
- Qa-CER
- Q-CER
- Glendower Formation
- Winton Formation
- Mackunda Formation
- Doncaster Member
- Santos Tenements
- Study Area

0 KILOMETERS 100

1:2,500,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. GEOLOGY SOURCED DEPARTMENT OF MINES AND ENERGY, QLD GOVERNMENT, 2007

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PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
SURFACE GEOLOGY

CONSULTANT

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2.4.3 Local Geological Setting and Petroleum Field Models

The following sections provide a summary of the Cooper Basin and Eromanga Basin geological settings. An overview of the stratigraphy and lithology for the study area is provided in Table 3. Figure 8 provides information on the continuity of the deposition process, and the discontinuities or major unconformities present in the stratigraphic sequence.

2.4.3.1 Cooper Basin Geological Setting and Model

The Cooper Basin comprises a thick late Carboniferous to middle or late Triassic non-marine sedimentary stratigraphic succession within a broad basin shaped setting in the interior of central Australia.

Structurally, the Cooper Basin is one of a number of remnant late Carboniferous to early Permian depositional centres which lay in the Australian interior of the Gondwana Supercontinent. The Cooper Basin differs from the smaller depositional centres by containing an additional sequence that ranges in age from late Permian to middle Triassic and spans the Permo-Triassic boundary without a break in deposition. It also differs as being the only such basin with major oil and gas production (Petroleum Geology of South Australia, Volume 4 - Cooper Basin, PIRSA, 1998). Three major troughs (Patchawarra, Nappamerri and Tanapperra) are identified within the basin, each separated by structurally high ridges.

The Cooper Basin depositional episode was terminated by a period of gentle regional compressional deformation resulting in landmass uplift and sustained erosion within the basin. Sedimentary basin development re-initiated subsequently with the formation of the Eromanga Basin (Section 2.4.3.2) during the Early Jurassic to Late Cretaceous times.

The Cooper Basin contains a succession of fluvio-lacustrine sandstone, shales and coals to a thickness of up to 1,800 m to the south and thinner in the north (up to 600 m thick). The target gas formations in the Cooper Basin lie at depths of 1,500 mbgl to greater than 2,000 mbgl.

The Cooper Basin is subdivided in two major geological groups: the late Carboniferous and Permian Gidgealpa Group and the Triassic Nappamerri Group. The earliest sediments within the Cooper Basin were of glacial origin. The subsequent formations generally consist of interbedded sandstone, coal and shale formations. The Tirrawarra Sandstone represents low sinuosity fluvial to glacial outwash deposits overlain by peat swamp, floodplain and high sinuosity fluvial facies of the Patchawarra Formation. Two lacustrine shale units (Murteree and Roseneath Shales) with intervening fluvio-deltaic sediments (Epsilon and Daralingie Formations) were deposited during a phase of continued subsidence. Early Permian uplift led to erosion of the Daralingie Formation and underlying units from basement highs (SA DPI, 1998).

The upper sequence of the Cooper Basin, the Gilpeppee Member of the Tinchoo Formation is dominated by siltstones and shales. Draper (2002) has mapped the thickness of shales of the Tinchoo Formation in SWQ. The mudstone (both shale and siltstone) thickness ranges from 80 to 160 m in the centre of the Cooper Basin with a maximum thickness of 182 m.

The Tirrawarra Sandstone, Patchawarra Formation, Epsilon Formation and Toolachee Formation (Table 3) are the main gas producers of the Cooper Basin. Minor gas reservoirs are also present in the Tirrawarra Sandstone, the Wimma Sandstone Member of the Arrabury Formation and the Tinchoo Formation. Some oil reservoirs are present in the Panning Member of the Arrabury Formation.

Geological contour maps illustrating the top and thickness of the following formations can be found in APPENDIX B (sourced from UWIR Report, Golder, 2012a). These maps include:

- Depth to the Toolachee Formation
- Depth to the Patchawarra Formation

- Thickness of the Patchawarra Formation
- Thickness of the Toolachee Formation
- Thickness of the shale within the Nappamerri Group.

2.4.3.2 Eromanga Basin Geological Setting and Model

The Jurassic to Cretaceous Eromanga Basin unconformably overlies the older Carboniferous to Permian Cooper Basin. The sedimentary sequences of the Eromanga Basin reach a thickness of up to 2,500 m and were deposited during a period of subsidence subsequent to that of the Cooper Basin. There are two main sub-basin centres in the Eromanga Basin: the *Central Eromanga Depositional centre* and the *Poolowanna Trough* to the west separated by the Birdsville Track Ridge (Figure 7). The top of the Eromanga Basin is also delimited by an unconformity.

The study area for this project is located in the *Central Eromanga Basin*.

The deposits of the Eromanga Basin follow three episodes (and three different origins) of deposition:

- Lower non-marine sediments from early Jurassic to Mid-Cretaceous corresponding to the Poolowanna Formation to the Cadna-Owie Formation. During that period the largest transgression over the Eromanga Basin was the “Birkhead Lake” transgression;
- Marine sediments from mid-cretaceous to late Cretaceous corresponding to the Wallumbilla Formation to the Mackunda Formation; and
- Upper non marine sediments (fluviolacustrine) of the Winton Formation.

The formations of the Eromanga Basin are a succession of well-defined sandstones, siltstones and mudstones with interbedded minor sandstones and occasional coal seams, as shown in Table 3. The formations of the Eromanga Basin often have an equivalent throughout the GAB. The nomenclature adopted in this section is the SWQ nomenclature as illustrated in Figure 8.

The target oil formations of the Eromanga Basin lie at depths ranging from 700 to 1,200 mbgl.

Geological contour maps for the following formations can be found in APPENDIX B (sourced from UWIR Report, Golder, 2012a):

- Depth to the Winton Formation;
- Depth to the Cadna-Owie Formation;
- Depth to the Hooray Sandstone;
- Depth to the Hutton Formation;
- Depth to the Poolowanna Formation;
- Thickness of the Cadna-Owie Formation ;
- Thickness of the Hooray Sandstone;
- Thickness of the Hutton Sandstone; and
- Thickness of the Poolowanna Formation.

2.4.3.3 Conceptual Geological Cross Sections

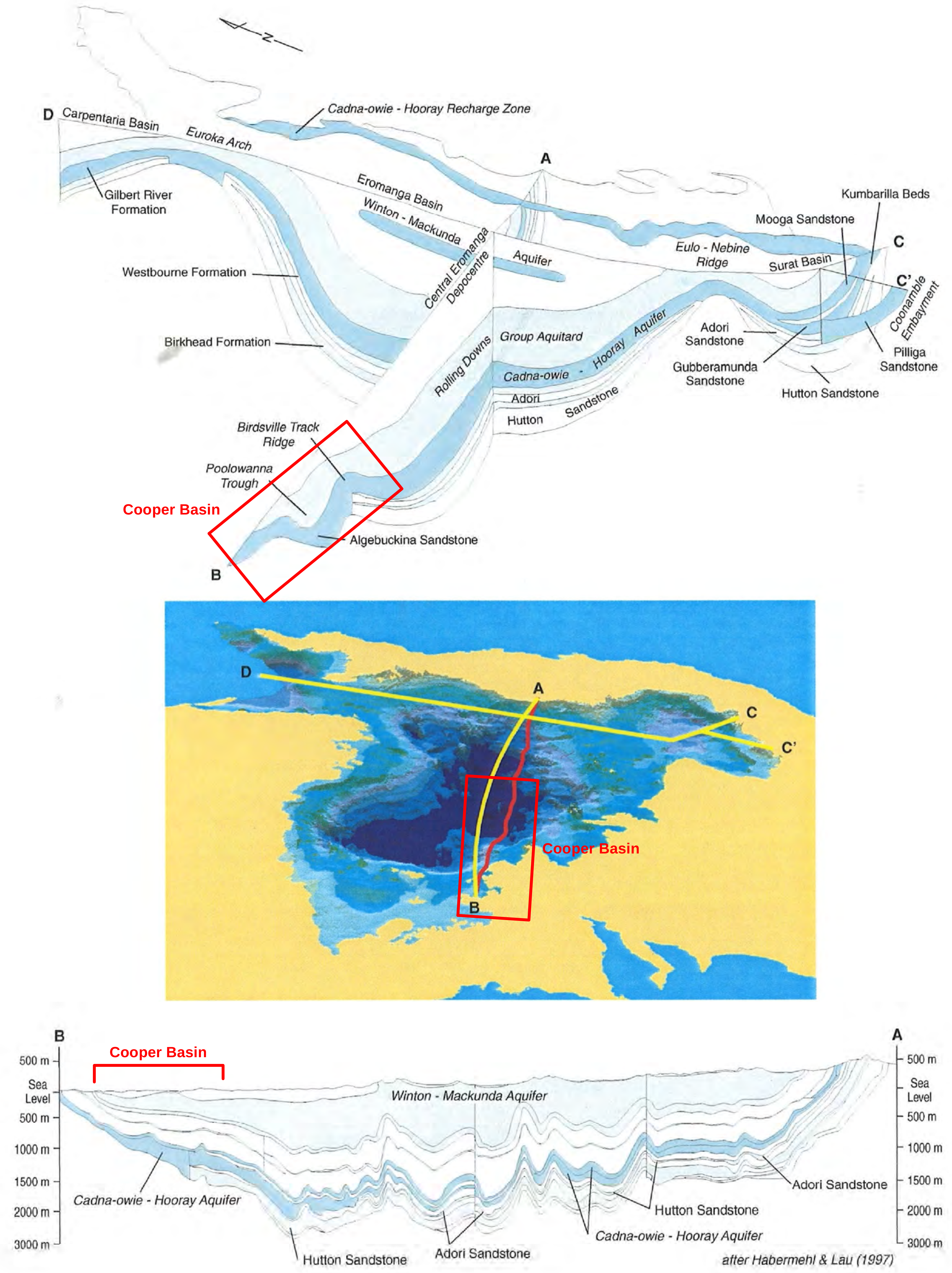
A schematic geological cross-section across the Eromanga Basin is presented in Figure 10. The “A-B” section cuts across the main depositional centre of the basin in SWQ. This corresponds to the general location of the study area. As displayed, the upper formations of the Eromanga Basin (from Cadna-Owie and Hooray Sandstone and younger) are continuous across the Basin. Older formations are restricted to areas within sub-basins (these formations or their equivalent may be present in several basins).

Abbreviations commonly used by Santos as stratigraphy markers or reservoir markers and used in some of the geological figures are summarised in Table 4.

Table 4: Geological Abbreviations for Stratigraphical Markers

Name of Marker	Definition
‘C’ Horizon	Top Cadna-Owie
‘E’ Horizon	Top Birkhead Formation
‘H’ Horizon	Top Hutton Sandstone
‘L*’ Horizon	Basal Eromanga Unconformity
‘PC00’ Horizon	Top Toolachee Formation (chrono-marker)
‘PU70’ Horizon	Basal Toolachee Formation (chrono-marker and un-named Unconformity)
‘VC00’ Horizon	Top Patchawarra Formation (chrono-marker)
‘VC50’ Horizon	Lower Patchawarra Formation (chrono-marker)
‘VCxx’ - Horizon	Chrono-stratigraphic marker within the Patchawarra Formation
‘ZU00’ Horizon	Top Pre-Permian (Basement)

A geological conceptual cross section across both the Cooper and Eromanga Basins has been generated in a SW to NE axis across the study area passing through the Barrolka fields (Barrolka Trough). The conceptual geological cross-section is presented in Figure 11.



SWQ HYDRAULIC FRACTURING
RISK ASSESSMENT

SANTOS

GEOLOGICAL SCHEMATIC CROSS SECTION ACROSS THE GAB EROMANGA BASIN

PROJECT: **127666004**
DATE: **19/12/2012**
DRAWN: **FA**
CHECKED: **RS**

FIGURE 10

GOLDER

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1. Figure taken from Hydrochemistry and Implied Hydrodynamics of the Cadna-Owie-Hooray Aquifer Great Artesian Basin – BRS, 2000
2. Golder Associates 2012a Cooper Basin UWIR Report

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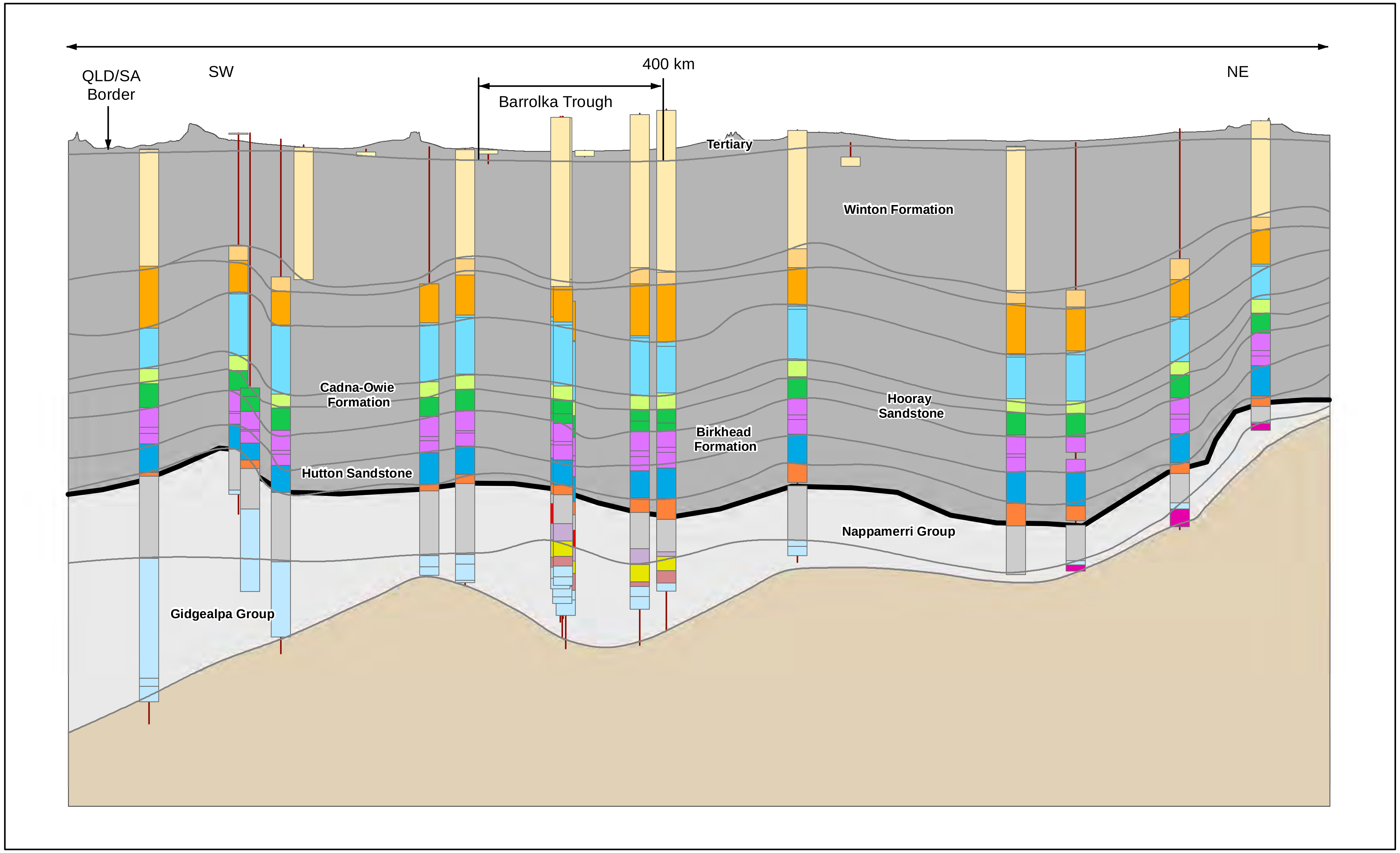
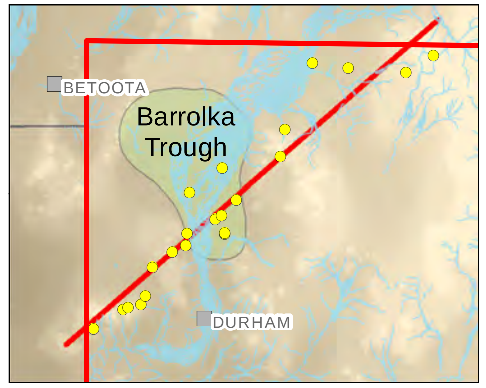


SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

GEOLOGICAL CONCEPTUAL CROSS SECTION ACROSS THE STUDY AREA



LEGEND

Litho-stratigraphy			
		Unit name	Sub-unit
		Tertiary sediments	
Eromanga Basin		Winton Formation	
		Mackunda Formation	
		Allaru Mudstone	
		Toolebuc Formation	
		Wallumbilla Formation	Coreena Member
			Doncaster Member
		Cadna-Owie Formation	Wyandra Sandstone member
			Lower Cadna-Owie
		Hooray Sandstone	Murta Formation
			McKinlay Member
			Namur Sandstone
		Westbourne Formation	
		Adori Sandstone	
		Birkhead Formation	Upper Birkhead
			Middle Birkhead
			Lower Birkhead
		Hutton Sandstone	
		Poolowanna Formation	Upper Poolowanna
			Lower Poolowanna
Cooper Basin	Nappamerri Group	Tinchoo Formation	Gilpepee Shale
			Doonmulla Member
		Arraburry Formation	Wimma Sandstone Member
			Panning Member
			Callamurra Member
	Gidgealpa Group	Toolachee Formation	
		Daralingie Formation	
		Roseneath Shale	
		Epsilon Formation	
		Murteree Shale	
		Patchawarra Formation	
		Tirrawarra Sandstone	
		Merrimelia Formation	

Study Area
Geological Contact
Major Unconformity
Eromanga Basin
Cooper Basin
Basement

0 10 20 40 60 Kilometres

Vertical Exaggeration 1:50

PROJECT: 127666004
DATE: 19/12/2012
DRAWN: FA
CHECKED: RS

FIGURE 11

GOLDER

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2.4.3.4 Primary Oil and Gas Producing Reservoirs

Oil and gas production in the study area targets sandstone reservoirs in both the Cooper and Eromanga Basins. Conventional gas reservoirs are predominantly present within the Cooper Basin sequence, whereas oil reservoirs present in the Eromanga Basin. The production of oil or gas is related to its deposition (sedimentological and lithological), hydrocarbon maturation (i.e. paleontological and age related) and charge.

Several types of reservoirs can form depending on the "trapping" mechanism for the hydrocarbons (Figure 12). The trapping mechanisms prevent further migration, and result in accumulation, of the hydrocarbon fluids in the sandstone reservoir. The hydrocarbon reservoir trapping mechanisms relevant to the Cooper and Eromanga Basins are shown in Figure 13.

Figure 12: Hydrocarbon 'Traps' Geological Settings

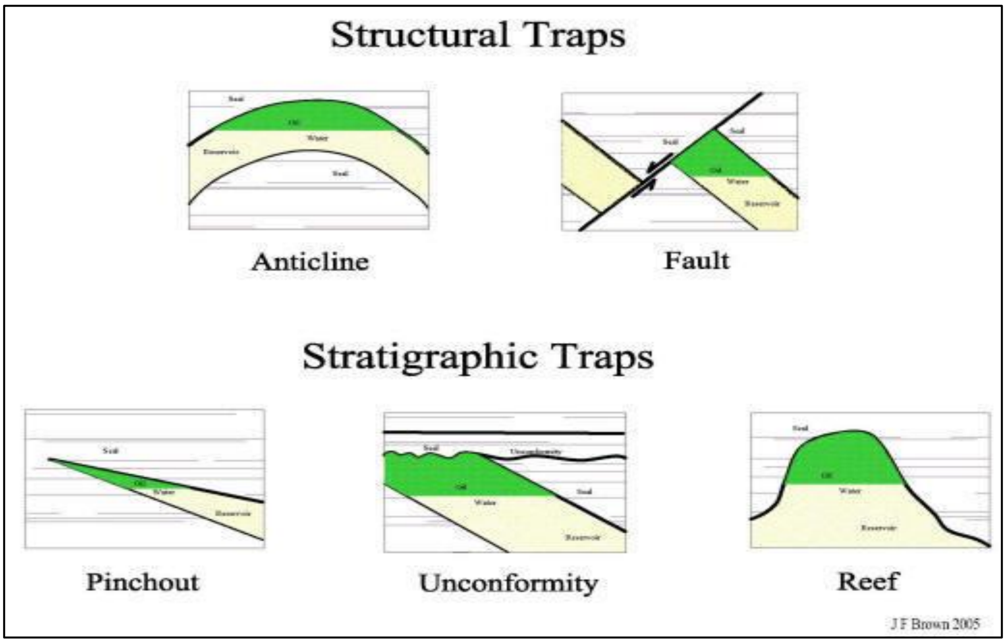
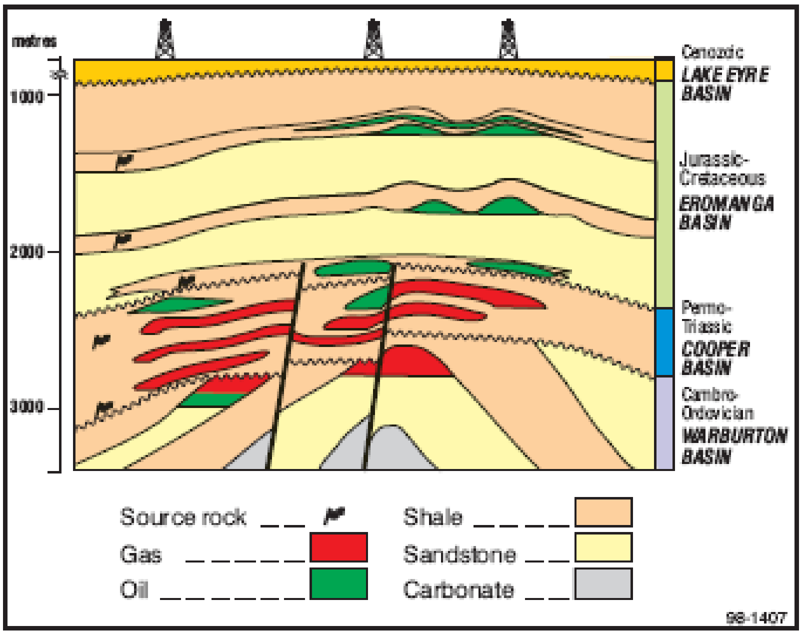


Figure 13: Petroleum Reservoirs Trapping Mechanisms of the Cooper and Eromanga Basins



Source: SA DPI, 1998

Cooper Basin

Anticlinal and faulted anticlinal traps have been identified as proven exploration targets in the Cooper Basin. The reservoir formations are capped by a series of fine-grained, laterally extensive seals. The predominantly fine-grained formations of the Nappamerri Group act as a regional seal to the Cooper Basin, providing several hundred metres of vertical separation between the primary gas reservoirs of the Cooper Basin and the overlying Eromanga Basin. Deeper in the basin, the Roseneath Shale acts as a regional top seal for the reservoir sands in the Epsilon Formation and the Murteree Shale seals hydrocarbon reservoirs in the Patchawarra Formation. These formations also provide effective barriers to prevent vertical migration of stimulation fluids during fracture stimulation treatments of Cooper Basin reservoir formations.

The reservoir formations of interest for Santos in the Cooper Basin (from deepest) include:

- The *Tirrawarra Sandstone* comprises fine to coarse-grained and pebbly sandstone with locally common interbeds of conglomerate and minor interbeds of carbonaceous siltstone, shale and coal. The Tirrawarra Sandstone is 30 to 40 m thick on average in the study area.
- The *Patchawarra Formation* comprises predominantly sandstone beds interbedded with siltstone, shale and coals. The Patchawarra Formation is thickest (up to 680 m) in the Nappamerri Trough, with an estimated maximum thickness of 550 m in the study area (Figure 7).
- The *Epsilon Formation* comprises a series of sandstones, siltstones and shales with minor coals. The maximum reported formation thickness (156 m) occurs in the Nappamerri Trough, however in the study area, the thickness typically ranges from 30 to 40 m.
- The *Toolachee Formation* consists of sandstones, siltstones and shale with thin coal seams and some conglomerates. In the study area the thickness is typically of the order of 25 to 50 m (Draper, 2002).
- Minor oil and gas reservoirs occur in sand units of the Nappamerri Group, but due to its predominantly fine-grained texture (mudstone and shale) it acts as a thick, regional seal to the reservoirs of the Cooper Basin (PIRSA, 1998).

Stimulation events related to gas production in the study area from 2012 to 2016 are planned for the deeper Patchawarra Formation, the Toolachee Formation, and to a lesser extent in formations within the Nappamerri Group.

Eromanga Basin

Trapping mechanisms in the Eromanga Basin are predominantly structural with a stratigraphic component (e.g. Hutton–Birkhead transition, Poolowanna facies, McKinlay Member and Murta Formation). Seals consist of intraformational siltstones and shales of the Poolowanna, Birkhead and Murta Formations. Where these units are absent, potential seals higher in the sequence include the Bulldog Shale and Wallumbilla Formation (SA DPI, 1998).

The reservoir formations of interest for Santos in the Eromanga Basin are (from deepest):

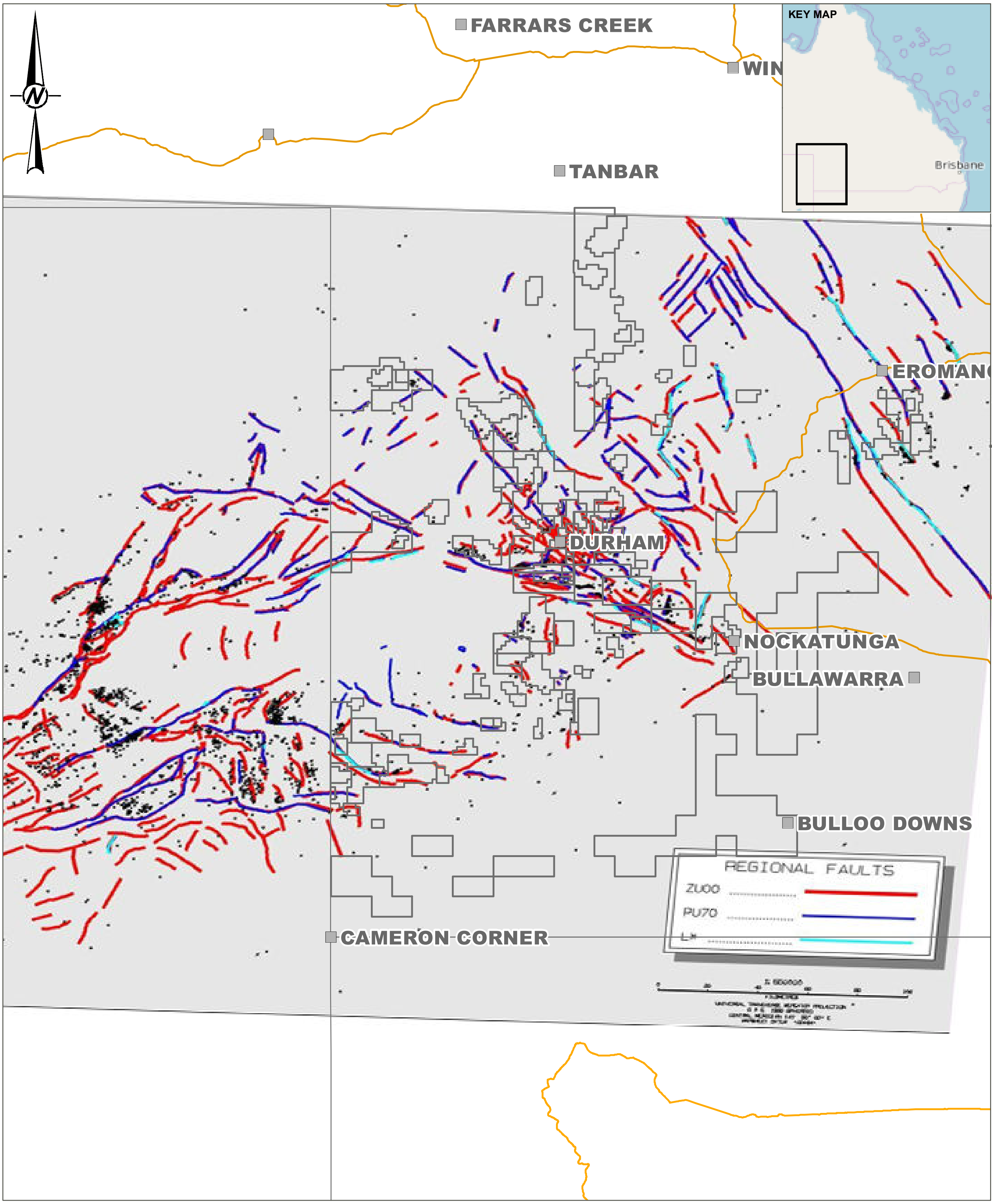
- The *Hutton* and *Poolowanna Formations* are major sandstone formations of the GAB. In the study area, the Hutton Formation is typically 90 to 210 m thick, and the Poolowanna Formation is up to 165 m thick;
- The *Westbourne Formation, Adori Sandstone* and *Birkhead Formation*: This group is dominated by shale and mudstone beds with thicknesses up to 140 m for the Westbourne Formation and 110 m for the Birkhead Formation in the study area. Interbedded sandstone layers within the Birkhead Formation comprise the primary oil targets. The Adori Sandstone contains the main sandstone beds of the group and is up to 55 m thick in the study area, and is reported to have a thick calcite-cemented zones (up to 45 m) developed in the base of the unit; and
- The *Cadna-Owie* and *Hooray Formations* consist of permeable sand units interbedded with siltstone, mudstone and shale that form intra-formational seals for hydrocarbon reservoirs. The basal unit of the Hooray Sandstone (the Namur Sandstone) is also strongly cemented.

2.4.3.5 Faults and Other Geological Controls

The structural framework of the Cooper Basin, particularly with regard to faulting is complex in the study area. Santos has undertaken an exercise of mapping (Figure 14; Santos, 2004) to simplify the tectonic features within the basins. The primary purpose of the mapping undertaken by Santos was to identify potential fault conduits (likely to enhance vertical migration of petroleum fluids), fault baffles (likely to prevent lateral migration of petroleum fluid) and identify potential gas targets.

Over the study area, the major episodic faults occurred in the top pre-Permian (basement), the basal Toolachee Formation and the basal Eromanga unconformity. The top pre-Permian faults provide the basin’s overall fabric, whereas the younger faults from the basal Toolachee Formation and basal Eromanga unconformity are generally reactivated Permian faults.

In the Eromanga Basin formations, very few regional faults are observed as very little fault movement occurred during deposition of Eromanga Basin sediments. Major faulting events and structural uplifts have occurred within the eastern part of the Eromanga Basin; however, they did not structurally affect the part of the Eromanga Basin covered by Santos’ SWQ tenements. Subsidence and compaction dominate the structural geology (PIRSA, 2006).



LEGEND

- Town/Locality
- Basal Toolachee Formation (PU70 Horizon)
- Top Pre-Permian (ZU00 Horizon)
- Basal Eromanga Unconformity
- Highway/Major Road
- Santos Tenements

0 KILOMETERS 100

1:2,500,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)
1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. FAULTS MAP SUPPLIED BY SANTOS (2004)

CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
SURFACE GEOLOGY

CONSULTANT
GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
127666004	011-R	2	14

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25mm

2.4.4 Stress Field Setting

2.4.4.1 Regional Setting

The origin and nature of near surface stress in Australia has been discussed in a number of publications, for example, Brown and Windsor (1990) and Enever and Lee (2000). The total stress at a point in the Earth's crust (including Australia) is generally considered to be made up of the following components:

- Gravity due to the weight of overburden. Gravity also contributes to the horizontal stress due to Poisson's effect;
- Tectonic component, which could be an active or a remnant tectonic stress, from movement of the earth's plates, and generally impacts the horizontal stress field; and
- Thermal and physio-chemical effects.

Analysis of stress in the SWQ study area has been undertaken through in-house services (discussed further under Section 2.4.5.3). The results of these studies are consistent with stress magnitude and orientation produced by broader plate tectonics as indicated on the publicly available Australasian Stress Map (Australasian Stress Map web site, University of Adelaide, Hillis et al., 1999; Hillis and Reynolds, 2003; and Reynolds et al., 2006).

Excerpts of the stress map are presented in Figure 15 and Figure 16 (from the web site, 2012) and illustrate the tectonic contribution to the regional stress field within continental Australia. Australia lies within the Indo-Australian tectonic plate and undergoes an absolute movement of approximately 7 cm per year to N-NNE. This is reflected in the N-NNE stress direction observed in SE Queensland (e.g. Bowen Basin, Figure 15). *However*, the Australian intra-plate stress field is highly variable and the maximum stress orientation at Cooper Basin, SWQ, is W-E and approximately perpendicular to the N-NE direction of the Indo-Australian plate. The stress field in Cooper basin appears to mark the apex of a horseshoe-shaped rotation in maximum horizontal stress direction across central eastern Australia (Reynolds, 2005). This is consistent with the project area that was mapped by Santos in 2004, which is discussed further in Section 2.4.5.2.

The minor horizontal stress will be approximately normal (90°) to this, i.e. N-S. The horizontal in situ stress is low but can be high and anisotropic and can *exceed* the vertical stress is some parts of the basin (Reynolds et al, 2006). The latter is an important consideration when stimulation pressures are calculated when designing and implementing a fracture event such that it is confidently contained entirely within the reservoir formations (Sections 3.2 and 3.3.5).

2.4.4.2 Basin Stress Regime

The primary stresses within the Cooper-Eromanga basin are vertical overburden stress σv, maximum horizontal stress σH, and minimum horizontal stress σh. The stress regime within the basins are characterised on the assumption that σv is a principal stress and therefore, σH and σh are also principal stresses, where σh is the least principal stress. This assumption is considered valid given the relatively flat topography across the basin.

The maximum horizontal stresses, σH, in the basin generally follow an east to west orientation, at approximately 101˚, as indicated by stress data from borehole breakout testing (Hills et al, 1998; Reynolds et al, 2004). The east-west trending nature of σH predominates in the Nappamerri trough, however, regional variations across the basin have been observed. In the Patchawarra Trough σH is oriented southeast to north-west; north-east of Gidgealpa σH was oriented west-northwest to east-southeast. This clockwise rotation of σH from the Nappamerri Trough to the Patchawarra Trough is accepted to be part of the larger stress rotation observed across the Australian continent. The orientation of σH does not exhibit significant variation with depth. (Reynolds et al, 2004).

The vertical overburden stress, σ_v is governed by overlying rock mass and the stress gradient does not exhibit significant variation with depth. The σ_v stress gradient is approx. 20.3 MPa/km at 1,000 m depth and approaches approximately 22.6 MPa/km at 3,000 m depth.

The magnitude of σ_h varies significantly across the basin; the σ_h stress gradient ranges from 13.6 MPa/km to 22.6 MPa/km across the basin, with σ_h approaching σ_v in some local areas (Reynolds et al, 2004). σ_h decreases with depth up to approximately 1 km below the surface and then stabilises. At 1 km to 4 km depth σh is between 0.6 σv to 0.7 σv, with σ_h generally approaching the higher end of this range (Hillis et al, 1998). At lower depths σ_h approaches, and may exceed, σ_v, resulting in σ_v becoming the minimum principal stress. (Reynolds et al, 2004).

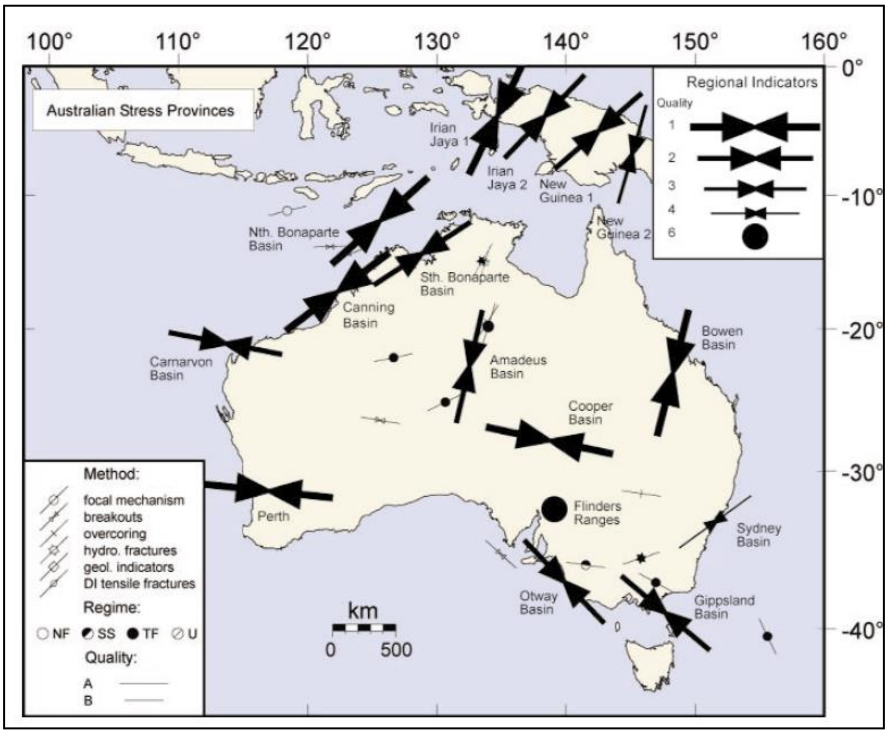
2.4.4.3 Stress Assumptions and Principal Stresses – General Faulting Regime

On the basis that σ_h is the minimum principal stress, the Cooper-Eromanga basin stress regime is primarily associated with strike-slip faulting (σ_H > σv> σ_h), normal faulting ($\sigma_v > \sigma_H > \sigma_h$), and transitional strike-slip/reverse faulting ($\sigma_H > \sigma_h \approx \sigma_v$) at depth, where $\sigma_h \approx \sigma_v$. Reverse faulting ($\sigma_H > \sigma_h > \sigma_v$) is not associated with the stress regime in the basin however, at lower depths where $\sigma_h > \sigma_v$ may occur some reverse faulting may exist. (Reynolds et al, 2004).

2.4.4.4 Hydrostatic Stress

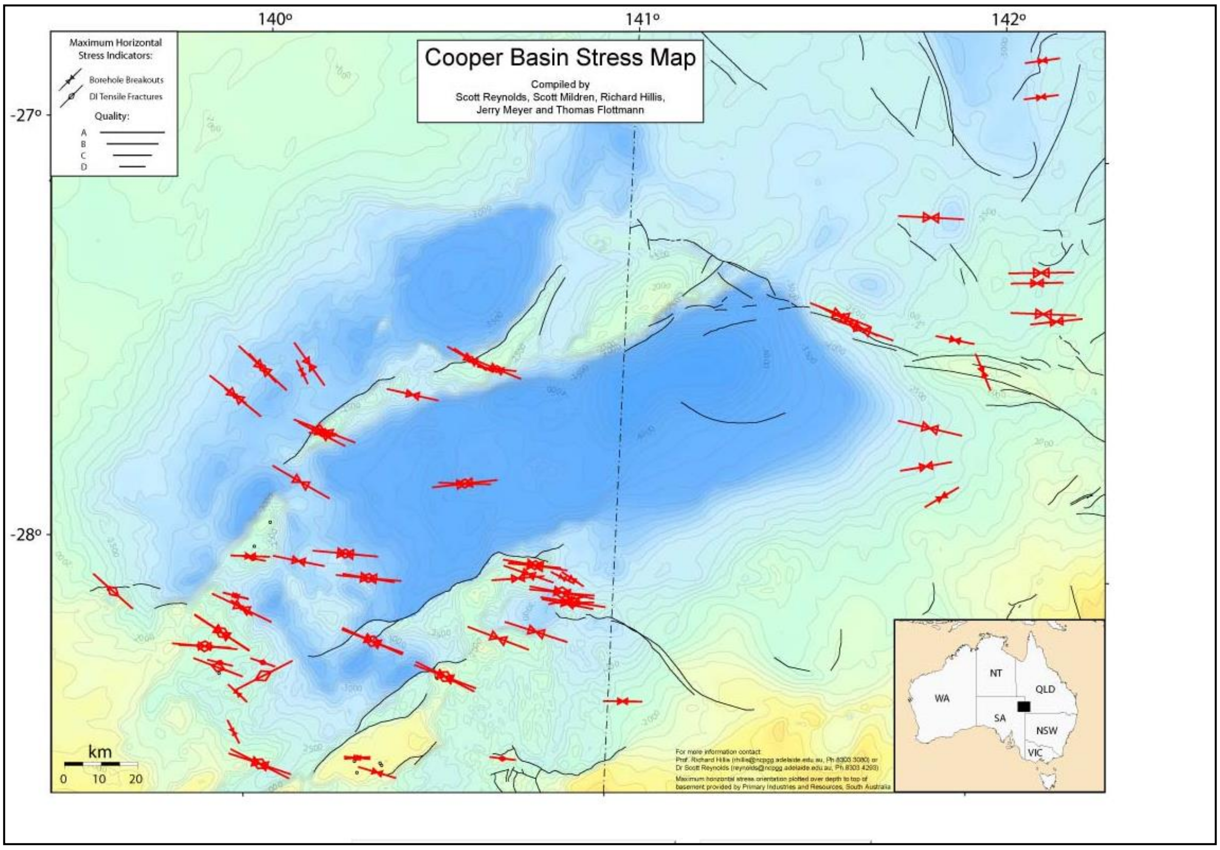
Pore pressures within the basin are generally hydrostatic. Overpressures are thought to occur in deeper shalier strata within the basin and have been observed in the Nappamerri Trough from depths of 2.7 km (Hillis et al, 1998). Local under-pressures have also been observed and are attributed to production within the basin (Reynolds et al, 2004). This is of particular importance when considering the impact of depressurising formations during oil and gas production. The implication is that impact translation though the depositional sequences are minimised or negated completely.

Figure 15: Continental Geomechanical Setting – Mean Stress Orientation within Australian Stress Provinces



Source: Hillis and Reynolds, 2003

Figure 16: Primary Stress Field Distribution for SWQ Queensland (Reynolds et.al, 2006)



2.4.5 Seismic History of the Project Region

2.4.5.1 Vulnerability

The continent of Australia does not demonstrate significant seismic activity, particularly compared to the western US, Japan, and New Zealand. Australia is on the Indo-Australian plate, relatively far from the plate boundaries, reducing the amount of seismic activity affecting the continent. Earthquakes in Australia are generally caused from the release of built-up stress in the interior of the Indo-Australian plate, which is being pushed north (NNE) and is colliding with the Eurasian, Philippine, and Pacific plates. Geosciences Australia (2012) reported that:

- On average 200 earthquakes of magnitude 3.0 or more occur in Australia each year;
- Earthquakes above magnitude 5.5 occur on average every two years; and
- About every five years there is a significant earthquake of magnitude 6.0 or more.

Santos' SWQ tenements are in one of the least seismically active areas on the Australian continent. The closest seismic activity area is the Adelaide region, SA, some 250 km southwest of Cameron's Corner. While more frequent and larger in magnitude earthquakes occur in the Adelaide area, very little impact is experienced within the SWQ tenement area. A study performed in the 1990's found that there is a 90% chance that the *unitless peak ground acceleration* (a term used in civil engineering to estimate forces on structures) will not exceed 0.05 in any 50-year period for this area. This indicates that regardless of the epicentre of any possible earthquake, little ground movement will occur in this region.

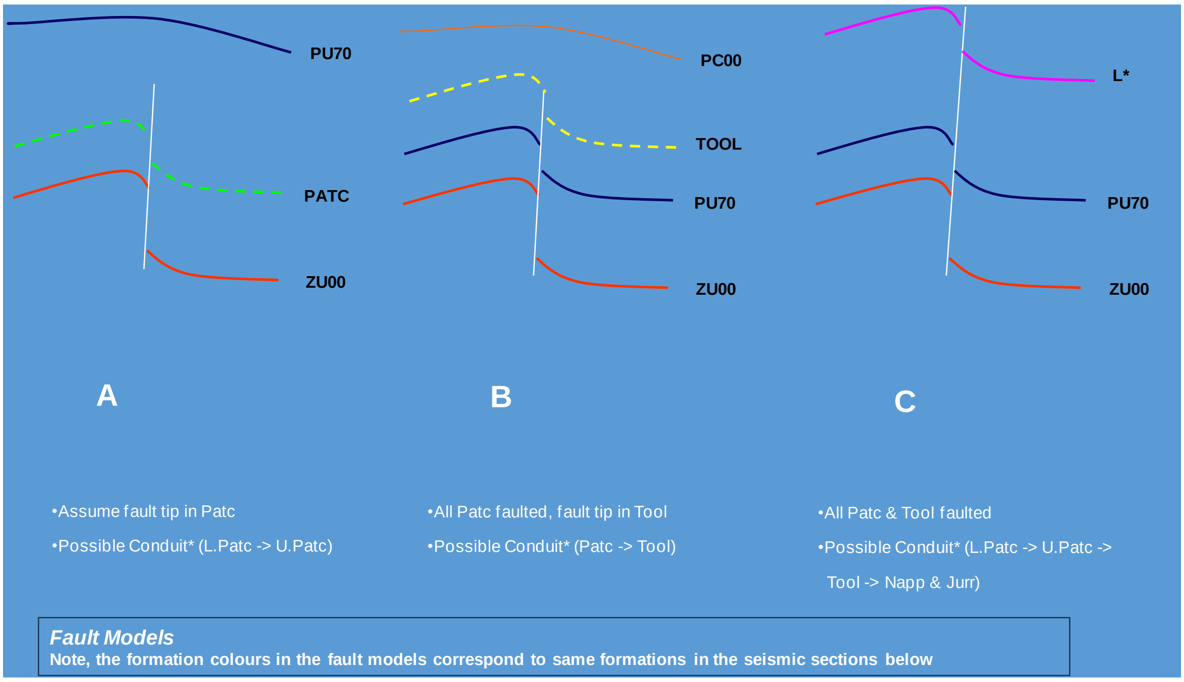
2.4.5.2 Local Historical Faults and Potential Seismic Activity

The Santos fault model is shown in Figure 17 (refer to Table 4 for stratigraphical marker abbreviations). This cross section illustrates the major fault and fold structures affecting the Cooper and Eromanga Basin sequences. Of particular note is the deep-seated nature of the basement structures, particularly faulting. The major episodic faults occurred in the top pre-Permian (basement), the basal Toolachee Formation and the basal Eromanga unconformity. These generally do not penetrate beyond the Eromanga Basin stratigraphy. The structures are predominantly compressional, and do not have large fault-throws within the Cooper Basin stratigraphy and negligible throws in the Eromanga Basin stratigraphy.

The episodic faults in the Santos fault model (Figure 17 (refer to Table 4 for stratigraphical marker abbreviations)) provide the basin's overall fabric. The basal Toolachee Formation (PU70) and basal Eromanga unconformity (L*) are generally affected by reactivated Top Pre-Permian (Basement; Zu00) faults. Figure 17 shows the Toolachee formation may be more elastic and does not fracture due to folding. The fault does not extend up through the Eromanga unconformity into the Eromanga Basin.

The episodic faults presented in Figure 17 provide the basin's overall fabric. The basal Toolachee Formation (PU70) and basal Eromanga unconformity (L*) are generally affected by reactivated Top Pre-Permian (Basement; Zu00) faults. Figure 17 shows the Toolachee formation may be more elastic and does not fracture due to folding. The fault does not extend up through the Eromanga unconformity into the Eromanga Basin.

Figure 17: N-S Seismic Section for SWQ Project Area Showing Fault Models



2.4.5.3 Active Seismic Area and Faults

While no major currently or potentially active faults exist near the study area, there was possibly a minor fault within a former tenement area. The potential minor fault is 5 to 10 km and is considerably smaller in size than the majority of faults mapped within Australia (Geosciences Australia, 2012). The fault is located within a former tenement (ATP 766P, current in December 2012, but no longer a Santos tenement) at approximately latitude and longitude 26.4°S 143.1°E (the north-eastern most tenements in the study area). As of January 2020, the closest oil and gas fields to the minor fault were located at 50 to 60 km from the fault zone, and it was therefore considered highly unlikely that the fault zone would be influenced by stimulation activities proposed for the fields. No significant seismic activity has occurred in the vicinity of this possible fault (ATP 766P; Figure 18) during the period 1950-2020.

2.4.5.4 Seismic History of the Cooper Basin Area

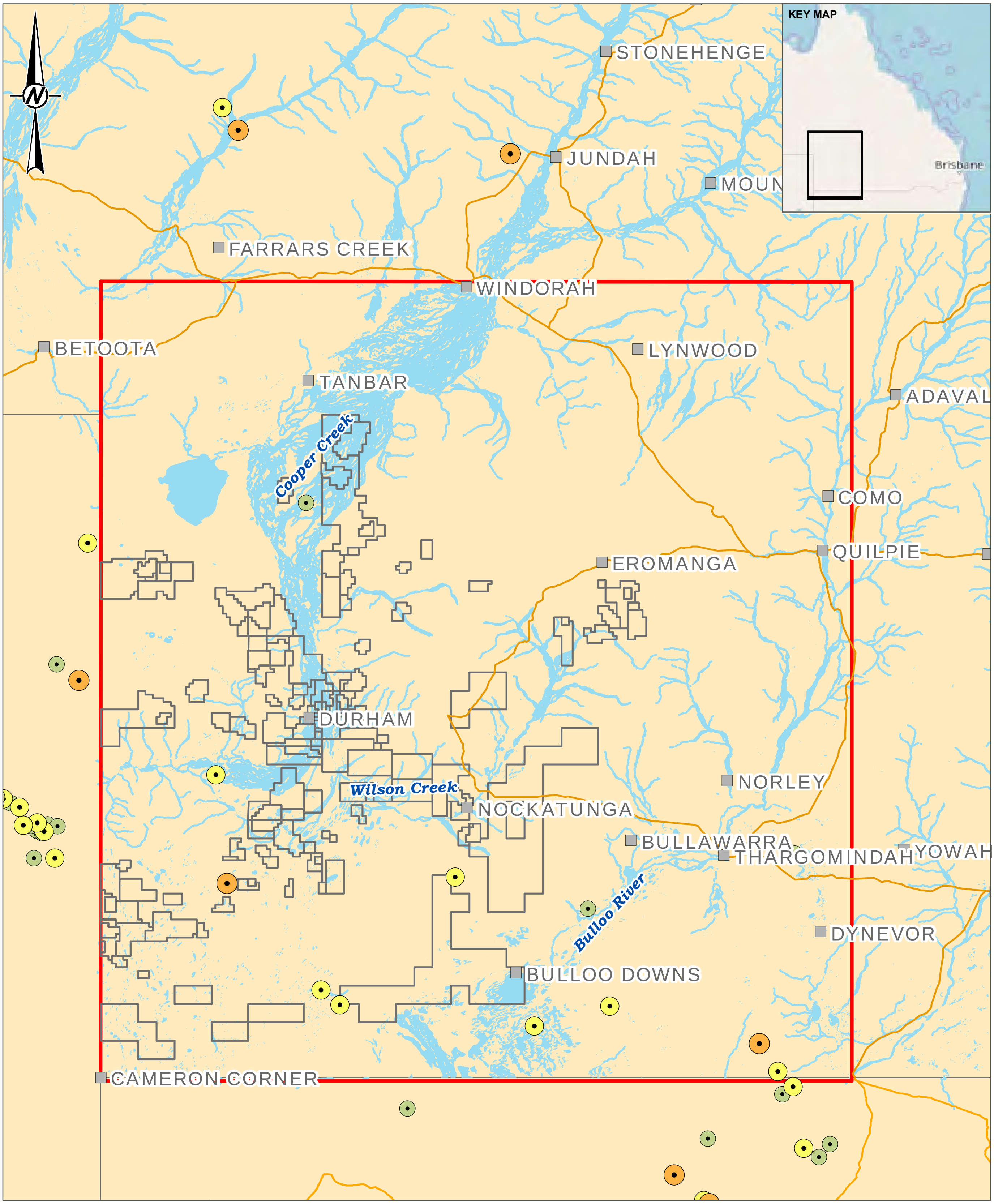
This region has experienced intermittent earthquakes of low to moderate magnitude since 1950 in the study area (Table 5). The location of the epicentre of these earthquakes is presented on Figure 18.

The majority of the earthquakes that have occurred since 1950 were approximately 8 to 11 km below the surface, with magnitudes ranging between 2.3 and 4.7 on the Richter scale. The earthquakes were generally located towards the south and western end of the study area.

Table 5: Earthquake Locations and Depths in the Study Area From 1950 - 2012

Magnitude	UTC	Latitude	Longitude	Depth (km)*
4.7	28/12/1961	-28.12	141.57	10
3.8	30/03/1963	-27.2	140.9	10
4	31/03/1963	-27.2	140.9	10
3.1	30/01/1985	-26.58	140.94	0
4	23/05/1989	-28.843	143.978	5
3.3	8/08/1989	-27.63	141.52	10
3.4	4/06/1996	-28.972	144.063	0
3.2	30/07/1997	-28.093	142.604	11
3.3	21/02/1999	-28.767	142.962	0
2.7	26/09/1999	-27.985	144.141	0
3.2	3/08/2000	-28.676	143.302	0
3.3	27/02/2001	-28.67	142.082	0
3.2	9/03/2001	-28.604	141.995	8
2.4	23/04/2001	-28.234	143.205	8
2.3	23/09/2002	-26.397	141.928	10

* Where depth is poorly constrained by available seismic data, a default depth of 0 or 10 km may be selected depending on the local earthquake activity in the area (Reference: Geoscience Australia www.ga.gov.au).



LEGEND

Town/Locality	Epicentre - Magnitude Range		4-4.9
Highway/Major Road			5-5.9
River/Creek		<1	6-6.7
Santos Tenements		1-1.9	
Study Area		2-2.9	
		3-3.9	

0 KILOMETERS 100

1:2,750,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019

CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
EPICENTRE AND MAGNITUDE OF EARTHQUAKES IN THE STUDY AREA

CONSULTANT

GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
127666004	011-R	2	18

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2.5 Hydrogeology and the Groundwater Resource

2.5.1 Introduction and Setting

The Cooper and Eromanga Basins are two chronologically successive stacked basins, with the Cooper overlying the Eromanga. Based on strict geological interpretation, the Cooper Basin is considered to be distinct and separate from the GAB, however it has been an historical convention in Queensland to include the upper sedimentary units of the Cooper Basin in the administration of GAB groundwater resources (GAB Resource Operating Plan (ROP), DERM 2007: GAB Water Resources Plan (WRP), DERM 2006). The Eromanga Basin is the largest of the three major sedimentary basins comprising the GAB and covers the whole of the Cooper Basin. The connection between the two basins is geologically marked by a major unconformity.

Both the Cooper Basin and Eromanga Basin are multi-layered systems comprising alternating layers of sandstone, shale, mudstone and siltstone formations (Section 0). The sandstone formations of the Eromanga Basin correspond to water bearing formations and aquifer formations; they support a range of beneficial uses such as potable water and stock and domestic supply. In other areas of the Basin (remote from Santos' tenements), they also supply groundwater to springs.

The siltstone, shale and mudstone formations are low permeability rocks and act as aquitards separating aquifer formations (and also as seals for hydrocarbon reservoirs). In the study area, a number of thick, competent and laterally extensive fine-grained formations are present within both the Cooper and Eromanga Basins that are important in providing vertical separation of water and hydrocarbon-bearing formations. Minor sandstone units occasionally occur as interbedded layers within predominantly fine-grained formations and may be capable of providing limited groundwater supply (e.g. <5 L/s), however in the study area water supply development preferentially targets the upper formations of the Eromanga Basin (e.g. the Winton and Glendower Formations).

For management purposes, the GAB has been subdivided into 25 Groundwater Management Areas (GMA) as defined in the *GAB Hydrogeological Framework for the GAB WRP Area* (DERM, 2005); the GMAs relevant to the study area are presented in Figure 19. GMAs are subdivided into groundwater management units (GMU), as represented in Table 3, comprising one or more geological formations with similar hydrogeological properties.

2.5.2 Hydrostratigraphy

As previously described, the formations of the Cooper and Eromanga Basin within the study area comprise a stacked sedimentary sequence of sandstone formations that act as aquifers and hydrocarbon reservoirs, interbedded with fine-grained formations that act as competent and laterally extensive aquitards and seals for hydrocarbon traps. The main aquifer and aquitard units are presented in Table 6. The main aquifer groupings, in terms of production of groundwater, include:

- The aquifers of the Quaternary sediments and Tertiary formations (potential water supply for agricultural and potable water);
- The GAB aquifers of the Eromanga Basin (possible water supply for agricultural and potable water, and produced formation water); and
- The older and deeper aquifers of the Cooper Basin (produced formation water).

The Quaternary and Tertiary deposits are preferentially developed as groundwater resources because they are shallow, accessible and able to yield productive quantities of groundwater to support beneficial uses relevant to the study area (principally, domestic supply and stock watering). In contrast, groundwater resources associated with the deeper aquifers of the Eromanga Basin have had limited development. The deep aquifers of the Cooper Basin are only accessed during the production of gas.

A summary of the groundwater resources within the study area is presented in the following section. A more detailed discussion of the groundwater resources is contained in the UWIR (Golder 2020).

Table 6: Hydrostratigraphy of the Study Area

GMA Unit	Basin	Group	Unit name	Sub-unit	Equivalent Formation other parts of the GAB
	Eromanga Basin		**Glendower Formation**		
			Winton Formation		
			Mackunda Formation		
			Alluru Mudstone		
Central 1 - Warrego West 1			**Toolebuc Formation**		Surat Siltstone
			Wallumbilla Formation	Coreena Member	Wallumbilla Formation
				Doncaster Member	
Central 2 - Warrego West 2			**Cadna-Owie Formation**	Wyandra Sandstone Member	Cadna-Owie Formation, Bungil formation, Gilbert River Formation
				Lower Cadna-Owie	
Central 3 - Warrego West 3			**Hooray Sandstone**	Murta Formation	Hooray Sandstone, Mooga Sandstone, Orally Formation and Gubberamunda Sandstone
				Namur Sandstone	
Central 4 - Warrego West 4			**Westbourne Formation**		Injune Creek Group
			Adori Sandstone		
			Birkhead Formation	Upper Birkhead	
				Middle Birkhead	
				Lower Birkhead	
Central 5 - Warrego West 5			**Hutton Sandstone**		
Central 6 - Warrego West 6			**Poolowanna Formation**	Upper Poolowanna	Precipice Sandstone
				Lower Poolowanna	
MAJOR UNCONFORMITY					
Central 7 - Warrego West 7	Cooper Basin	Nappamerri Group	**Tinchoo Formation**	Gilpeppee Member	Moolayember Formation
				Doonmulla Member	
			Arrabury Formation	Wimma Sandstone Member	Clematis Sandstone
				Panning Member	Rewan Formation
				Callamurra Member	

GMA Unit		Unit name		Sub-unit	Equivalent Formation other parts of the GAB
		Gidgealpa Group	**Toolachee Formation**		
		Gidgealpa Group	**Daralingie Formation**[1]		
		Gidgealpa Group	**Roseneath Shale**		
		Gidgealpa Group	**Epsilon Formation**		
		Gidgealpa Group	**Murteree Shale**		
		Gidgealpa Group	**Patchawarra Formation**		
		Gidgealpa Group	**Tirrawarra Sandstone**		
		Gidgealpa Group	**Merrimelia Formation**		
		Aquifer			
		Water Bearing in part			
		Confining Bed			

[1] The Daralingie Formation is considered to be water bearing in some areas of the Cooper Basin but has been classified as a confining bed within this study area.
Source: DERM, 2005

2.5.2.1 Eromanga Basin

The main GAB aquifers in the study area occur within the Eromanga Basin stratigraphy, and include the Winton Formation, Cadna-Owie Formation, Hooray Sandstone, Hutton Sandstone and Poolowanna Formation (Precipice Sandstone equivalent).

Hydrogeological contour maps are provided (where data was available) in APPENDIX C for the following hydrostratigraphic units. Note that the Quaternary and Tertiary sediment aquifers and the Winton Formation are not administered under the GAB ROP (DERM 2007).

Poolowanna Formation (Central 6 - Warrego West 6)

Also referred to as the Basal Jurassic Formation (older name in the nomenclature), the Poolowanna Formation is the equivalent of the Precipice Sandstone (in SE QLD). No further information is available.

Hutton Sandstone (Central 5 - Warrego West 5)

The Hutton Sandstone is a significant GAB aquifer however its depth in the study area (approximately 2,000 mbgl; refer to Figure 11) has precluded access for water supply development. Based on limited available data, the groundwater flow is expected to be to the southwest (i.e. consistent with the regional flow direction of the major GAB formations).

The water quality of the Hutton Sandstone in the study area cannot be commented upon as produced water quality data was not readily available, and no data was available in the DEHP database.

Westbourne Formation, Adori Sandstone and Birkhead Formation (Central 4 - Warrego West 4)

The Westbourne Formation is considered to be a confining layer of relatively homogeneous characteristics (lacustrine deposits associated with a large transgression). However, in the southeast section of the study area, it is possible that a number of private bores are completed in the Westbourne Formation, possibly accessing minor sandstone beds within the formation.

The Adori Sandstone is considered to be an aquifer (at least in part) in the study area, however insufficient information is available to characterise it further. The basal portion of the Adori Sandstone is noted as having a thick calcite cemented zone up to 45 m thick.

The Birkhead formation comprises a succession of non-continuous confining beds and water bearing sandstone units.

Water quality data for these formations are not available in the DEHP database and were not available in regard to Santos produced water extracted from this formation. Data collected during a Water Bore Baseline Assessment (WBBA) of the study area is limited and not conclusive.

Hooray Sandstone (Central 3 - Warrego West 3)

The Hooray Sandstone is a significant unit in GAB. In the study area it is considered to be a major aquifer. Oil reservoirs and minor gas reservoirs are also contained with this unit. Two sub-units are identified in the Hooray Sandstone:

- The Murta Formation (equivalent formations in other GAB basins include the Mooga and Gubberamunda Sandstones). In the study area it is considered to be a confining bed, the main confining unit being a siltstone bed located at the base of the Murta Formation and found widespread over the Cooper region. Minor oil and gas reservoirs are noted to be present as fine-grained sandstone units capped by intra-formational siltstone and shale seals.
- The Namur Sandstone consists predominantly of fine to coarse grained sand with minor fine-grained interbeds, and is the major water bearing unit of the Hooray Sandstone. Oil can also be present in this unit.

The water quality in the Hooray Sandstone is generally fresh to slightly brackish with electrical conductivity (EC) values (DEHP database) ranging from 675 to 3,930 µS/cm (or approximately 470 to 2,750 mg/L) with a median value of approximately 1,000 µS/cm (approximately 700 mg/L). This water quality is suitable for potable water supply, and the few available long-term records (i.e. 40 year monitoring period) indicate that water quality has remained consistent over time.

A number of bores within the Hooray Sandstone may be artesian. Groundwater bores for that unit seem to be concentrated to the southeast of the study area (APPENDIX C). No reliable water level and salinity data are available for this formation in the vicinity of Santos' tenements.

According to the available data the groundwater flow direction is towards the southeast (APPENDIX C).

The Hooray Sandstone is considered to yield productive quantities of groundwater, and a town water supply bore is potentially completed with the Hooray Sandstone (to be confirmed as part of continuing field works for the WBBA).

Cadna-Owie Formation (Central 2 - Warrego West 2)

The Cadna-Owie Formation is considered to be a major aquifer of the GAB, and in the study area comprises two sub-units: the upper the Wyandra Sandstone and the Lower Cadna-Owie. The Wyandra Sandstone is considered to be an aquifer however its thickness is limited in SWQ. The Lower Cadna-Owie comprises siltstone and very fine-grained sandstone and is considered to be an aquitard.

The few data points available in the DEHP groundwater database indicate fresh to slightly brackish water quality with the Wyandra Sandstone. Insufficient water level information is available to describe water flows and water levels.

Habermehl (1986 and 1997) defines this unit as non-artesian; however, the DEHP groundwater database does identify artesian bores in the Cadna-Owie Formation.

Winton Formation (Central 1 - Warrego West 1)

According to the DEHP database, the Winton Formation is a significant aquifer for the local community that supplies a number of stock and domestic bores. The depth and thickness of the Winton Formation are illustrated in the maps of APPENDIX B. The top of the Winton Formation is approximately 50 mbgl and thickness can reach up to 970 m.

Santos' geology team however dispute the role of the Winton Formation as a significant aquifer in SWQ and consider it to be water bearing at best. Although the Winton Formation is a significant aquifer in a large area of Queensland, the quality of the Winton Formation as an aquifer appears to diminish westward from central to southwest Queensland and into South Australia (Pers. Comm. N. Lemon, Santos, November 2011). The top and bottom of the Winton are so poorly defined in the subsurface that it is difficult to confirm whether water production currently assigned to the Winton Formation is coming from the overlying Tertiary (Eyre Formation in South Australia) or underlying Mackunda Formation. This situation is supported in SA by the findings of Gravestock and al. (1995).

The Winton Formation directly underlies the Tertiary sediments; some degree of hydraulic connectivity is expected however no data is available to confirm this.

The water quality in the Winton Formation is fresh to brackish with EC values ranging from 900 to 13,000 µS/cm (approximately 630 to 9,100 mg/L). Groundwater flow in this aquifer is generally to the southwest (APPENDIX C).

Quaternary and Tertiary Alluvium

Quaternary and Tertiary alluvial deposits cover a large proportion of the study area. They are often associated with the very flat structures of the flood plains and are absent where the Winton Formation outcrops.

Cendon et al. (2010) have described the groundwater resources associated with Quaternary sediments of the Cooper Creek basin as comprising predominantly saline water (reported total dissolved solids (TDS) values up to 38,000 mg/L) that occurs within fluvial and aeolian sand deposits that are extensively overlain by thick, low permeability mud deposits. The surficial fine-grained deposits limit recharge to the sand units, even below the waterholes that are present in the main creek channels during extended periods of low (or no) stream flow. Episodic flood events are thought to occasionally scour through the low permeability deposits within major creek channels and provide temporary recharge to the underlying sand beds, resulting in discrete and discontinuous freshwater lenses in the otherwise saline groundwater environment.

Evaluation of water level and water quality data (including major and minor ion chemistry and stable isotope analysis) suggests that the surface water features in the study area do not receive shallow groundwater recharge (Hamilton et al., 2005; Bunn et al., 2006; Costelloe et al., 2007, Cendon et al., 2010). However, they may receive seepage through their basal mud layers to provide limited recharge to the underlying saline groundwater system. The lack of connectivity between surface water systems and shallow groundwater is an important consideration with respect to exposure pathway analysis (as is discussed in corresponding hydraulic stimulation service provider reports).

The Glendower Formation is the main Tertiary formation within the study area. The Glendower Formation consists of consolidated sediments comprising sandstones, sandy siltstones and minor conglomerate and mudstones (Australian Stratigraphic Database, Geosciences Australia). The Australian Stratigraphic Database identifies the Whitula Formation as overlying the Glendower Formation; however, the significance of the Whitula Formation in the study area is unknown.

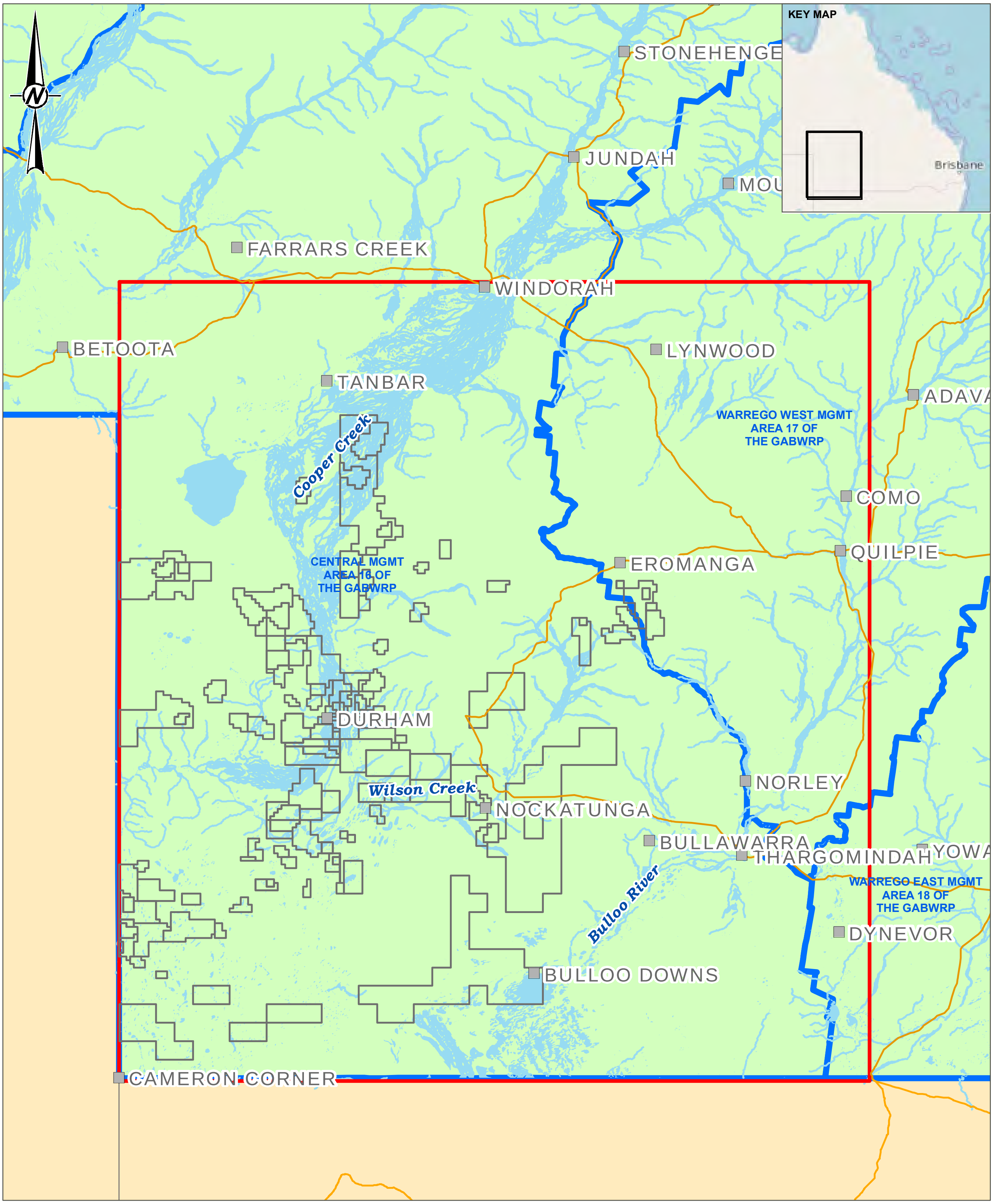
Groundwater flow in these formations follows topography in the study area and is influenced by outcrop areas of the underlying Winton Formation. As illustrated on the hydrogeological map (APPENDIX C), the hydraulic gradient is very small.

The quality of the Tertiary aquifers is brackish, with EC values ranging from 3,000 to 7,000 µS/cm (approximately 2,100 to 4,900 mg/L).

2.5.2.2 Cooper Basin

The upper formations of the Cooper Basin are included in the administration of GAB groundwater resources under QLD regulations. This includes the Panning and Wimma Sandstone Members of the Arraburry Formation, and the underlying Toolachee formation.

Insufficient information is available to provide a detailed description of the hydrostratigraphy of the Cooper Basin formations.



LEGEND

- Town/Locality
- Highway/Major Road
- River/Creek
- Groundwater Management Area
- Santos Tenements
- Study Area

0 KILOMETERS 100

1:2,750,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. GROUNDWATER MANAGEMENT AREA SOURCED DEPARTMENT OF NATURAL RESOURCES & WATER, QLD GOVERNMENT, 2008

CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
GROUNDWATER MANAGEMENT AREAS FOR THE STUDY AREA

CONSULTANT
GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
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2.5.2.3 Observed Reservoir Pressure Data

The hydrostatic pressure of water-bearing stratum is measured during drilling activities by:

- Drill stem test (DST);
- Repeat formation tester (RFT); or
- Formation micro tester (FMT).

Pressure testing is undertaken to assess the likely thickness of the oil or gas column found at any particular depth interval. This is calculated by comparing the pressure in the hydrocarbon-bearing zone with the expected water pressure as predicted by the water pressure-depth line (Figure 20).

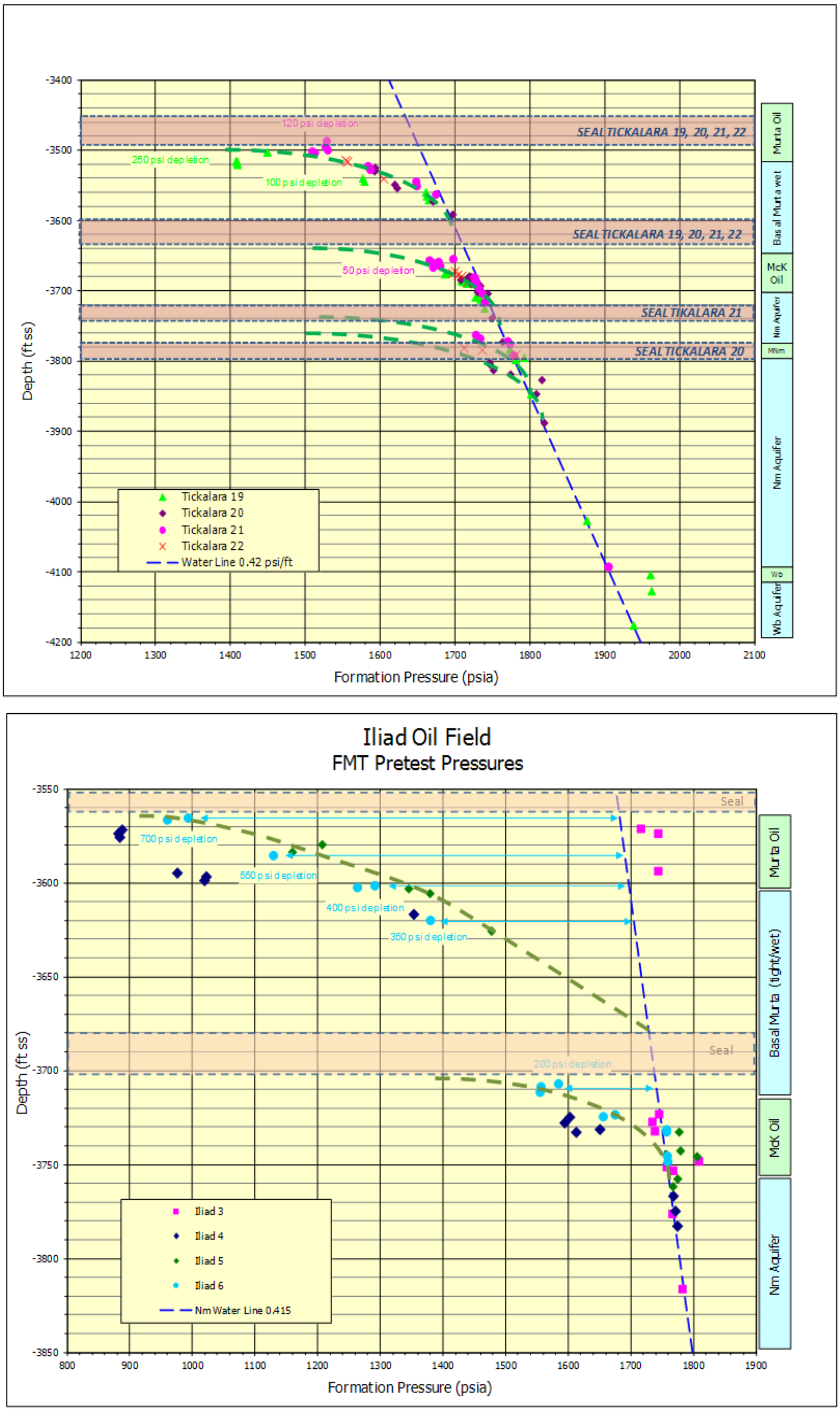
Models for predicting the influence of gas and oil, and associated water production at depth require input data on the pressure transmissibility of the strata that separates the target formations (referred to as seals). In the case of SWQ:

- Seals between the Glendower and Winton aquifers; and
- Seals between the Murta, Namur (Hooray) and Hutton Sandstone, from which oil is produced.

Numerous Santos wells have undergone pressure measurements in the Cadna-Owie Formation to establish water pressure-depth lines and this data can be re-assessed to see if depletion from underlying hydrocarbon production zones has influenced the aquifers utilised for water supply. If no depletion is observed in the Cadna-Owie Formation, then this provides evidence of the integrity of the cap rock separating the Cadna-Owie Formation from the underlying hydrocarbon reservoirs.

Figure 20 demonstrates how formation pressures are depleted below the predicted water pressure line (the blue dashed line increases in pressure with increasing depth) and are confined within each target formation (yellow layers) by the presence of an overlying aquitard (seal bed, orange layers). This data demonstrates the competence of the confining units in isolating hydrocarbon reservoirs from overlying and underlying aquifers.

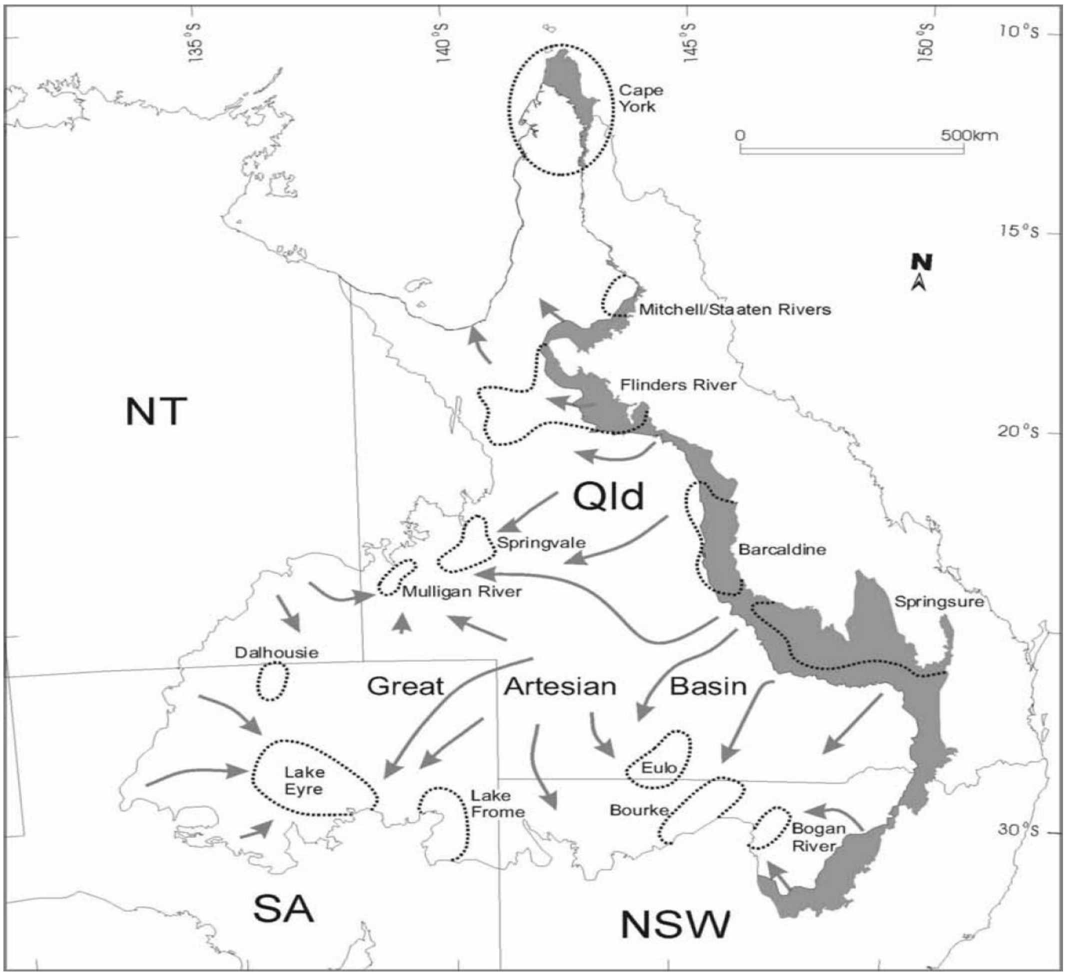
Figure 20: Observed Tickalara (top) and Iliad Field Pressure with Depth Plots



2.5.3 Groundwater Flow

In general, groundwater flow through the majority of the deeper units of the Eromanga Basin is to the south to southwest. This is consistent with the direction of flow in the major GAB units (Figure 21; BRS, 2000). Potentiometric surface contours for select Eromanga Basin aquifers are presented in APPENDIX C (sourced from the UWIR (Golder, 2012a) based on information available for the study area in the DEHP database). This data supports a southward flow direction but exhibits a high degree of variability which is attributable to the limited data available from the database. Shallower groundwater flow in the Tertiary Formation appears to be influenced by surface topography. The shaded patterns in Figure 21 broadly represent the recharge area; arrows represent modelled flow lines after Welsh (2000). Dashed lines represent spring clusters updated from Habermehl.

Figure 21: Map of GAB Extent, Regional Flow Paths, Recharge Beds, and Spring Clusters



Source: After Habermehl and Lau (1997)

Structural Influence on Groundwater Flow

Section 2.4.4 presents a summary of the tectonic setting and basin stress regime within the Cooper-Eromanga Basins. The stress regime is primarily associated with strike-slip faulting, normal faulting, and transitional strike-slip/reverse faulting at depth. When taking the observed (and sustained) overpressures into account, this stress regime is predominantly more conducive to tight compressive (non-tensional) fault creation, and as such largely self-sealing fault systems. This would infer the faults are not likely to form conduits for groundwater (or gas or oil) flow. This is supported by pressure profiles and sustained overpressures, such as presented in Figure 20.

2.5.4 Recharge/Discharge

The upper GAB aquifers are recharged by infiltration (rainfall), and leakage from streams into outcropping sandstone formations, mainly on the eastern margins of the GAB along the western slopes of the Great Dividing Range. Regional groundwater flow is from the topographically higher recharge areas around the basin margins towards the lowest parts of the basin in the southwest (Figure 21).

Outcropping areas of the major GAB units, which are considered as the recharge areas for the GAB, do not occur within 300 km of the study area.

Discharge areas in the GAB typically manifest as springs, supplied by leakage to alluvial aquifers (Tertiary-Recent), and discharge to inland lakes and water supply bores. In the study area there are no identified GDEs (Section 2.6.2.4); the only discharge of water is through water supply bores or as a by-product during oil and gas production.

2.5.5 Aquifer and Aquitard Hydraulic Properties

A review of hydraulic parameters was undertaken for the strata in the vicinity of the study area. The hydraulic parameters characterising the formations are presented in Table 7. The data presented in the table are based on field measurements and available published values.

Table 7: Hydraulic Parameters

Basin	Formation	Hydraulic Conductivity (m/d)		Porosity (fraction)
		Min	Max	
Eromanga Basin	Quaternary and Tertiary Alluvium	-	-	-
	Winton Formation	-	-	-
	Mackunda Formation Alluru Mudstone Toolebuc Formation Wallumbilla Formation	-	-	-
	Cadna-Owie Formation	-	-	-
	Hooray Sandstone	4.3×10^{-4}	4.3×10^{-1}	-
	Westbourne Formation, Adori Sandstone and Birkhead Formation	8.0×10^{-7} [2]	2.5×10^{-4} [2]	0.2 [2]
	Hutton Sandstone	3.5×10^{-1}	9.8×10^{-3}	
	Poolowanna Formation	1×10^{-7} [2]	3.7×10^{-3} [2]	0.18 [2]
Cooper Basin	Tinchoo / Arrabury Formations			
	Toolachee Formation	2.0×10^{-3} [1]	4.3×10^{-3}	0.15 0.08 to 0.12[3]
	Daralingie, Roseneath Shale, Epsilon and Murteree Shale Formations	-	-	-
	Patchawarra Formation	3.3×10^{-4} [1]	3.5×10^{-3} [1]	0.13 0.08 to 0.12[3]

[1] Gov. of South Australia, Primary Industries and Resources, SA. Petroleum and Geothermal in South Australia – Cooper Basin, 2009.
[2] Alexander, E.M., Reservoirs and Seals of the Eromanga Basin (undated).
[3] Recent information provided by Santos (Santos, 2011a).

Note that insufficient data is available to provide transmissivity, which is a function of the thickness of an aquifer (T = Kb).

2.5.6 Groundwater Quality

Groundwater quality data was reported in a metadata table from the UWIR (Golder, 2012a; 2020). The metadata table includes both automated database enquiries and manually interpreted data for target formations using the available depth and construction information. Water quality data extracted from the DEHP database included a total of 772 samples collected from 437 groundwater bores located within the study area. However, only 494 of the samples collected were considered suitable for interpretive use, based on cation-anion balance, and could be assigned to a particular aquifer formation.

Groundwater quality data in the study area was available for the aquifers associated to the following formations[4]:

- Tertiary sediments (10 samples):
- Glendower Formation (31 samples):
- Winton Formation (160 samples):
- Mackunda Formation (16 samples):
- Alluru Mudstone (7 samples):
- Wallumbilla Formation (97 samples)[5];
- Cadna-Owie Formation (20 samples);
- Hooray Sandstone (147 samples);
- Adori Sandstone (1 sample); and
- Hutton Sandstone (5 samples).

Groundwater pH values in the study area ranged from 6.2 to 9.9. The slightly acidic pH (6.2) was associated with groundwater from the *Winton Formation* aquifer. The most alkaline sample was collected from the *Wallumbilla Formation.* For the majority of samples, the pH ranged between 7.5 and 8.5.

Total hardness was calculated from the chemical composition and refers to the sum of calcium and magnesium (expressed in mg/L of CaCO3). Approximately 49% of samples represent soft groundwater, 16% moderately hard, and approximately 15% of groundwater samples would cause scaling.

2.5.6.1 Water Types of the Study Area Formations

A piper diagram of all groundwater samples within the study area is presented as Figure 22, and piper diagrams for individual formations are presented in Figure 23. The red line represents conservative (non-reactive) mixing of fresh water and sea water. The position of the markers away from the conservative mixing line is an indication of a geochemical reaction. As presented in Figure 22 and Figure 23 the dominant ions are sodium, bicarbonate and chloride, and water types are either sodium-bicarbonate or sodium-bicarbonate-chloride types. Groundwater from the Winton Formation, Wallumbilla Formation, Hooray Sandstone and Tertiary Sediments/Glendower Formation appear to have higher proportion of sodium and magnesium.

2.5.6.2 Total Dissolved Solids

Based on TDS concentrations the majority of the groundwater samples (87%) are slightly brackish (TDS <3,000 mg/L). The rest of the samples from Winton Formation, Wallumbilla Formation, Glendower Formation

[4] Data current as of December 2012

[5] The Alluru Mudstone and Wallumbilla Formation are considered to be confining beds in the study area. Interpretation of water quality and completion formation is based on the target formation interpretations in the DEHP database. It is possible that samples may have been mis-identified.

and Hutton Sandstone are classified as brackish with TDS concentrations in the range of 3,000 to 10,000 mg/L. The most saline sample was collected from the *Winton Formation* aquifer.

A measure of salinity and sodium hazard is presented in a Wilcox plot in Figure 24. Both salinity hazard (C) and sodium hazard (S) are each divided into four classes based on EC values and sodium absorption ratio (SAR): S1 or C1 indicates low sodicity or salinity (respectively) and S4 or C4 indicates high results. Figure 22 indicates that groundwater from the study area plot within a wide range of both sodium and salinity hazard classes. The groundwater from all of the formations from SWQ aquifers fall into high sodicity (S2-S4) and very high salinity classes (C4).

Figure 22: Piper Diagram

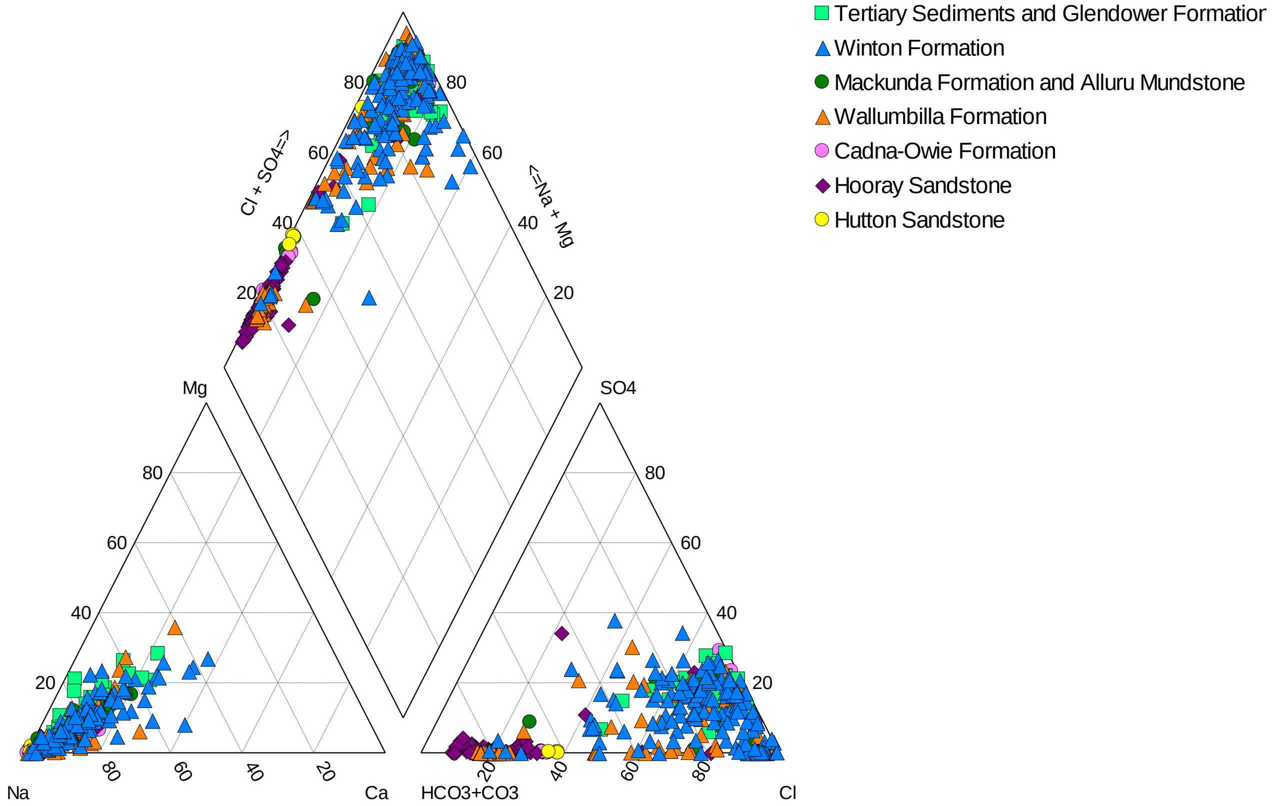
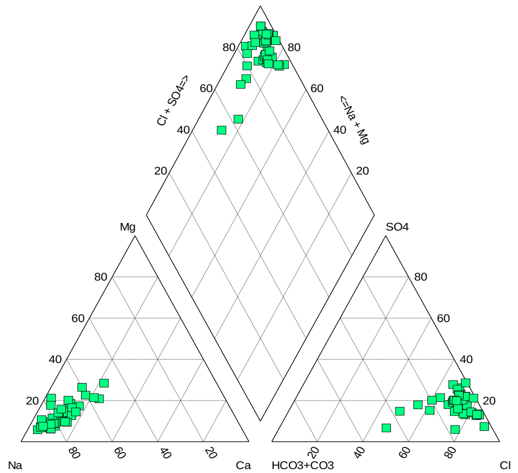
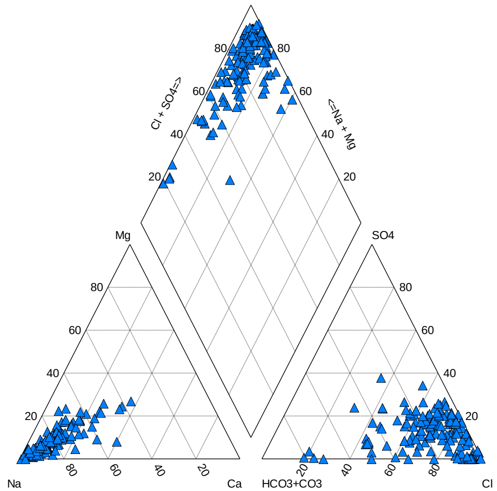


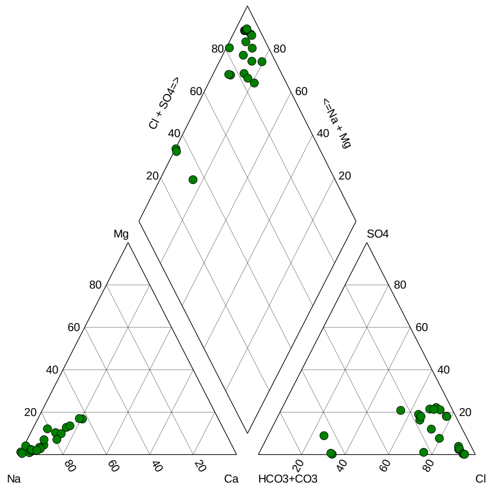
Figure 23: Piper Diagrams of Individual Formations



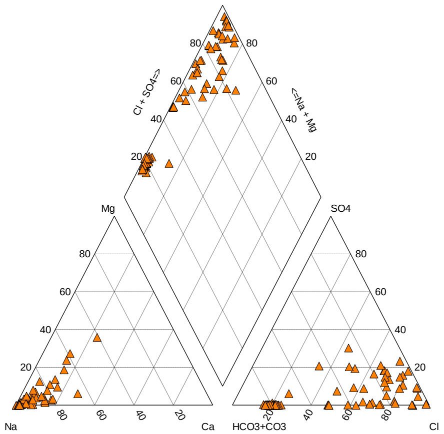
Tertiary Sediments and Glendower Formation



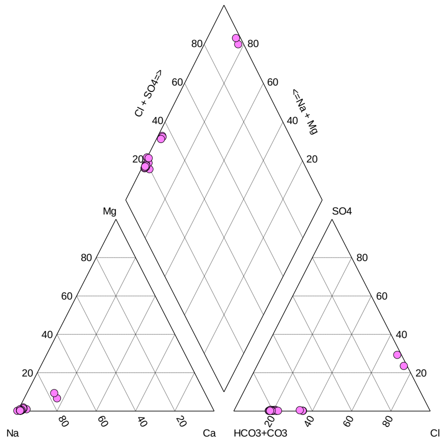
Winton Formation



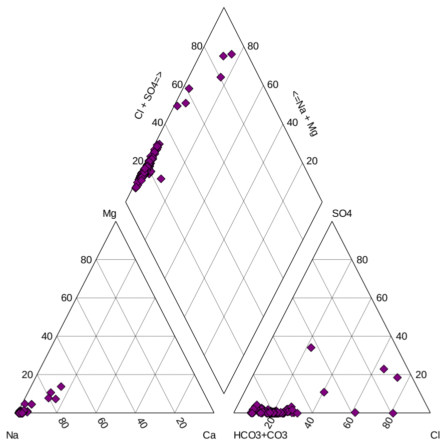
Mackunda Formation and Alluru Mudstone



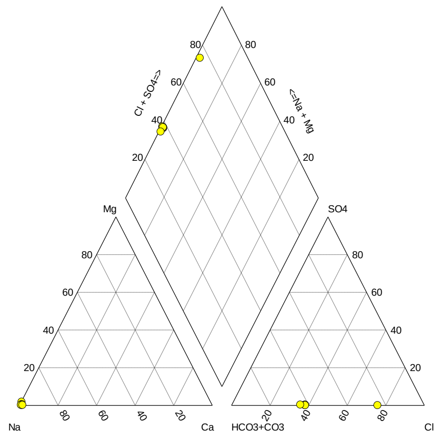
Wallumbilla Formation



Cadna-Owie Formation

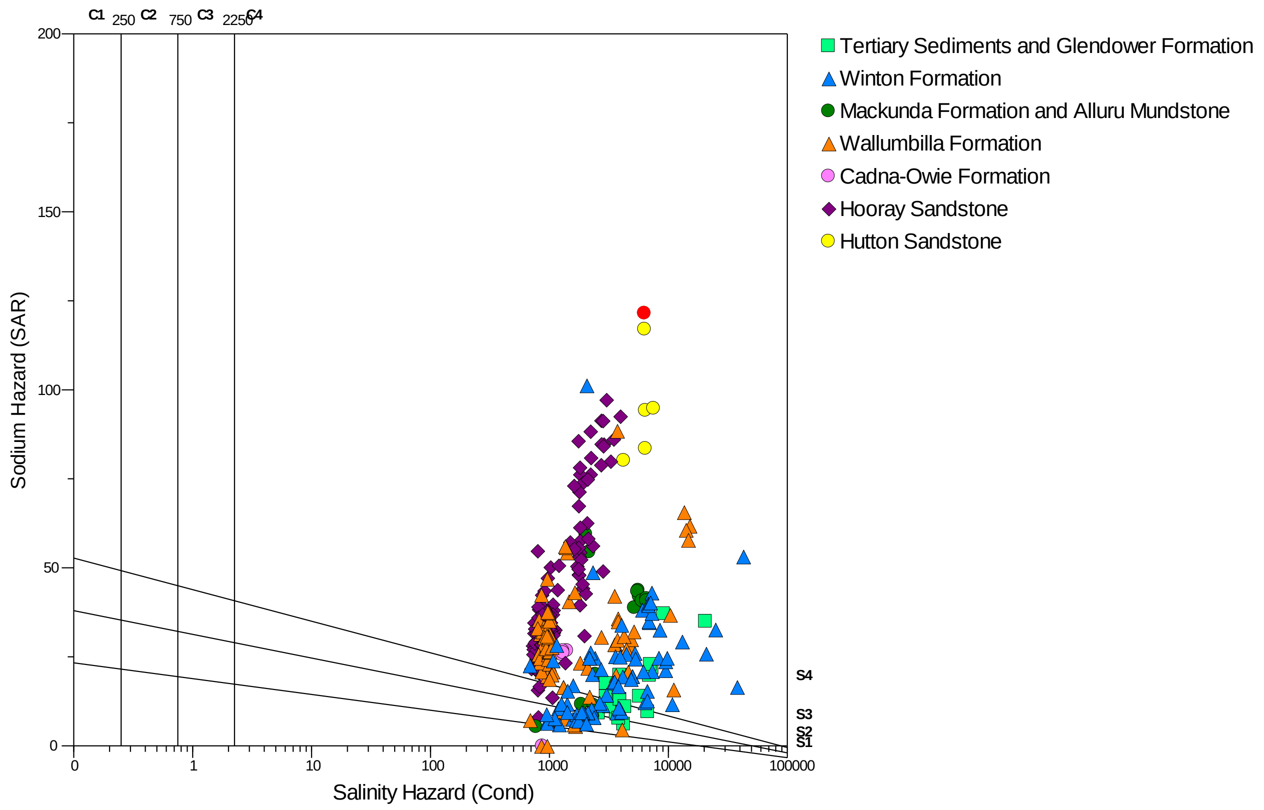


Hooray Sandstone



Hutton Sandston

Figure 24: Wilcox Plot Showing Salinity and Sodicity Hazard Classes



2.5.7 Groundwater Use (Excluding Produced Water)

Groundwater use is largely for stock and domestic purposes, with some town and camp water supply also sourced from groundwater (Figure 25).

There are no large groundwater users albeit for municipal supply in the study area, based on the available data in the DEHP Water Entitlements System (WES) database (previously WERD database). The bores for municipal supply licensed in the WES database are for Eromanga and Thargomindah.

There are 99 existing water production bores known to Santos within the Project Area. Of these, 55 are currently operated by Santos (SWQ EMP 2014).

Groundwater is primarily sourced from the Tertiary formations and the upper GAB formations of the Eromanga Basin. Figure 26 illustrates the distribution of groundwater sources for registered water supply bores within the study area[6]. The geographical distribution of private bores and Santos bores is presented in Figure 27.

[6] Data current as of December 2012

Figure 25: Groundwater Use within the Santos Study Area

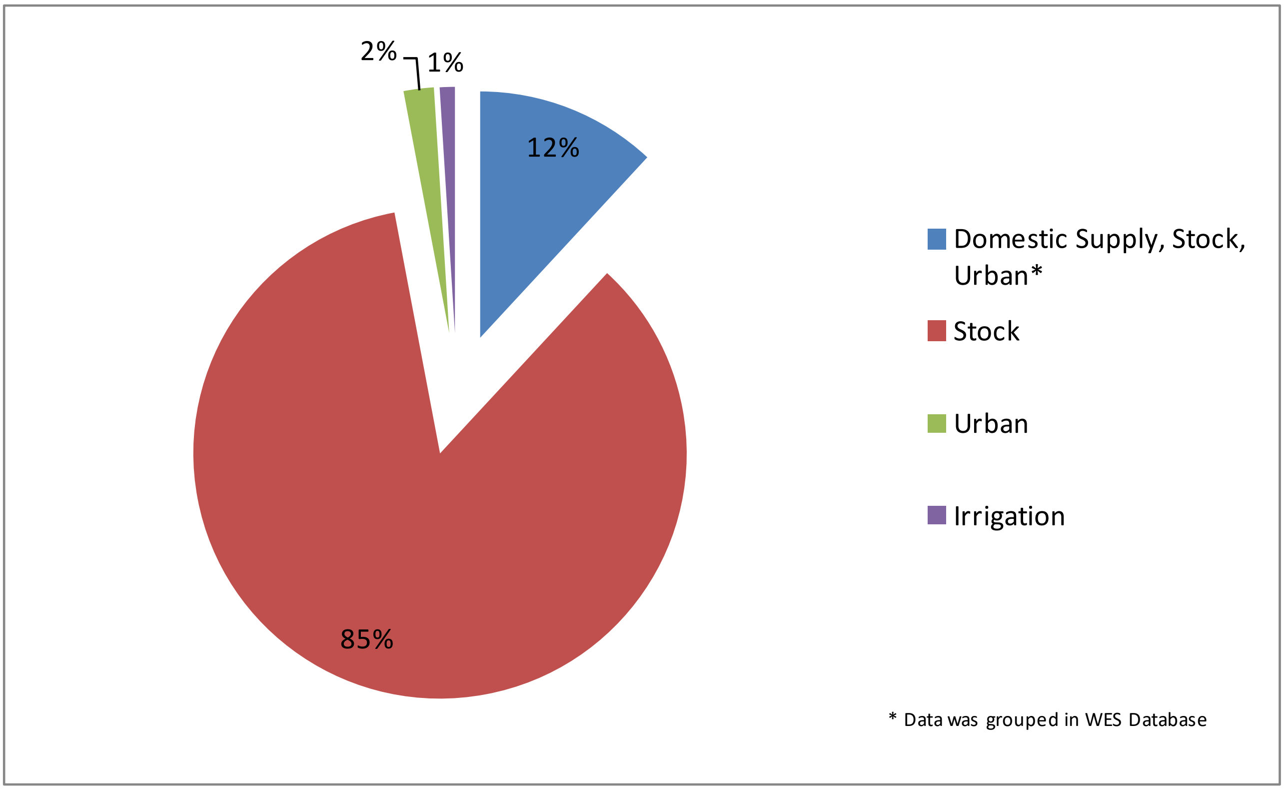
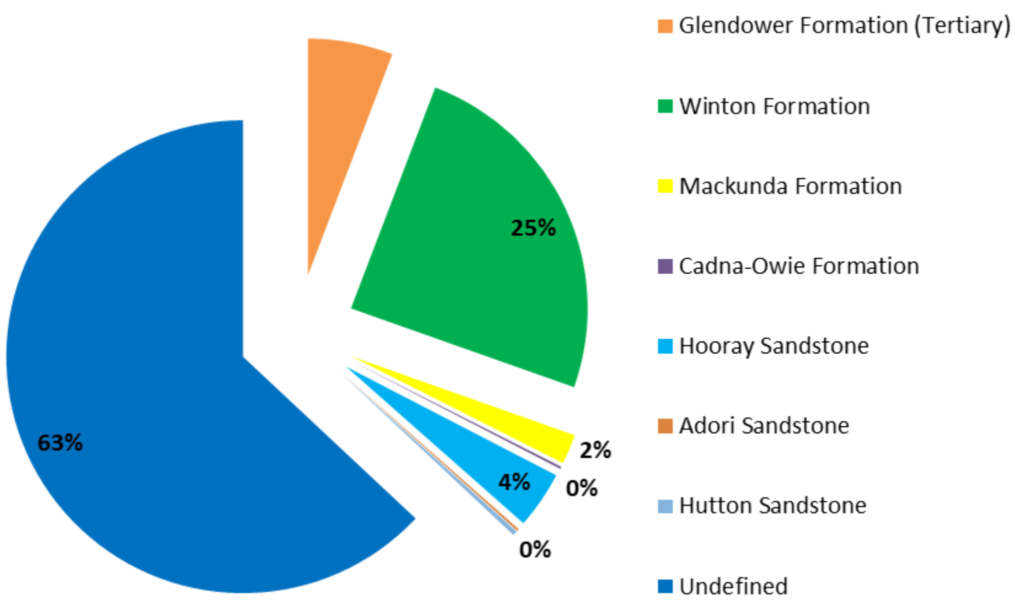


Figure 26: Target Groundwater Sources for Groundwater Usage in the Study Area



Note: Figure 26 was prepared using the data from the DERM groundwater database (Golder, 2020). A total of 138 bores have information on pump type or are indicated as artesian and have been assumed to be used for groundwater supply. Of these 138 licensed bores in the study area, 63% are assigned to the Hooray Sandstone aquifer.

Most private properties are expected to have access to their own water supply through stock and domestic entitlements as part of the basic landholder rights to access water. Groundwater use is limited to domestic consumption and cattle farming (not including industrial cattle operations). There is no volumetric groundwater entitlement associated to these licences however it is commonly assumed that those bores extract a maximum of 5 ML/year.

As of January 2020 (UWIR, 2020), the total volumetric water entitlements in the study area is 2,390 ML/yr for urban and town supply from seven bores; however, four of these licensed bores (totalling 900 ML) were listed as “Lapsed/Never Constructed” and/or expired. The total nominal allowance for stock and domestic bores is 635 ML/yr for 127 bores. The total extraction volume for the 135 licensed bores listed in the DEHP database is therefore 2,125 ML/yr (excluding lapsed/non-constructed bores entitlements).

Santos water production associated with oil and gas production (Golder, 2012a) is mostly from the Hutton Sandstone (82% of average annual production), the Birkhead Formation (7.8%) and the oil reservoirs of the Hooray Sandstone (8.6%).

2.5.8 Regional Bore Inventory

In parallel with the UWIR (Golder, 2012a) Santos engaged Golder to undertake a Water Bore Baseline Assessment (WBBA) in SWQ (Golder, 2012b; reference no. 117666006-019-R-Rev0). The purpose of the WBBA was to verify the existence and operation of water supply bores in the study area, and where possible to collect water extraction, level and quality data. In 2012, Santos identified 242 water bores within the study area which required assessment according to the following criteria:

- *Priority 1*: within leased areas and inside a 2 km radius of a production bore;
- *Priority 2*: within leased areas and outside a 2 km radius of a production bore;
- *Priority 3*: outside of the established leased areas but within Santos tenement boundaries.

The WBBA works undertaken were generally consistent with the DEHP requirements outlined in the *Baseline Assessment Guideline* (2011) (now DES Baseline Assessment Guidelines Version 3.02, effective 5th July 2017), and condition J13 of the draft CSG model conditions for Level 1 EAs, and included assessment of the following information:

- Capacity, quality, and water level of existing bores in the vicinity of oil and gas production areas;
- Details on bore construction, where available;
- Type of infrastructure used to pump water from the bore;
- Identifying bores with potential for inclusion in a regional groundwater monitoring network; and
- Providing an opportunity for bore owners to have direct communication with a field scientist and Santos Land Access Staff (LAS) and for developing positive relationships with these groundwater users.

As of December 2012, 89 bores were located within leased areas (*Priority 1* and *2* bores). Of these, only eight active water supply bores were confirmed within Santos tenements. Details are presented in Table 8 and Figure 27. Refer to the WBBA (Golder 2012b) for a detailed description of field observations.

Table 8: Summary of WBBA Priority 1 and 2 Bores Observed to be Used by Third Parties (Assumed Private Landowners)

Santos Priority	Bore Name	DEHP RN	Santos' Permit	Measured Water Depth (m btoc)	Bore Depth (mbgl) (source: DEHP database)	Target Aquifer (source: DEHP database)*
1	Palara Bore	6057	PL 59	-	243.80	(no data)
1	Mt Margaret No 14	9096	PL 170	-	129.60	Winton Formation
1	Walla Wallan Bore 5	6373	PL 295	15.40	156.70	(no data)
2	Mt Margaret No 20	10565	PL 295	-	89.00	(no data)
2	Cherry Cherry Bore	6369	PL 39	-	285.40	(no data)
2	Tarbat Job No 1947	12036	PL 295	30.40	209.80	Winton Formation
2	Grahams Bore	14955	PL 110	-	94.80	Glendower Formation
-	Moon Road Field Bore	0**	ATP 259P (now referred to as ATP 1189)	-	-	-

Notes:
* Data extracted from the DEHP database (bore depth and target aquifer) is considered to be indicative only, as the original data source is unknown and was not confirmed with field measurements.
** Bore not observed in database records. Referred to as "Moon Field Road Bore" in WBBA.

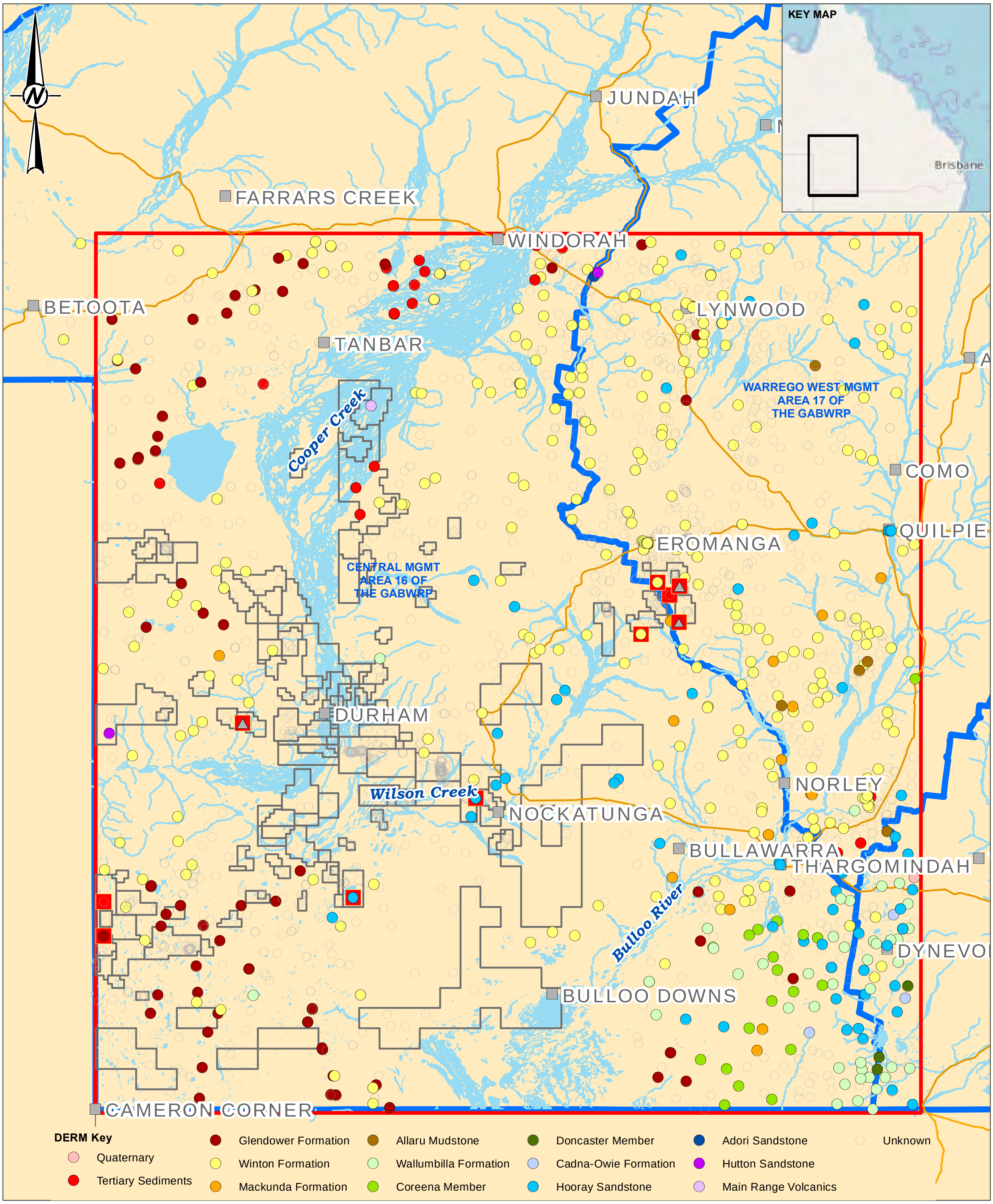
Significant data gaps have been identified between the DEHP database (used in preparing the UWIR), Santos records and the actual existence of bores (Refer to Section 4.8 of the WBBA). Active bores were also observed not to have corresponding DEHP registration numbers. In general, reliable historic and bore construction records were limited and records indicating the aquifer in which bores are screened were not available.

The Golder UWIR indicates that oil and gas production may produce groundwater drawdown in some locations within the study area. Two bores highlighted in the UWIR as being within potential impact zones (in addition to the eight identified private bores) were identified within the affected areas:

- **5032: Whim Well**
  Coordinate location visited in 2012; however, the bore was not observed and the DEHP records could not be verified. In 2016, the bore was located by Santos and was found to be non-operational (A. Stannard, pers. comm.).
- **5033: Coothero Water Bore**
  This bore is monitored by Santos as part of the UWIR Monitoring program (UWR 2020). It is located outside of the established leased areas but within Santos tenement boundaries (i.e., *Priority 3;* location shown on Figure 27*)*. This bore targets the Hooray Sandstone at 1,415 m depth, which is vertically within several hundred metres of hydrocarbon reservoirs in which hydraulic stimulation may occur. Bore uses may include road maintenance and stock watering (based on observations at the site). This bore was investigated by DES and found not to be an authorized bore (does not have a license that permits the

owner to extract groundwater). It therefore does not qualify for protection and management in accordance with s363 of the Water Act (as advised by DEHP on 29 July 2014) (UWIR 2020). Water level measurements between 1988 and 2009 show a 40 m decline in this well, potentially as a result of water extraction due to oil and gas field activities, this however has not been confirmed and could be a result of climatic factors (long-term drought cycles) (UWIR 2020).

The locations of the eight identified private bores and the additional identified bores (Whim Well and Coothero Bore)are shown within the Santos tenements on Figure 27. The locations of these bores in proximity to the stimulation activities are discussed further in Section 3.5.



LEGEND

Santos Bores

- Unknown
- WBBA Bores
- Town/Locality
- Highway/Major Road
- River/Creek
- Groundwater Management Area
- Santos Tenements
- Study Area

0 KILOMETERS 100

1:2,500,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. GROUNDWATER MANAGEMENT AREA SOURCED DEPARTMENT OF NATURAL RESOURCES & WATER, QLD GOVERNMENT, 2008

CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
GEOGRAPHICAL DISTRIBUTION OF GROUNDWATER USE

CONSULTANT

GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
127666004	011-R	2	27

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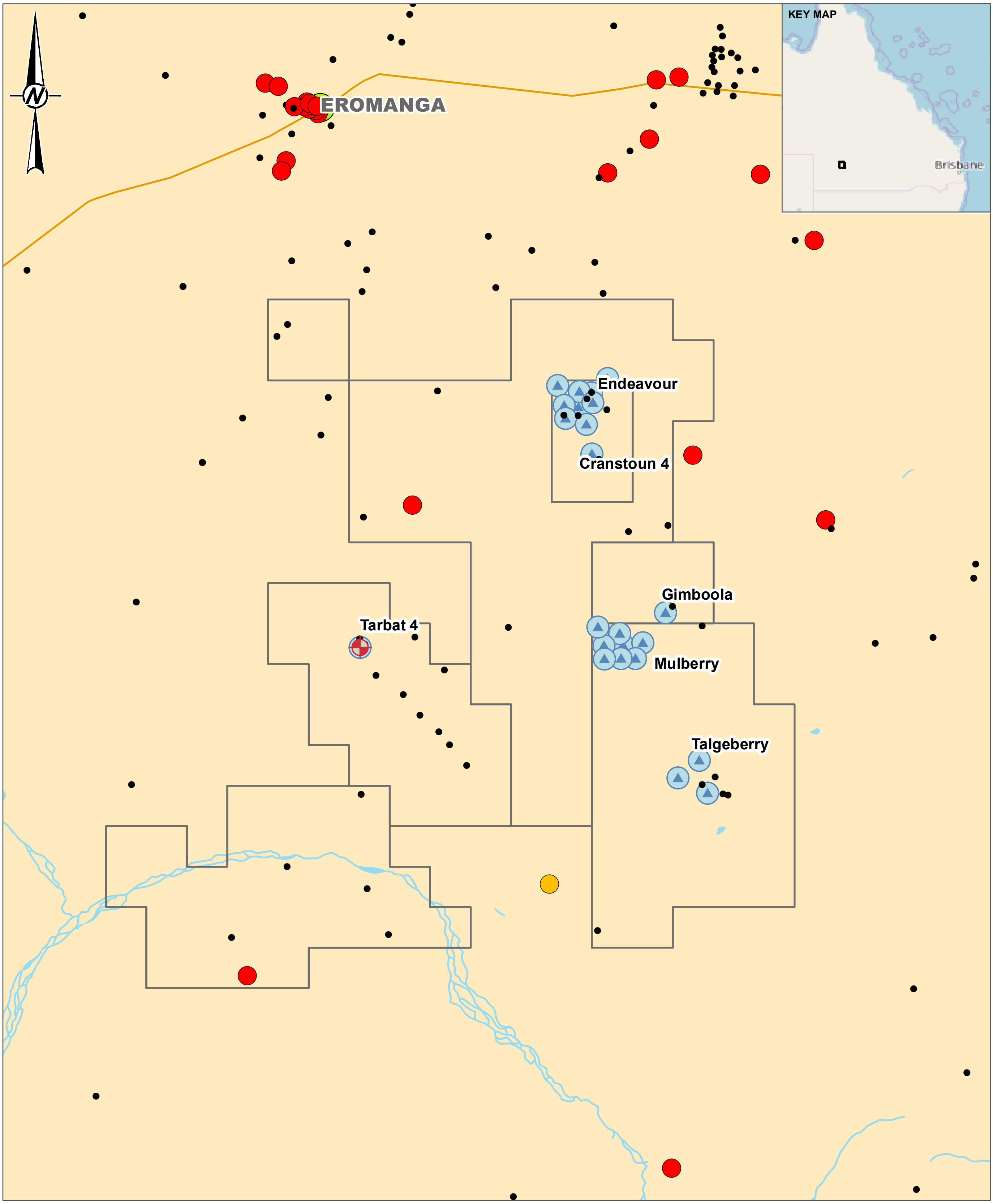

LEGEND

Private Bores - Target Aquifer
- Hooray Sandstone
- Winton Formation
- Mackunda Formation
- Unknown
- Water Source Well

- Water Injection Wells
- Town/Locality
- Highway/Major Road
- River/Creek
- Santos Tenements
- Study Area

0 KILOMETERS 10

1:250,000 GCS GDA 1994

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. GROUNDWATER MANAGEMENT AREA SOURCED DEPARTMENT OF NATURAL RESOURCES & WATER, QLD GOVERNMENT, 2008

CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
WATER FLOODING ACTIVITIES

CONSULTANT

GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
127666004	011-R	2	28

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2.6 Environmental Values in the Study Area

2.6.1 Introduction

For the purpose of this study, environmental values (EVs) relate to surface water or groundwater resources within the study area and are defined as "those qualities of the waterway that make it suitable to support particular aquatic ecosystems or human use" (*Environmental Protection (Water) Policy, 2009*, referred to as EPP Water, 2009). The EPP 2009 provides guidelines on determining the environmental value that should be considered for a particular project site or area, which follow the framework set out in *Appendix H* of the *Queensland Water Quality Guidelines 2006* (QWQG 2006).

Terrestrial environmental values of the study area, defined as the terrestrial ecosystems (flora and fauna) present within the study area, have also been considered, with information obtained from the Department of Environment and Energy (DoEE) formerly the Department of Sustainability, Environment, Water, Population and Communities (SEWPaC) Interim Biogeographic Regionalisation of Australia (IBRA), and the Environment Protection and Biodiversity Protection (EPBC) Act Protected Matters Search Tool.

With the exception of updated tenements, this section of the SRA is largely unchanged from the Rev0 (December 2012) version of this report.

2.6.2 Environmental Values of Groundwater

The EVs relevant to groundwater resources in the study area include:

- Town water supply;
- Stock and domestic water supply;
- Sandstone aquifers of the GAB; and
- Groundwater Dependant Ecosystems (GDEs).

2.6.2.1 Town Water Supply

Groundwater is a common potable water source for many inland arid to semi-arid areas of Australia, especially where productive, good quality aquifers are present at reasonably shallow depths. Use of groundwater in the region is further encouraged by the low average rainfall, which is significantly exceeded by the pan evaporation potential (Section 2.1).

Municipal water supply accounts for most of the larger licensed groundwater allocations across the study area. Municipal water supply bores identified in the WES database are licensed to extract from the Hooray Sandstone.

2.6.2.2 Stock and Domestic Water Supply

Groundwater is an important resource for stock and domestic water supply for many inland areas of Australia, especially where productive, good quality aquifers are present at reasonably shallow depths.

Groundwater supply development by the local communities predominantly targets the Glendower and Winton Formations (according to the DEHP database), and to a lesser extent the deeper formations of the Eromanga Basin. The WBBA undertaken by Golder (2012b; 2020) identified eight private water supply bores in use from a total list of 242 *Priority 1* and *2* bores within the Santos tenements (Section 2.5.8).

Groundwater for stock and domestic supply is considered to be an important environmental value in the study area.

2.6.2.3 Sandstone Aquifers of the Great Artesian Basin

The main GAB aquifers present within the study area (Section 2.5.2.1) are the Winton Formation, Cadna-Owie Formation, Hooray Sandstone, Hutton Sandstone and Poolowanna Formation (Precipice Sandstone equivalent). The sandstone formations of the Cooper Basin are not considered by the regulator to fall within the definition of "*sandstone aquifers of the GAB*".

In the study area, only the upper aquifers within the stratigraphic sequence are of interest to the local community (Section 2.5.7). The deeper aquifers are not economically viable for use as domestic supply due to the drilling costs to access them. As such, the Hutton and Poolowanna Sandstone aquifers are not used by the community with the possible exception of a couple of oil and gas exploration bores converted to private bores.

Any activity interfering with recharge to the aquifer may impact on the greater GAB. However, outcropping areas considered as the recharge regions of the major GAB units do not occur within 300 km of the study area.

2.6.2.4 Groundwater Dependant Ecosystems

GDEs can be defined as those ecosystems whose ecological processes and biodiversity are wholly or partially reliant on groundwater. There is currently no national GDE database, however, the *Environmental Water Requirements of Groundwater Dependent Ecosystems* report prepared by Sinclair Knight Merz Pty Ltd (SKM; 2001) provides an overview of key threatened GDEs in Australia and the framework for assessing environmental water provisions for GDEs. The extent of GDE dependency on groundwater can range from being marginally or episodically dependent to being entirely dependent on groundwater.

Examples of GDEs include:

- Springs and associated aquatic ecosystems in spring pools;
- Aquatic ecosystems in rivers and streams that receive groundwater baseflow;
- Terrestrial vegetation supported by shallow groundwater;
- Wetlands, which are often established in areas of groundwater discharge; and
- Aquifers and caves, where stygofauna (groundwater-inhabiting organisms) reside.

The potential presence of GDEs in the study area was assessed from literature sources (DERM, 2005 and 2007; Fensham and Fairfax, 2005) and public databases (e.g. Queensland wetlands project, Queensland spring database, EPBC Act Protected Matters database). The results of the GDE evaluation in the study area are presented in Figure 29 and are summarised below:

- No discharge springs (according to the GAB registers) are located within the vicinity of proposed stimulation activities. The nearest GAB discharge spring is located 95 km southeast of Santos tenements, and 150 km east of the nearest tenement proposed for stimulation (Figure 29);
- No GAB recharge springs, or watercourse springs have been registered within the study area;
- The *Cooper Creek Basin Wild River Area Summary: Natural Values Assessment* (DERM, 2010) concludes that "the persistence of waterholes in the Cooper Creek is largely influenced by surface water flows and evaporation, with little inputs from groundwater". This is supported by published peer-reviewed research into the surface water – groundwater connectivity of Cooper Creek waterholes, as discussed in Section 2.3 and 2.5.2.1. As a consequence, the Cooper Creek drainage system, including the associated watercourses and waterholes, is *not* classified as a GDE;
- Within the study area, one listed wetland of international significance and 11 wetlands of national significance were identified (Table 10). The Ramsar-listed Currawinya Lakes is located in the south-eastern corner of the study area, more than 170 km from the closest Santos lease and is not considered further in this report. Of the nationally important wetlands, three are located (partially) within Santos

tenement boundaries, two are within 25 km of a Santos tenement boundary, and the rest are 40 km or more from tenement boundaries. Similar to the discussion of the groundwater dependency of waterholes above, it is considered that the wetlands in this region are likely to be sustained by episodic flood events or surface water from the semi-permanent waterholes, as the relatively deep and saline water table aquifer characteristic of the study area is unlikely to sustain the wetlands. Further discussion of the wetlands is provided in Section 2.6.3.1; and

- Nearby national parks include the Lake Bindegolly National Park, west of the town of Thargomindah and the large Innamincka Recreation Reserve in SA, which do not have registered GDEs.

In summary, according to the GDE databases and literature referenced above, the only registered GDEs within the study area are discharge springs located more than 95 km from Santos tenements. These have not been considered further in this report.

2.6.2.5 Proximity of Oil and Gas Targets to Overlying and Underlying Aquifers

The key aquifers identified in the study area are considered to be the following: the Tirrawarra Formation, Patchawarra Formation, Epsilon Formation, Toolachee Formation and Wimma Sandstone of the Cooper Basin; and the Poolowanna Formation (Precipice Sandstone equivalent), Hutton Sandstone, Hooray Sandstone, Cadna-Owie Formation, Winton Formation in the Eromanga Basin (refer to Section 2.5.2).

The general ranges of stratigraphic thickness that separate the aquifers from the nearest hydrocarbon reservoirs are also presented in Table 9.

The average offset between the base of the Hutton Sandstone and the top of the Permian gas reservoirs is between 200 to 300 m, with most of the intervening stratigraphy consisting of very low permeability mudstones and shales. For economic reasons landholder bores will generally access the shallowest beneficial use aquifer, typically being the Glendower and Winton Formations in the study area. The vertical offset between these aquifers and the top of the gas-bearing Permian interval is of the order of 1,400 m to 1,800 m for the Glendower Formation and between 1,000 m to 1,500 m for the Winton Formation.

Across the study area, the typical depth range between the Glendower Formation and the Cadna-Owie Formation in which the shallowest oil reservoirs are present is of the order of 500 m to 1,400 m, and between 400 m to 800 m for the Winton Formation.

Table 9: Stratigraphic Thickness between Hydrocarbon-Bearing Formations and Aquifers

Basin	Stratigraphic Unit	Relative to Nearest Potential Oil/Gas Target Formation	Vertical Distance
Eromanga	*Winton Formation (GAB)*	Wyandra Oil (Upper Cadna-Owie)	400 – 800 m
	Cadna-Owie Formation (GAB)		0 – 90* m
	Hooray Sandstone (GAB)	Murta Oil (Upper Hooray)	0 – 85* m
	Hutton Sandstone (GAB)	Middle Birkhead Oil (Birkhead Formation)	40 - 80 m
	Poolowanna Formation (GAB)		140 – 220 m
		Wimma Gas (Nappamerri Grp)	140 – 200 m
Cooper	*Wimma Sandstone (GAB)*		0 – 115* m
	Toolachee Formation (CB)	Toolachee Gas (Gidgealpa Group)	0 – 190* m
	Epsilon Formation (CB)		<180**

Basin	Stratigraphic Unit	Relative to Nearest Potential Oil/Gas Target Formation	Vertical Distance
		Patchawarra Gas (Gidgealpa Group)	<50**
	Patchawarra formation (CB)		0 – 150 *
	Tirrawarra Formation(CB)		0 - 40 m

GAB = Great Artesian Basin (Eromanga Sub-basin, Triassic-Cretaceous), CB = Cooper Basin (Permian-Triassic),
* maximum thickness of unit (where the nearest gas or oil unit is a sub-unit of the aquifer).
** Maximum (uncertain due to lack of information)

In Table 9, where aquifer formations also contain hydrocarbon reservoirs the vertical range between the aquifer and reservoir formation is indicated as zero up to the maximum thickness of the formation. The water-bearing zones are separated from hydrocarbon reservoirs by intra-formational seals; however, there is not enough information available to discretise the internal stratigraphy of these formations. Where petroleum activities (including stimulation) occur within a formation that hosts both aquifers and hydrocarbon reservoirs, the lateral distance of the water supply bores accessing the aquifer to Santos' tenements was considered.

According to the DEHP database and the interim results of the WBBA program, groundwater supply development in the vicinity of Santos' tenements is limited to the Glendower and Winton Formations, and to a lesser extent the Hooray Sandstone. The minimum vertical offset between these aquifers and the shallowest hydrocarbon reservoirs (oil reservoirs of the Cadna-Owie Formation) is 400 to 800 m, which includes the low permeability formations of the Wallumbilla Formation and Allaru Mudstone, which form a thick, competent and regionally extensive seal between the Cadna-Owie Formation and the shallower aquifers.

The closest beneficial use bore to the Santos tenements targeting the Hooray Sandstone in the DEHP database records is the Coothero Bore, which has a DEHP database recorded depth of 1,165 m, is at least 25 km from the closest tenement proposed for hydraulic stimulation and more than 80 km from the closest tenement with activities proposed at a similar depth (i.e. oil production from the Hooray Sandstone). Santos monitors the Coothero Bore as part of the UWIR monitoring program.

2.6.3 Environmental Values of Surface Water

Specific EVs for the watercourses within the study area are not defined within the EPP (Water) 2009 and there are no detailed local plans relating to environmental values for the catchments.

Based on the land uses present within the catchment area the EVs which would apply to watercourses within the Cooper Creek Catchment are:

- Protection of aquatic ecosystems;
- Recreation and aesthetics: primary recreation with direct contact, and visual appreciation with no contact; and
- Cultural and spiritual values.

The Santos EMPs (March 2014) discuss the cultural and spiritual values of the study area. These are summarised in the UWIR (Golder 2020). The EMPs identify ten sites of Aboriginal cultural heritage significance related to surface water within or in close proximity to the study area. These are presented in the UWIR (2020) and are listed in the Register of the National Estate (RNE) and or the Queensland Heritage Register.

2.6.3.1 Aquatic Ecosystems

The EVs associated with aquatic ecosystems comprise two inter-related aspects:

- The intrinsic value of aquatic ecosystems, habitat and wildlife in waterways and riparian areas – for example, biodiversity, ecological interactions, plants, animals, key species (such as waterfowl or frogs) and their habitat, food and potable water; and
- Waterways that include perennial and intermittent surface waters, groundwater, tidal and non-tidal waters, lakes, storages, reservoirs, dams, wetlands, swamps, marshes, lagoons, canals, natural and artificial channels and the bed and banks of waterways.

As discussed in Section 2.3, water flows in the Cooper Creek vary greatly over time. The Cooper Creek drainage channel system is predominantly ephemeral. Every three to four years a major flood event occurs (Figure 6) and during extended periods of no flow, the Cooper contracts to a series of semi-permanent waterholes, which provide drought refuges for a variety of flora and fauna.

The Cooper Creek Basin is the largest catchment in the Lake Eyre region. This area resides within the Channel Country Strategic Environmental Area and may include threatened plants, birds and marine and estuarine species. Hence, the aquatic ecosystems associated with the waterholes and billabongs that form between flood events are considered to be of high ecological value.

2.6.3.1.1 Wetlands

For the purpose of this study, wetlands are defined as areas of permanent or periodic/intermittent inundation, with water that is static or flowing fresh, brackish or salt (Wetlandinfo, 2012). Wetlands must have one or more of the following attributes:

- at least periodically, the land supports plants or animals that are adapted to and dependent on living in wet conditions for at least part of their life cycle; or
- the substratum is predominantly undrained soils that are saturated, flooded or ponded long enough to develop anaerobic conditions in the upper layers; or
- the substratum is not soil and is saturated with water or covered by water at some time.

The Queensland Wetland Program identifies eleven wetlands of ecological importance and one Ramsar Wetland (Commonwealth of Australia, 2010) within the study area. These wetlands and their proximity to Santos' tenements are summarised in Table 10.

Table 10: Identified Wetlands of National and International Significance in the Study Area

Wetland Name	Reference Number	Area (ha)	Approximate Distance to Santos SWQ Tenement
International Importance [1]			
Currawinya Lakes[1]	43	151,300	130 km E of ATP 1063P
National Importance [2]			
Cooper Creek – Wilson River Junction	QLD027	63,925	Within ATP 1189, PL25 PL133, PL150, PL177, PL208, PL1051 and PL1060
Bulloo Lake	QLD024	83,227	Within ATP 1063P
Cooper Creek Swamps – Nappa Merrie	QLD026	106,311	Within ATP 1189, PL131 and PL146
Lake Yamma Yamma	QLD037	86,548	17 km NE of ATP752 and 25 km W of PL38
Lake Bullawarra	QLD031	1,287	50 km E of ATP765

Wetland Name	Reference Number	Area (ha)	Approximate Distance to Santos SWQ Tenement
Nooyeah Downs Swamps Aggregation	QLD041	6,241	40 km E of ATP765
Lake Cuddapan	QLD033	1,704	61 km NW of ATP1189
Cooper Creek Overflow Swamps – Windorah	QLD025	124,853	20 km N of ATP1189
Lakes Bindegolly and Toomaroo	QLD125	9,677	113 km E of ATP765
Quilpie (Bulloo River FP) water holes	QLD167	30	87 km NE of PL295
Mitchell Swamp	QLD170	500	140 km NE of PL295

1. List of Wetlands of International Importance of the Ramsar Convention
2. A Directory of Nationally Important Wetlands in Australia (Environment Australia, 2001)

2.6.3.1.2 Ecological Investigation of the Study Area

The unpredictable flow regime and spatially complex environment has created a distinctive ecology, with the Cooper Creek Catchment (Section 2.3) providing important habitats for a range of species, especially in times of flood.

Most species of aquatic fauna are well adapted to the extreme flood-drought regime prevailing in the region. Life cycles are completed rapidly during favourable conditions, and temperature, salinity and oxygen tolerances are often high. Several species are highly dependent upon the refuge habitat provided by permanent waterholes for survival during the long droughts that regularly occur in the region.

A brief overview of the biology of the study area, as evidenced from the field surveys undertaken to better understand the implications of the Commonwealth EPBC Act 1999 (Carpenter and Armstrong, 2001 and 2002; Santos 2003), is summarised below:

- Aquatic Flora: No rare or threatened species of aquatic flora have been recorded from the waterways in the oil and gas fields;
- Aquatic Macroinvertebrate Communities: Several species of crustaceans inhabit the creeks and waterholes of the Cooper Basin. They are dependent upon permanent water for survival, and generally retreat to permanent waterholes during droughts. Some species, however, can survive for prolonged periods, buried in the dry bed of creeks and waterholes. Species include freshwater crabs, the common yabby, shield shrimps, freshwater shrimps and freshwater mussel;
- Fish Communities: Most of the fish species within the study area can tolerate a large range of water quality conditions. Golden perch, mosquito fish, western carp-gudgeon and central Australian catfish are tolerant species that can live in water characterized by low DO levels, high salinity and relatively high turbidity;
- Waterfowl: Sixteen species of waterbird were surveyed near water holes along the flood plain. These include the pink eared duck, glossy ibis and brolga. Brolga is a large silvery-grey waterbird with a red face and nape and is listed as vulnerable. It inhabits shallow lakes, swamps, wet grasslands and dry land adjacent to these areas.

2.6.3.2 Recreational Values

The Cooper Creek Catchment is a popular recreational fishing destination. Fishing for golden perch and catching common yabby are popular within the study area in:

- the waterholes of the Bulloo River at Thargomindah;
- the Wilson River at Nockatunga; and
- Cooper Creek, in the channel country (Bulloo Shire Council, 2012).

The portion of the Cooper Creek system in South Australia, downstream of Cooper Basin, is a popular destination for tourists from all over the world. With only a few permanent waterholes in South Australia section of the Cooper Creek system, fish must survive droughts by colonising as many temporary waterholes as possible during the Cooper Creek catchment flood events (Section 2.3).

2.6.3.3 Proximity of Santos Tenements to Surface Water with Environmental Values

The proximity of Santos tenements and proposed petroleum activities to surface water EVs are described below:

- *Aquatic Ecosystems* – The proximity of aquatic ecosystems to Santos' tenements are described in detail in Section 2.6.3.1 and illustrated in Figure 29. Cooper Creek, is largely influenced by surface water flows and evaporation, with negligible contribution from groundwater. Waterholes and billabongs occur throughout the Cooper Creek floodplain and channel complex, some of which coincide directly with Santos tenements;
- *Wetlands* – As indicated in Table 10 reveals that three of the identified wetlands (Cooper Creek – Wilson River Junction, Bulloo Lake and Cooper Creek Swamps – Nappa Merri) are within boundaries of Santos' tenements. It should be noted that stimulation activities may be completed within any tenement boundary over the life of the Project;
- *Recreational Values* – The Cooper Creek catchment and downstream Lake Eyre are popular recreational fishing destinations. The proximity to popular fishing spots from Santos activities are listed below:
  - Bulloo River at Thargomindah is 55 km from the Santos tenement boundaries, and 90 km to the closest active lease area; and
  - Cooper Creek flows (episodically) through some of the western tenements.

These wetlands, waterholes and rivers with ecological and recreational values are identified and spatially managed in a DEHP GIS database of Environmentally Sensitive Areas (ESAs), a copy of which was provided to Santos for all of their tenements. The ESAs form a routine part of the constraints analysis in the planning of all Santos well leases and associated disturbance proposals in SWQ. Prior to any greenfield disturbance, or subsequent re-disturbance, a Santos Environmental Advisor or external ecologist inspects the site for potential environmental impact. The resultant assessment, and any recommendations for mitigation, is managed via the Santos *Environmental Approval Request Tracking Form* (EART). Approval conditions must be accepted by the relevant project proponent prior to any physical works occurring.

2.6.4 Terrestrial Environmental Values

For the purpose of this assessment, terrestrial environmental values are considered to comprise the native flora and fauna of the study area. Based on information obtained from the SEWPaC (now referred to as DoEE) IBRA (online at: http://www.environment.gov.au/parks/nrs/science/bioregion-framework/ibra/index.html), three biogeographical regions cover the study area, as follows:

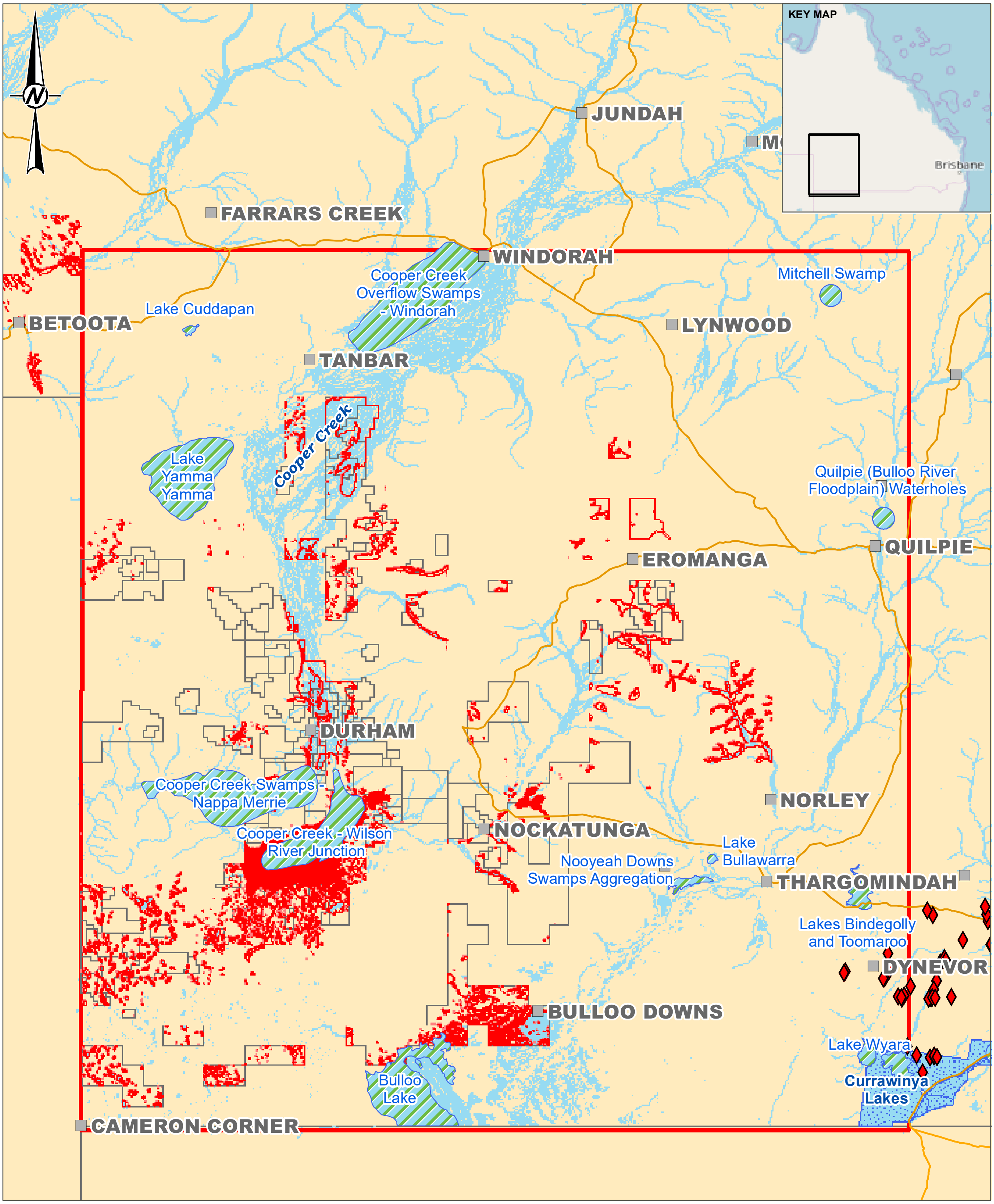
- Channel Country, which covers the central portion of the study area and is characterised by vast braided, flood and alluvial plains surrounded by gibber plains, dunefields and low ranges. Native vegetation is predominantly Mitchell grass, gidgee and spinifex, and various weeds are known to exist in the area. The region is predominantly used for stock grazing (approximately 91%) and is home to several invasive animals. Native species are abundant and include red, eastern, and western grey kangaroos, with various marsupials and reptiles adapted to the variable ecosystems ;
- Mulga Lands, which covers the eastern portion of the study area and is characterised by flat to undulating plains with outcrops of low ranges and tablelands. The dominant native vegetation types are mulga and eucalypt woodland, with some weed species well established particularly where grazing occurs. The region is predominantly used for stock grazing (approximately 94%) and is home to several invasive animals, but also supports an assemblance of diverse native species; and

- Simpson Strzelecki Dunfields, which covers the southwest corner of the study area and comprises long parallel sand dunes, fringing dunefields, extensive sand plains, ephemeral watercourses and saltpans. Vegetation is predominantly spinifex hummock grasslands with sparse acacia shrublands and some narrow river red gum and coolibah riverine woodlands. The region is partially used for stock grazing (approximately 49%) and is home to several invasive animals, as well as highly adapted native species.

A study area specific report generated from the interactive EPBC Act Protected Matters Search Tool (http://www.environment.gov.au/epbc/pmst/index.html, assessed 2012) indicated matters of national environmental significance, as follows:

- Threatened species including 5 birds, 1 fish, 6 small and medium sized mammals, 1 reptile and 8 plants;
- Migratory species including 3 marine birds, 2 terrestrial birds and 6 wetland birds;
- Listed species including 9 birds;
- Indicative and registered indigenous and historic areas;
- Reserves and wetlands; and
- Invasive plant and animals.

It is considered that some of these terrestrial environmental values could be in close proximity to Santos stimulation activities. Consistent with before mentioned procedures, prior to greenfield disturbance, or subsequent re-disturbance, a Santos Environmental Advisor or external ecologist inspects the site for potential environmental impact. The resultant assessment, and any recommendations for mitigation, is managed via the Santos Environmental Approval Request Tracking Form (EART). Approval conditions must be accepted by the relevant project proponent prior to any physical works occurring.



LEGEND

- GAB ROP Discharge Spring
- GAB ROP Recharge Spring
- Town/Locality
- Highway/Major Road
- River/Creek
- Nationally Important Wetland
- Ramsar Site
- Constraint Areas
- ESA (Primary)
- ESA (Secondary)
- Santos Tenements
- Study Area

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1:2,500,000 GCS GDA 1994

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019

CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
ENVIRONMENTALLY SENSITIVE AREAS IN TENEMENTS WITHIN THE SANTOS STUDY AREA

CONSULTANT

GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
127666004	011-R	2	29

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3.0 STIMULATION PROCESS

3.1 Introduction

The description of the stimulation process is covered under the following headings:

- Description of the oil-bearing units and the oil they contain;
- Description of the gas-bearing units and the gas they contain;
- Purpose of the stimulation process;
- Description of the stimulation process;
- How is stimulation carried out;
- Infrastructure and equipment used;
- Stages of stimulation;
- Assessment techniques for determining extent of stimulation activities;
- Practices and procedures used to ensure fracture remains in target zone;
- Program for wells to be stimulated;
- Frequency of stimulation;
- Distribution of wells stimulated to date and to be stimulated;
- Location of landholders' active bores; and
- Chemical constituents in acid and stimulation package.

3.2 Well Design and Stimulation - General Considerations

Prior to considering the practice of stimulation to enhance conventional oil and gas well production, two important matters require addressing in accordance with the requirements anticipated of the EA conditions that will apply to new areas proposed for production, namely:

- Comparison to *international best practice* –the procedures employed by Santos' and its contractors follow a design philosophy predicated on the guidance, specifications and recommended practices of the American Petroleum Institute (API), considered to represent international best practice;
- *Well mechanical integrity and surveillance* – the procedures employed by Santos' and its contractors for mechanical integrity and surveillance follow a design philosophy with international best practice. Practices for ensuring well mechanical integrity consist of a robust surveillance plan, which includes;
  - *Well integrity checks including casing pressure surveys, downhole isolation checks (where applicable), casing top-ups with inhibited fluid and casing pressure tests.*
  - *Operator surveillance involving quarterly casing pressure surveys and visual inspections.*
  - *Wellhead maintenance requiring valve function testing and maintenance.*
  - *Cement integrity involving acoustic logging and casing pressure tests.*

3.2.1 Comparison to International Best Practice

Within Australia and the world, the oil and gas industry is reliant on a number of experienced stimulation contractors.

These contractors, along with operating companies, have developed and defined industry best practices in the field of stimulation. These practices have been transferred to applicable operations in Australia.

These practices have been developed over 60 years using experience and technological innovation. These experiences and practices are communicated and shared via academic training, professional and trade associations, extensive literature and documents and, importantly, industry standards and recommended practices.

The industry best practice guidelines, arising from this body of knowledge, experience and leading edge research, are distilled in a series of guidance documents published by the API. It should be noted that API Technical Reports (TRs) and Recommended Practices (RPs) are not legal requirements and the use of these documents is voluntary. The key guidance documents relevant to the contractor's operations in the SWQ oil and gas fields of the Cooper Basin include:

- API Guidance Document HF1, *Hydraulic Fracturing Operations – Well Construction and Integrity Guidelines*
- API Guidance Document HF2, *Water Management Associated with Hydraulic Fracturing*
- API Guidance Document HF3, *Practices for Mitigating Surface Impacts Associated with Hydraulic Fracturing*
- API Specification 5CT/ISO 11960, *Specification for Casing and Tubing*
- API Specification 6A/ISO 10423, *Specification for Wellhead and Christmas Tree Equipment*
- API Specification 10A/ISO 10426-1, *Specification for Cements and Materials for Well Cementing*
- API Recommended Practice 10B-2/ISO 10426-2, *Recommended Practice for Testing Well Cements*
- API Recommended Practice 10B-3/ISO 10426-3, *Recommended Practice on Testing of Deepwater Well Cement Formulations*
- API Recommended Practice 10B-4/ISO 10426-4, *Recommended Practice on Preparation and Testing of Foamed Cement Slurries at Atmospheric Pressure*
- API Recommended Practice 10B-5/ISO 10426-5, *Recommended Practice on Determination of Shrinkage and Expansion of Well Cement Formulations at Atmospheric Pressure*
- API Recommended Practice 10B-6/ISO 10426-6, *Recommended Practice on Determining the Static Gel Strength of Cement Formulations*
- API Specification 10D/ISO 10427-1, *Specification for Bow-Spring Casing Centralizers*
- API Specification 10D-2/ISO 10427-2, *Recommended Practice for Centralizer Placement and Stop Collar Testing*
- API Recommended Practice 10F/ISO 10427-3, *Recommended Practice for Performance Testing of Cementing Float Equipment*
- API Technical Report 10TR1, *Cement Sheath Evaluation*
- API Technical Report 10TR2, *Shrinkage and Expansion in Oil Well Cements*
- API Technical Report 10TR3, *Temperatures for API Cement Operating Thickening Time Tests*
- API Technical Report 10TR4, *Technical Report on Considerations Regarding Selection of Centralizers for Primary Cementing Operations*
- API Technical Report 10TR5, *Technical Report on Methods for Testing of Solid and Rigid Centralizers*
- API Specification 13A /ISO 13500, *Specification for Drilling Fluid Materials*
- API Recommended Practice 13B-1/ISO 10414-1, *Recommended Practice for Field Testing Water-Based Drilling Fluids*
- API Recommended Practice 13B-2/ISO 10414-2, *Recommended Practice for Field Testing Oil-based Drilling Fluids*
- API Recommended Practice 45, *Recommended Practice for Analysis of Oilfield Waters*
- API Recommended Practice 53, *Blowout Prevention Equipment Systems for Drilling Operations*
- API Recommended Practice 65, *Cementing Shallow Water Flow Zones in Deep Water Wells*
- API Recommended Practice 65-2, *Isolating Potential Flow Zones During Well Construction*
- API Recommended Practice 90, *Annular Casing Pressure Management for Offshore Wells*

The stimulation contractors operating in Australia and used by Santos currently follow the intent and detail of these guidance documents as they apply to the site-specific conditions for each hydrocarbon bearing field. In conjunction with these activities, other stimulation technologies are also being used, such as use of pneumatic techniques (gases, such as CO_2) to fracture the sandstone hydrocarbon reservoirs. The process of researching alternate methods is an ongoing process, and descriptions and results of trialled alternative methods will be provided as the findings become available and are considered field-ready.

3.2.2 Well Mechanical Integrity and Integrity Testing

3.2.2.1 Background

One of the major controls in providing a high degree of protection to the Cooper and Eromanga aquifers is through robust well design, well construction, and scheduled integrity checks throughout the lifecycle of the well i.e. from production to abandonment. Quality control procedures are implemented through the material selection, sourcing process, installation as well as maintenance and checks to ensure the casing and seals are adequate barriers for hydraulic isolation.

A properly designed production well provides full containment of hydrocarbons within its internal casing and/or completion conduit from the subsurface to the surface and affords:

- Protection of groundwater resources;
- Protection to the environment; and
- A safe working and operable environment.

Full containment is achieved by cementing in place multiple strings of steel casing and installing mechanical plugs or packers after a well is drilled to depth. The primarily objective of the well design is to prevent communication with aquifer systems and cross flow of fluids (gas, oil and water) between sedimentary layers. Of particular note is that important casing design parameters are factored to ensure that the well's integrity is maintained during the high treatment pressures imparted during fracture stimulation. Examples of specified casing parameters include pipe weight, metallurgy, burst and yield pressures.

In addition to the subsurface well construction, the surface well head integrity is of equal importance to ensure hydrocarbon containment. A properly designed wellhead ensures that the control measures (or barriers) are in place for well production, but more critically, that the well can be secured and isolated in events such as an uncontrolled release of hydrocarbons to atmosphere. Santos has embedded Standards and Procedures (EHSMS 11.5, AIMS and PESP 9.1, Santos 2009) to ensure that integrity controls and measures have been performed prior to stimulation. Typically, this would involve running a cement bond log to check the quality of the cement and/or pressure testing of the internal and annular sides of the well.

The hydrocarbon reservoirs are accessed through perforations in the steel casing and cement sheaths opposite the respective reservoir zones, with the produced oil and gas contained within the well casing all the way to the surface. This *containment* and barrier philosophy along with continued zonal isolation is what is meant by the term “well integrity.” Should an issue with casing be identified, fracture stimulation is postponed until the well is remediated. If remediation of the well is physically or economically unfeasible, the well is completed without fracture stimulation or plugged and abandoned to regulatory specifications.

Routine integrity checks are scheduled while the well is on production in accordance with the well design, well plan, and permit requirements, until such time that the well is abandoned.

NOTE: The discussion of well integrity has been drawn from discussions and information provided by Santos and supplemented by information directly sourced from API HF1 (API, 2009). The reader is urged to consult this document for a detailed description of the well completion process.

3.2.2.2 Drilling and Well Completion

Drilling a typical oil or gas well consists of several cycles of drilling, running casing (steel casing for well construction), and cementing the casing in place to ensure isolation. In each cycle, steel casing is installed in sequentially smaller sizes inside the previous installed casing string. The last cycle of the well construction is well completion, which can include perforating (creating holes in the steel casing) and stimulation or other techniques depending on the well type and formation characteristics.

The main stages of drilling and completing a well comprise:

- Lease preparation;
- Rigging up of major drilling equipment (e.g. tanks, pumps, rig, draw works, hydraulic and power packs);
- Drilling the surface hole;
- Cementing in place the surface casing;
- Installation of the Bradenhead and Blow Out Preventor (BOP);
- Running in to continue drilling in the production hole to depth;
- Petrophysical logging of the open borehole section;
- Cementing in place the production casing;
- Securing the well and rig release;
- Cased hole logging (for well integrity);
- Installation of wellhead or Frac Tree;
- Perforation of the first zone in preparation for stimulation;
- Fracture stimulation and initial flowback of well;
- Installation of artificial lift (if necessary);
- Installation of the final completion design;
- Installation of production well head, flowlines and telemetry;
- Well on production;
- Monitoring of well's production and integrity checks; and
- Rehabilitation of surrounding well's lease.

3.2.2.3 Selection and Sourcing of Casing Materials

To ensure long term casing integrity, Santos has developed detailed specifications for all well casings and well completion materials. The casing materials are specifically rated to handle stimulation treatments at Permian depths and pressures. Parameters such as yield and burst pressures are specified and triaxial load modelling are sometimes performed to ensure that the well's integrity is maintained during the high treatment pressures applied during fracture stimulation and for the lifecycle of the well.

All materials are inspected by Santos and the contractors prior to installation to ensure compliance with the Santos specifications. A similar process of inspections and testing are utilised throughout the drilling and casing installation program. This testing and inspection is discussed in the sections below.

3.2.2.4 Logging the Borehole

All of Santos oil and gas wells are routinely logged with tools to obtain specific information on the hydrocarbon bearing reservoirs. The results of these logs are used as important indicators that aid in fracture target selection.

Open-Hole Logging

Once the production hole/reservoir section is drilled to final depth, open-hole logging tools are run on wireline to obtain petrophysical information. A typical suite of electric logging tools would include the following:

- *Gamma Ray*: a receiver tool that detects natural radiation from rock. The main isotopes of thorium, potassium, and uranium can indicate the presence of clay mineralogy;
- *Laterolog*: tools which measure the resistivity of the fluids contained in the rock. This is used as an indication of water bearing zones. Higher resistivity values can be an indication of hydrocarbon bearing zones;
- *Spontaneous Potential (SP log)*: measures the salinity contrast between mud filtrate and formation water. This data can be used to assess permeability and potentially some information on lithology;
- *Density Tool*: measures the bulk density of the rock and indicates the presence of porosity;
- *Neutron Tool:* a source/receiver tool which measures rock porosity;
- *Calliper Tool*: measures hole diameter and can provide an indication of borehole geometry. Useful in terms of planning for casing running and cementing design; and
- *Sonic Tool*: a source/receiver tool measuring the transit time of acoustic waves passing through the rock. This data can be used as an indicator of porosity but is primarily used for geomechanical calculations, including minimum horizontal stress. This is a key value required in hydraulic fracture stimulation design.

Logging produces detailed information on the rock formations drilled and the water and hydrocarbons they might contain. This assists with installation of casing strings to the correct depth in order to achieve the well design objectives and to properly achieve the isolation benefits of the casing and cement sheath.

Many other types of logging tools are available and may be run on a case specific basis such as cased hole evaluation logs in place of open hole logs.

Cement Integrity (Cased-Hole) Logging

After cementing the casing in place (refer to Section 3.2.2.5), “cased-hole” logs can be run inside the casing to validate the quality and integrity of the cement sheath bond to the casing. Typically, these logs include the following:

- gamma ray (described previously);
- casing collar locator (CCL; a magnetic device that detects the casing collars); and
- cement bond log (CBL), segmented bond tool (SBT) and variable density log (VDL) that measures the acoustic properties of the cement sheath and the quality of the cement bond or seal between the casing and the formation.

The CBL-VDL or SBT is an acoustic device that can detect cemented or non-cemented casing. These acoustic devices work by transmitting a sound or vibration signal, and then recording the amplitude of the arrival signal. Casing that has no cement surrounding it (i.e. free pipe) will have large amplitude acoustic signal because the energy remains in the pipe. Casing pipe that has a good cement sheath (fills the annular space between the casing and the formation) will have a much smaller amplitude signal since the casing is “acoustically coupled” with the cement and the formation causing the acoustic energy to be absorbed.

Santos uses experienced contractors to identify the key features of the cement operation to ensure the integrity of the cement seal for each casing pipe sheath. The cased-hole logs are also useful when the well is perforated to position the perforating guns with respect to the formations (by comparing with the gamma-ray response of the open-hole log and the CBL).

Santos most commonly uses the CBL-VDL or SBT cement evaluation logs to evaluate cement integrity, however other types of cement evaluation tools are available and, depending on the situation, are considered as a part of the cement evaluation program.

A key result of the cased-hole logging program is to know the exact location of the casing, casing collars, and quality of the cement relative to each other and relative to the subsurface formation locations. This ensures that the well drilling and construction is adequate and achieves the desired design integrity and longevity objectives. It is also used to provide information in subsequent surveys of well integrity and seals over the production life of the production well.

3.2.2.5 Casing Design

A casing completion design is prepared by the engineering team based on rock cuttings and/or borehole core retrieved from the drilling of the well hole; information gained from geophysical logging of the borehole; the regional geological model; reservoir analysis; and the history of nearby wells. Historical problems encountered in the area (lost returns, irregular hole erosion, poor hole cleaning, poor cement displacement, etc.) are considered during the design process. A typical casing design is illustrated in Figure 30.

The basis of the site-specific design for the casing construction emphasises barrier performance and zonal isolation (including aquifer, low quality groundwater and poor ground isolation), as well as gas and oil production efficiency. It includes wellbore preparation, mud removal, casing pipe running (Section 3.2.2.6), and cement placement (Section 3.2.2.7) to provide barriers that prevent fluid and gas migration and well leakage. The well design process also includes contingency planning to mitigate the risk of failure due to unforeseen events.

The casing design process also accommodates analysis of those factors which determine the stimulation outcomes. These include defining the optimal location and orientation of perforations such that the zone of stimulation is contained entirely within the target hydrocarbon-bearing formations. The latter involves the assessment of borehole core, porosity analysis, fracture orientation and density testing, joint orientation, bedding plane analysis and stress field analysis.

3.2.2.6 Casing Completion

The first borehole drilled is for installing the conductor pipe (Figure 30). This is followed by drilling a series of sequentially deeper boreholes for installation of the various casing pipes as follows: surface casing, intermediate casing (if necessary), and the production casing. Specific considerations for each of these casing strings are presented below. It is important to note that the shallow portions of the well have multiple concentric strings of steel casing installed.

- The *conductor casing* stabilises the surficial sediments from the drilling action of subsequent drilling phases (prevents the loose soils from caving into the borehole) and is cemented into place to ensure an appropriately robust seal (up to ground level). Is also serves to isolate the surface water table and perched aquifers, if present;
- The *surface casing* is typically installed to protect the shallow formations (weathered or unconsolidated rock layers) and to stabilise the well from the later drilling phases of deeper sections of the borehole. This portion of the well completion can extend from 30 m to 60 m depth. This casing pipe is also cemented into place to ensure an appropriately robust seal, with cementing taking place from bottom to top to ensure an effective seal. The surface casing is designed to achieve all regulatory requirements for isolating groundwater and also to contain pressures that might occur during the subsequent drilling process;
- The *intermediate casing* pipe may be installed to isolate deeper aquifer systems (if present), for example, the Wallumbilla Formation may be cased off to reduce the risk of impact to this layer. As with the shallower casing strings, this casing pipe is also cemented into place to ensure an appropriately robust seal, again with cementing taking place from bottom to top to ensure an effective seal. A formation pressure integrity test is performed immediately after drilling out of the intermediate casing;
- After the production hole is drilled and logged, *production casing* pipe is lowered to the total depth of the borehole and cemented in place (total depth is typically 10 m to 20 m below the base of the lowermost hydrocarbon-bearing unit, but not penetrating the underlying aquifer systems, if present). The purpose of

the production casing is to provide the final isolation between the hydrocarbon reservoirs and all other overlying formations, and for containing and pumping the various fluids used to stimulate the target zones from the surface into the producing formation without affecting the shallower layers penetrated by the well. It also houses the downhole production pumping equipment (oil wells) when the well becomes operational. During the operational phase of the well, its most important function is internally containing the hydrocarbons produced from the oil and gas units.

The production casing pipe is pressure cemented, from bottom to top, to achieve robust and effective isolation of the well from the various subsurface layers (aquifers and aquitards alike):

- Prior to perforating and stimulation operations, the production well casing is pressure tested. This test should be conducted at a pressure that is greater than what is expected during stimulating and operations, to ensure that the casing integrity is adequate. A CBL, VDL and/or other diagnostic tools are run to establish that the cement integrity is satisfactory for the completion and operational conditions designed for the wells life (see Section 3.2.2). Remedial cementing operations are implemented if there is evidence of inadequate cement integrity: and
- Santos is increasingly moving to *deviated* and potentially *horizontal* production wells to reduce the oil and gas fields' footprint (multiple horizontal wells from a single surface location, thereby, reducing the cumulative surface impact of the production operation). Selection and use of these techniques are in its infancy and trials are currently underway.

Casing pressure tests are carried out at each stage to ensure integrity of the casing pipe for further drilling or operational conditions. These tests are conducted at pressures that will determine whether the casing integrity is adequate to meet the well design and construction objectives.

3.2.2.7 Cementing

Cement types, additives and mixes are higher quality materials produced specifically for oil and gas operations. Materials are selected and designed to address site-specific conditions relevant to a particular well. Cement mixtures and installation techniques are employed to provide a robust seal that isolates the well from the surrounding formations and protects the well materials from potentially aggressive groundwater or formation conditions. The cements are not typical building/construction cements, but are tailored cements designed for use in well construction and the subsurface conditions encountered.

Cement is placed using appropriate centralising equipment to completely surround the casing pipe to create a hydraulic seal against the rock face of the borehole, thereby achieving pipe integrity. Effective isolation of the well pipe from the various subsurface formations requires complete and even annular filling and tight cement interfaces with the formation and casing.

Following the casing design, these materials selection and cement procedures are typically implemented at Santos well casing completion sites:

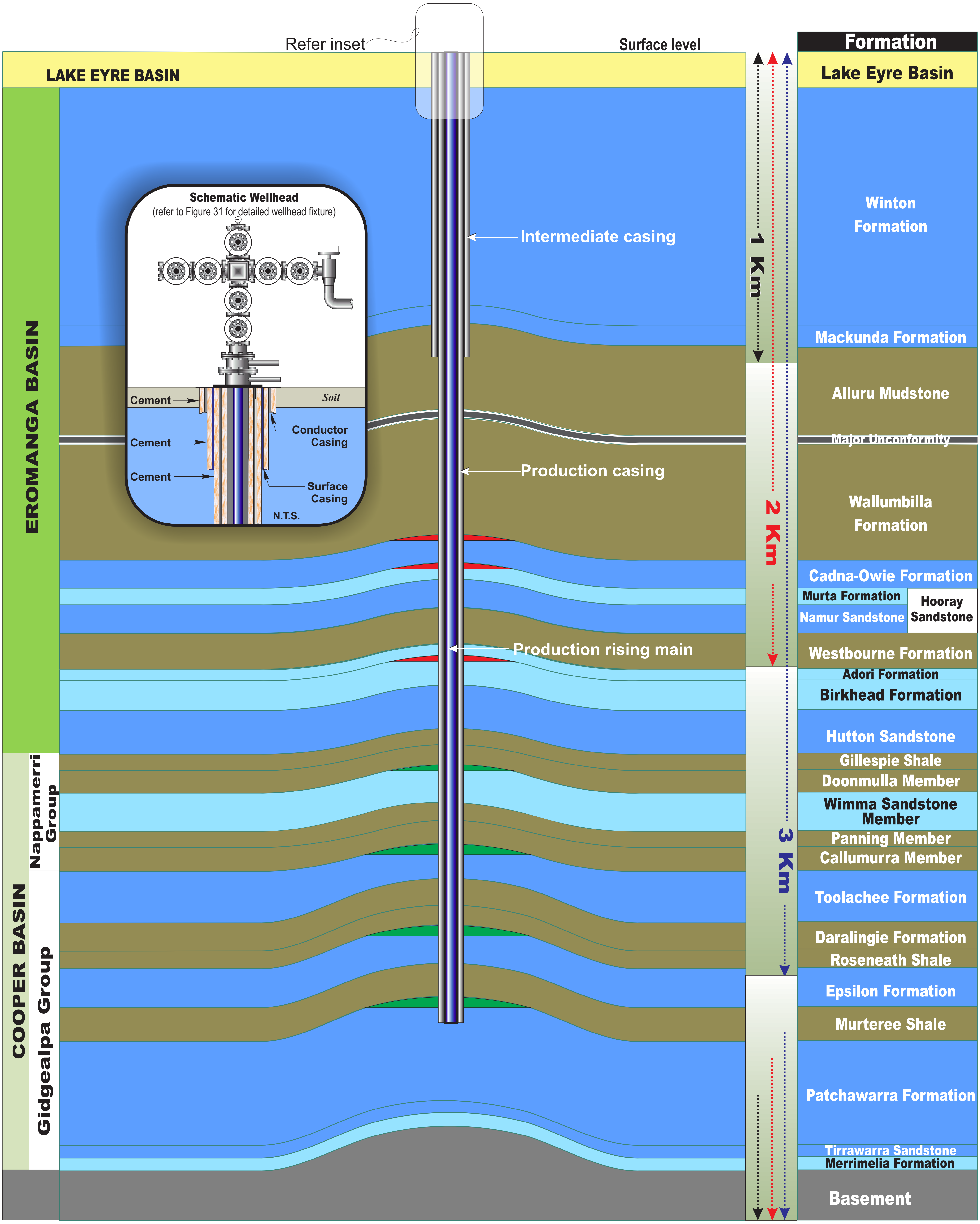
- Computer simulation and completion planning is carried out to optimise cement placement procedures;
- Santos drilling contractors are selected based on their reputation, and their adherence to industry best practice methods and regulatory requirements. Importantly, as it affects cementing, they are required to use established, effective drilling practices to achieve a uniform, stable well borehole with the desired hole geometry. Additionally, they are required to satisfy Santos health-safety-environmental (HSE) requirements with regard to their personnel and equipment. They are required to ensure that their cementing equipment provides adequate mixing, blending, and pumping of the cement in the field;
- Santos drilling contractors are required to ensure that the drilling fluid selection is appropriate for the designed well and the geologic conditions likely to be encountered, and present a low risk to the environment;
- Site drilling and cementing equipment are selected to adequately achieve the well design that will meet the well design objective and ensure effective isolation;

- Santos drilling contractors are required to employ casing pipe centralisers to help centre the casing pipe within the borehole and provide for good mud removal and cement placement, especially in critical areas, such as hydrocarbon-bearing zones, and groundwater aquifers;
- Santos cementing contractors are required to use appropriate cement testing procedures to ensure cement slurry quality and designs are adequate. These include implementation of appropriate cement slurry quality controls - with testing to measure the following parameters depending on site-specific geological and groundwater quality conditions:
  - slurry density;
  - thickening time;
  - fluid loss control;
  - free fluid;
  - compressive strength development;
  - fluid compatibility (cement, mix fluid, mud).
  - sedimentation control;
  - expansion or shrinkage characteristics of the set cement;
  - static gel strength development;
  - mechanical properties (e.g. Young's Modulus, Poisson's Ratio, elastic/compressibility characteristics); and
- Cement design may include placement in two stages, using a "lead" cement of lower density and a "tail" cement of higher density and compressive strength.

Appropriate setting times are adhered to ensure that the cement seals are optimal prior to further drilling, stimulation and/or operational testing. The cement is tested using specific quality assessment and quality control (QA/QC) procedures such as circulation testing and logging as outlined in Section 3.2.2.4.

3.2.2.8 Well Completion Design

The final well completion is not typically run until after fracture stimulation, although there are situations where it is run before the well is stimulated. Completions design is the process of running in of a separate piece of pipe or conduit in the already cased well. This pipe is secured with mechanical packers above the producing zones and is usually performed with a separate Completions/ Work Over Rig. The purpose of the final completion string is to allow the hydrocarbons to produce from it, but on a well integrity perspective, it acts as the secondary barrier control such that if the primary barrier (being the casing) fails, there is not an uncontrolled release of hydrocarbon to surface.



Key

- Aquifer
- Water Bearing
- Confining Bed
- Gas Accumulation
- Oil Accumulation

Source: Stratigraphy and scale based on DMITRE, 2012. Road map for unconventional Gas Projects in South Australia. Energy Resources Division, April 2012.

GOLDER www.golder.com GOLDER ASSOCIATES PTY LTD	CLIENT SANTOS			PROJECT SWQ HYDRAULIC FRACTURING RISK ASSESSMENT				
	DRAWN HC	DATE 16.11.2012		TITLE CONCEPTUAL CONVENTIONAL OIL OR GAS WELL CONSTRUCTION DETAIL				
	CHECKED RS	DATE 19.12.2012						
	SCALE VERTICAL SCALE: AS SHOWN HORIZONTAL SCALE: N.T.S.		A3	PROJECT No. 127666004	DOC No. 011	DOC TYPE R	FIGURE No. F030	REV No. 0 FIGURE 30

3.3 Description of the Stimulation Process

3.3.1 Introduction

This section describes the process of hydraulically fracturing/stimulating a conventional oil or gas well, including:

- Description of the reservoir formations and the hydrocarbons they contain;
- Purpose of the stimulation process;
- Description of the stimulation process;
- Infrastructure and equipment used;
- Stages of stimulation;
- Assessment techniques for determining extent of stimulation activities;
- Practices and Procedures used to ensure fracture remains in target zone;
- Program for wells to be stimulated;
- Frequency of stimulation;
- Distribution of wells stimulated to date and to be stimulated; and
- Chemical constituents in stimulation fluid systems.

3.3.2 Description of Hydrocarbon Reservoir Formations in the Study Area

3.3.2.1 Conventional Gas

Conventional gas is mostly methane and is produced predominantly from stacked sands of the Toolachee and Patchawarra Formations (Gidgealpa Group), which lie within the Cooper Basin. The fluvial sandstone reservoirs are separated by shales and coals, which act as intra-formational seals (refer to detailed stratigraphy in Section 2.4). Minor gas production also occurs from other sediments within the Gidgealpa Group (e.g. the Epsilon Formation), from various localised sediments within the overlying Nappamerri Group (also part of the Cooper Basin) and from the Hutton Sandstone (within the Eromanga Basin). Generally, however, the Nappamerri Group shales act as a regional top-seal for gas.

The gas is predominantly stored as free gas within pore spaces in the sandstone reservoirs. Much of the porosity found in sandstone reservoirs is preserved primary intergranular porosity. The sandstone reservoirs often have low permeabilities (usually of the order of 1 to 10 milliDarcies, equivalent to a hydraulic conductivity range of 10^{-2} to 10^{-3} m/d), such that fracture stimulation is essential in order to achieve economic flow-rates and production volumes. Under the natural confining pressure of a typical reservoir the gas exists in a near liquid state.

A key element that distinguishes conventional gas production from CSG production is that conventional sandstone reservoirs do not require the depressurisation of the target beds (with respect to groundwater). When a conventional gas well is completed with its final production string, pressure drawdown (i.e. differential pressure between the reservoir and wellbore) is created by opening up the well to the gathering system. Gas is then able to flow by virtue of the conductive path to the well via the formation’s permeability. In general, most gas reservoirs naturally deplete through a gas expansion drive mechanism. In contrast to the drive mechanisms associated with oil reservoirs and unconventional coal bed methane reservoirs, the drive mechanism in conventional gas reservoirs are such that gas will move from high pressure in the reservoir to low pressure at surface without the aid of mechanical lifting devices.

3.3.2.2 Conventional Oil

The conventional oil reservoirs in the study area are associated with sandstone formations of the Eromanga Basin. The oil is present in discontinuous oil reservoirs within interbedded sandstones beds or larger sandstone formations (in the sandstone units of the Cadna-Owie, Hooray Sandstone and Birkhead formations); with reservoirs typically comprising structural and sedimentary traps (Section 2.4.3.4).

The sandstone reservoirs are generally interbedded with shales, mudstones, siltstones and coals, which act as intra-formational seals. The primary oil reservoir formations are separated by low permeability formations comprising shale-mudstones-siltstones-sandstone assemblages of the Eromanga Basin, themselves situated at depth within a thick sequence of highly variable sedimentary rock types (Table 3).

The porosity found in oil sandstone reservoirs is preserved primary intergranular porosity. Water and oil commonly occur together, having a film of water separating the pore boundaries from the oil. Oil reservoirs that lack a film of connate water at pore boundaries can occur but are rare.

Oil production wells generally do not free flow, so gas lift is typically used to aid oil or condensate production. The produced water is separated from the oil and treated and is typically used in water flooding activities to restore and maintain reservoir pressure and enhance production (Figure 28; Golder, 2012a).

3.3.3 Purpose of the Stimulation Process

Hydraulic stimulation is employed in the petroleum industry to improve the production efficiency of many gas and oil producing wells. This is achieved by creating an area of increased conductivity within the reservoir. This increased reservoir contact, through a highly permeable fracture, creates an efficient pathway for the flow of gas and oil. In the majority of cases, the low permeability nature of the hydrocarbon bearing reservoirs are too tight to produce from at economic rates and without this increased flow potential many of the gas wells within the Cooper Basin could not sustain economic flow rates.

Santos include conventional fracture stimulation as part of the final completion process. Once the production casing is cemented, cement evaluation has occurred, and a frac tree is installed at the surface; the stimulation operation can begin. Perforations are placed across the required interval of the reservoir formation and the surface fracturing equipment is rigged up and tied-in to the well.

Production wells may be subject to multiple stimulation events during the completion process. In order to produce from all of the reservoirs intersected by a well, Santos uses methods to selectively isolate and individually stimulate each hydrocarbon-bearing zone. As a result, a typical gas well will have more than one stimulation treatment and the current average is about six treatments per well. The typical Santos oil well will rarely have more than one stimulation treatment due to the limited number of oil reservoirs and the fact that oil-bearing formations are not as dependent on stimulation to be commercially viable.

The subsequent sections describe stimulation design and the stimulation process.

3.3.4 Stimulation Treatment Design Considerations

As discussed in detail in Section 3.2, drilling, open hole and cased hole logging of the reservoir section provides information useful in the stimulation design process. Data is acquired providing information on reservoir parameters, as well as lithology variations and stress contrast from layer to layer. All of this data is used within an industry accredited stimulation software to develop an optimal design.

The basis of well specific design is to exploit the reservoirs through an optimal number of stimulation stages, fracture length, fracture conductivity, and fracture height within the targeted reservoir formation. A number of considerations influence the final design for each fracture design:

- Depth and thickness of the target zone;
- Lithology of target and bounding layers;
- Minimum horizontal stress across all layers (target and bounding);
- Thickness of the ‘seals’ (aquitard layers) above and below the target reservoir formation;
- Porosity and permeability;
- Pore fluid saturations (percentage of pore volume occupied by each fluid e.g. oil, gas or water);
- Pore fluid properties (e.g. density, water salinity);
- Well performance data, including flow rates, formation pressure and produced fluid properties;
- Formation boundaries (as identified from seismic data);
- Bulk density, elastic properties and compressibility;
- Bedding planes, jointing and mineralisation;
- Thickness of underlying formations and rock strength; and
- Stress field analysis to determine the maximum principle stress direction and the minimum principle stress direction.

The completion design process accommodates detailed analysis of these parameters to specify a stimulation design that provides containment within the target formation. The stimulation design models can model the fracture geometry; including fracture length and fracture height based on the geomechanical rock properties input into the model. The models do not predict the fracture orientation; however, Santos has regional stress information that is used to predict the fracture orientation across the basins. There is an increased use of micro-seismic sensing within the industry to monitor fracture orientation. Santos has experience with this technology and may consider additional projects in the future.

Stimulation fractures are designed to provide an optimal geometry within the formation of interest. A complete layer description, including lithology, stress contrasts between layers, and reservoir parameters is input into the fracturing simulator. Various pumping schedules are input to evaluate the simulated fracture geometry. Economics are optimised by designing a treatment that maintains the fracture height within the target formation. Fracture propagation into non-reservoir units will result in sub-optimal economics. Growth into non-reservoir units can have two outcomes: Firstly, the fluids and proppant are wasted and the hydrocarbon production may be reduced due to poor placement of proppant; secondly, there is a risk of fracturing into a water bearing interval which could lower production due to liquid loading. This would lead to an expensive workover to shut off the water production.

As discussed in Section 2.4.4, at the local scale, the regional stress field (magnitude and orientation) will be affected by discontinuities in the rock mass such as faults. The magnitude of horizontal stress will also be influenced by the geotechnical properties of the layered sedimentary rocks. The stiffer, more brittle rock layers, such as sandstone, have a low apparent fracture toughness (i.e. requires relatively little energy to fracture) compared to shale which is considered ductile (high apparent fracture toughness) and requires relatively large quantities of energy to fracture. Sandstones are porous and permeable in nature and have a significantly higher permeability compared with the overlying shale.

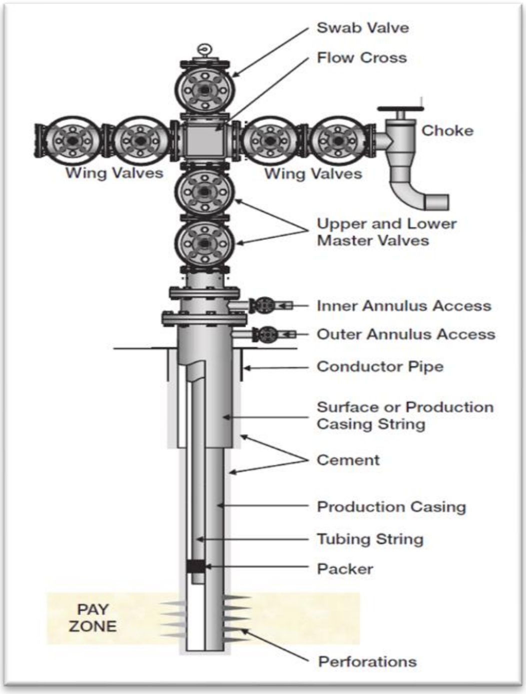
Stimulation is initiated with hydraulic pressure applied to the rock, through the perforations, such that the rock fails in tension against the minimum horizontal stress. With continued fluid injection, the fracture will continue to propagate in the direction of maximum horizontal stress. The fracture will also grow in height until a higher stress boundary is encountered. This stress contrast will prevent the fracture height growth to continue until the pressure in the fracture exceeds the barrier stress. Bottom hole fracturing pressures, at the depth of Cooper Basin reservoirs, can be of the order of 50 MPa to 80 MPa depending on depth of the reservoir rock being fractured/stimulated and its geomechanical properties. Fractures within the basin, at the depths of the reservoir sands, are expected to be near vertical and orientated parallel to the major horizontal in-situ stress direction. Fracture height growth is likely to truncate along a low shear strength plane such as the top of the sedimentary layer. Alternatively, if a fracture propagates from a brittle (sandstone) layer into a formation that is ductile (shale often exhibits plastic properties), extra energy would be required to continue the fracture propagation. Consequently, contrasts in apparent fracture toughness form effective fracture height barriers.

In multi-target production wells, casing isolations are used to isolate the fracture pressures to the targeted reservoir rock and to limit the potential for fracturing of sequences above and below the target intervals. Two techniques are commonly used by Santos within the Cooper Basin. The first technique referred to as “plug and perf”, uses composite bridge plugs to mechanically isolate stages prior to perforating the next sand above. The second technique uses coiled tubing with the ability to mechanically isolate a stage below and jet perforate the next stage above, prior to fracturing.

3.3.5 Stimulation Process Description

Stimulation uses specially designed fluids, primarily consisting of water and sand or ceramic proppant, mixed on the surface. The fluids are injected into the well and through the perforations into the reservoir formation (‘pay zone’ in Figure 31), to create the hydraulic fracture. A typical well head used to inject into and control the well, during fracturing operations, is illustrated in Figure 31.

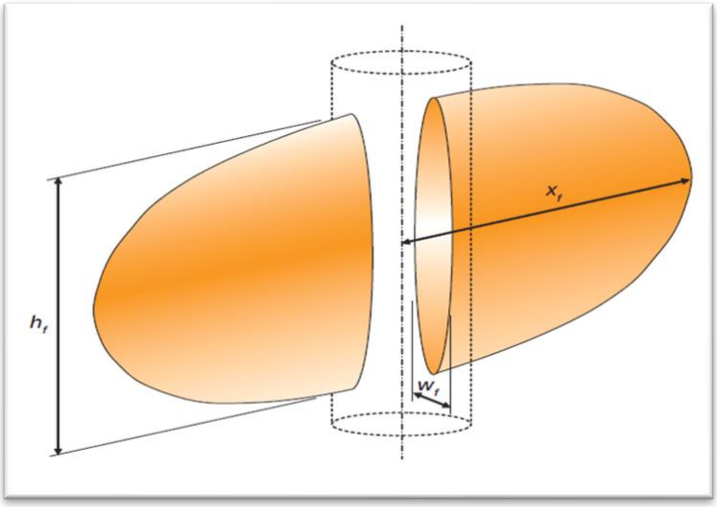
Figure 31: Typical Stimulation Wellhead Fixture



Source: Economides and Martin, 2007

As discussed above, the stimulation process occurs under high hydraulic pressures in order to physically fracture the reservoir rock. The stimulation fluids are injected through perforations (10 to 20 mm diameter holes created with jet perforating) in the well casing pipe. The stimulation fluids are injected from the surface via the wellhead or frac tree (Figure 31). A simplified schematic of the created fracture geometry is indicated in Figure 32. A hydraulic fracture in deep reservoirs, similar to the Cooper Basin, will propagate laterally from the well in a vertical plane, based on the in-situ stresses. Common dimensional terminology for hydraulic fractures includes fracture half length (x_f) and fracture height (h_f) and propped width (w_f).

Figure 32: Conceptualised Shape of Stimulation Zone of Influence



Source: Economides and Martin, 2007

The intent of stimulation is to place a highly conductive channel into the reservoir, to increase the flow capacity. Typically used in low permeability reservoirs, that cannot sustain economic production, it can be analogous to increasing the effective wellbore radius. This increase in flow area will increase the production rates and, in some cases, can contact additional reserves. A number of steps make up the stimulation process:

1) Perforate the interval to be fracture stimulated. The perforations are through jet perforating or abrasive jetting with coiled tubing and sand to jet holes through the casing and cement;
2) Pre-frac injection test with shut-down and decline to evaluate near wellbore entry friction, fracture gradient, fluid leakoff, and minimum horizontal stress. This stage is not always included;
3) Main fracture treatment; consisting of pad volume, slurry stages with increasing proppant concentrations, and flush stage to displace last slurry stage to the perforations. On occasion a pre-pad stage including weak hydrochloric acid to assist with remediating near wellbore entry friction may be pumped ahead of the pad stage;
4) Prepare to mechanically isolate the fracture stage completed, if a multi-stage well completion;
5) Perforate the next stage to be fracture stimulated and repeat the process in 2 to 4 above until final stage is completed; and
6) Flowback well to clean up injected fluids and monitor hydrocarbon production.

The following sections describe some of the specialised equipment required for stimulation and a further description on some of the various stages of the treatment.

3.3.6 Infrastructure and Equipment Used

Within SWQ stimulation is used on both oil and gas reservoirs. For the most part the process is the same. The differences may involve slight fluid formulation changes due to temperature variations with depth and some variation on the equipment used. Smaller oil reservoir stimulation treatments usually use less pumping horsepower and less stimulation fluid and proppant, and therefore require a smaller set-up than gas reservoir treatments (refer to .

Figure 33 and APPENDIX D for a typical equipment set up). Deeper gas reservoirs usually require variations in the fracturing fluid due to higher bottom-hole temperatures and higher in-situ stresses. The higher stresses mean that higher horsepower is usually required.

Santos uses two methods to pump and isolate fracture stages within multiple target gas wells within the Cooper Basin. The first method, referred to as “plug and perf”, uses wireline-conveyed jet perforating across each reservoir target. Sands are stimulated sequentially, one at a time, from the bottom of the well upwards. Between each pumping sequence a mechanical bridge plug is set above the sand completed to isolate the sand while fracturing the next sand above.

Another technique is to use coiled tubing assisted annular fracturing which can be used to provide a conduit for “pin-point fracturing”. Coiled tubing is run into the well to the deepest target. The bottom-hole assembly incorporates a jetting assembly which allows for low concentration sand slurry to be pumped into the coil and exit this assembly with high velocity. The jet created, along with the abrasive properties, will cut holes or slots into the casing and cement. These provide access to the reservoir similar to what jet perforating accomplishes. The stimulation treatment is then pumped into the coiled tubing / casing annulus to initiate and propagate the fracture. The other function of the coiled tubing is to include a packer as part of the bottom-hole assembly that can be used to isolate the fractured formation while fracturing the next formation/target above.

Figure 33 and APPENDIX D indicates the coiled tubing equipment, which may or may not be required on the actual treatment. Some further descriptions of equipment are provided below:

- **'Clean Fluids' Pit or Turkeys nest** – on site, a pre-dug lined pit (turkey's nest) provides temporary clean water storage for use in the stimulation process. Source water is generally trucked from a nearby water supply bore or recycled water from a nearby production facility. Small dosages of biocide are added to control algal growth particularly under warm and stagnant conditions. Often in smaller fracture treatments (e.g. oil wells), the volume of source water is small enough that the use of turkey's nests is not required, and the source water is stored and treated in tanks instead.
- **Sand Trailer Unit** – a large, multi-compartment trailer that holds proppant (sand or ceramic material) required for the treatment. When proppant is required, a conveyor system distributes proppant from the compartments to the downhole blender.
- **Blender Units** – In general, two different blending units are use: A pre-gel blender; and a downhole blender. The pre-gel blender combines the source water with additives required for the base stimulation fluid (also known as "linear gel") and proportions all required additives to provide the final stimulation fluid. The downhole blender unit then proportions proppant to the stimulation fluid to provide the proppant concentrations specified in the fracture design. The final stimulation fluid, without proppant, is referred to as the "clean fluid". The final stimulation fluid, with proppant added, is referred to as "slurry". Most of the stimulation fluids used within the Cooper Basin for the main stimulation treatment are cross-linked fluids to assist with fracture geometry and proppant transport. In small stimulation jobs for oil wells, the linear gel is "batched mixed" in tanks and negates the use of the pre-gel blender, thus reducing the overall equipment footprint on site. Chemicals are precisely, measured controlled and recorded by the blender throughout the stimulation treatment.
- **Hydration Units** – The hydration unit is generally situated between the pre-gel and downhole blenders and serves to prepare the linear gel for crosslinking. Water from the pond or tank is pumped to the hydration unit where a polymer, such as guar gum, is proportioned into the water. A sufficient residence time is available for the polymer to hydrate and provide sufficient viscosity for the fluid designed. The final result is the base gel, or linear gel, for the final stimulation fluid.
- **High Pressure Pumps** – reciprocating triplex or quintaplex pumps that receive low pressure stimulation fluid from the downhole blender and inject these fluids at sufficiently high pressure into the well during the stimulation process.
- **Control or Data Acquisition Unit** – telemetry from all units are connected to a central control room during the stimulation treatment. Treatment parameter data, including surface and bottom-hole pressure, pumping rate, chemical rate and fluid density, are monitored, recorded and plotted. Treatment supervisors and a Santos representative monitor and control the treatment to ensure that the treatment is pumped according to design.
- **'Coil Tubing' Unit** – a Coiled Tubing unit (CTU) has many uses within Santos operations but is not always required as part of a stimulation operation. On some occasions the stimulation treatments are placed using coiled tubing assisted annular fracturing, as opposed to "perf and plug" completions. The coiled tubing can be used in place of wireline jet perforating by jetting holes through the casing and cement using abrasive jetting. Once the perforations are jetted, the coiled tubing is left inside the well and the stimulation treatment is pumped down the coiled tubing / casing annulus. Part of the coiled tubing bottom-hole assembly allows a mechanical barrier to be set which protects a fractured interval below, while pumping a stimulation treatment in a subsequent target above. Following a treatment, the coiled tubing is pulled up to the next interval and the abrasive jetting procedure is repeated.

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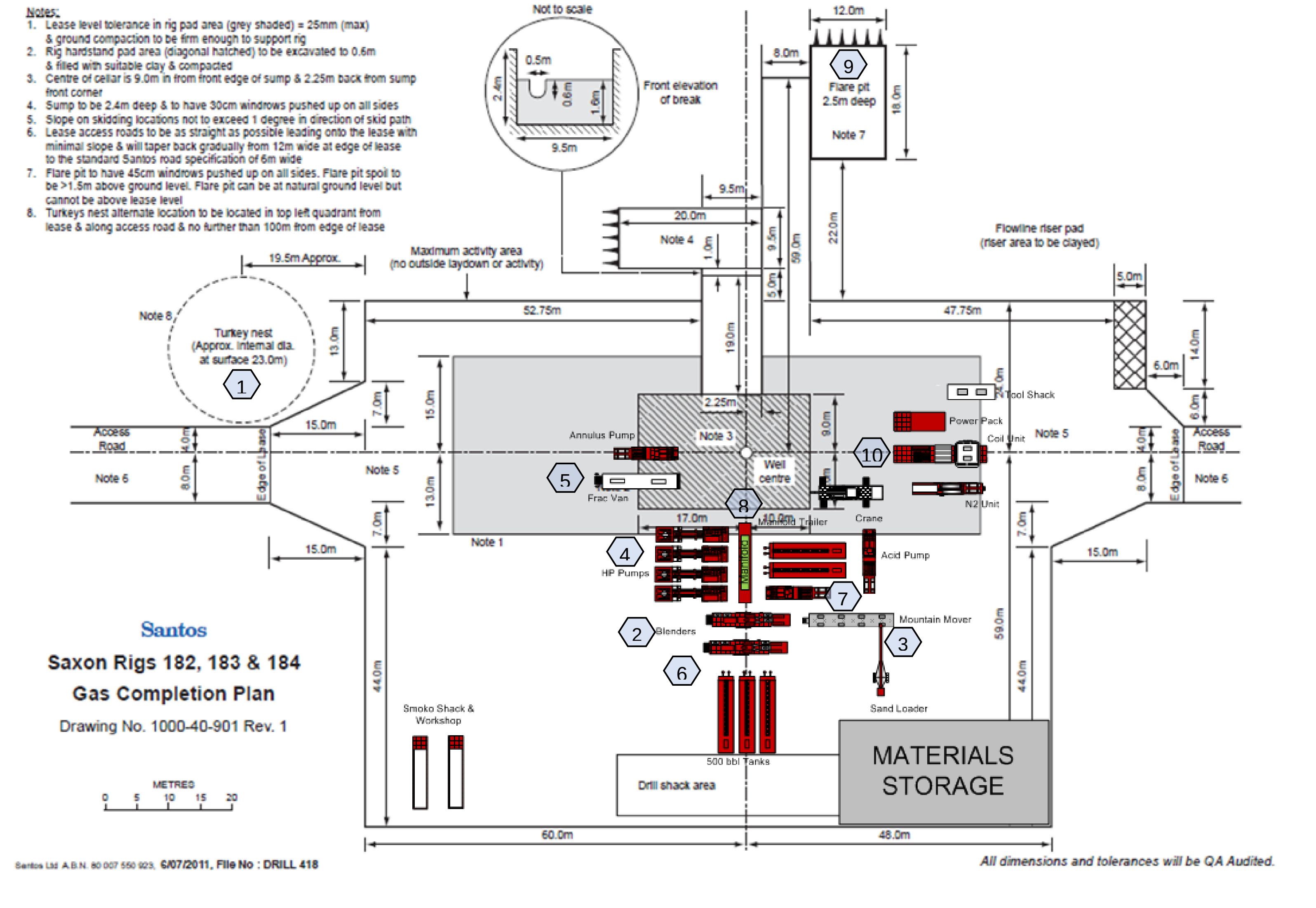
Figure 33: Diagrammatic Layout of a Typical Stimulation Operation on a Conventional Oil or Gas Well Lease (Saxon Rigs 182, 183 and 184)*



1) 'Clean Fluids' Pit or Turkeys nest
2) Blender Units *(one hydration blender and one down-hole blender)*
3) Proppant Storage Unit
4) High Pressure Pumps
5) Control or Data Acquisition Unit
6) Frac Tanks for water storage
7) Additional Pump Unit
8) Manifold Trailer
9) Lined Flare Pit or 'Return Fluids' Pit
10) Coiled Tubing equipment and associated equipment (if required: power pack, N_2 Unit, coil unit, crane, acid pump)

*Note: This figure shows a deep gas well set up for Coiled Tubing Assisted Annular Stimulation. Conventional oil or gas rig set up is similar (lacks items 10 above).

3.3.7 Stages of Stimulation

3.3.7.1 Stimulation Event Design

Stimulation events are individually designed in detail as part of the well completions design process described in Section 3.2. The design input parameters are described in that section.

Key to a successful and contained stimulation event is the inclusion of detailed fracture modelling and fracture monitoring by Santos Fracture Stimulation Engineers and its contractor of each targeted reservoir zone using computer modelling methods.

Design outcomes include:

- Equipment requirements based on expected treating pressures and pump rates;
- Stimulation fluid type and volumes required;
- Volumes of water required on location to be available for designed treatment;
- Proppant types and volumes required;
- Simulated hydraulic fracture geometry and expected treating pressure;
- Fluid pumping schedule describing stage volumes, rates, and proppant concentration;
- Shut-down and flowback procedures; and
- Site preparations and logistics for material supply and accessory equipment required.

3.3.7.2 Stage Perforation/Jetting

To provide communication between the wellbore and the reservoir, perforations are required. In wireline deployed perforation, these are created using charges. Alternatively, perforations are created using a CTU, where low concentrations of an abrasive sand slurry are used to create holes of much lower shot density.

The length of the perforated interval is determined by the thickness of the sand layer to be stimulated. A typical perforated interval across a given sand layer is 3 m in length; however, this interval can vary between 0.3 m to 6 m or more. The perforations within the interval are placed at varying shot densities, or shots per metre. Typical perforation or shot densities are 9 shots per meter (spm) to 20 spm. The perforation diameter will vary based on the method of perforating, as well as other variables, but typical dimensions are 10 mm to 25 mm in diameter.

The preference for deploying one method over another depends on several factors, the main ones being: resource availability; number of zones to be stimulated in the well; efficiency and cost.

3.3.7.3 Pre-Treatment

In some formations, the initial breakdown can create significant near wellbore pressure (NWBP) drop and can be calculated from Minifrac results (Section 3.3.7.4). This can be caused by various conditions but can result in difficulties placing the proppant volumes and concentrations designed for. This NWBP loss needs to be remediated in some cases prior to pumping the main treatment. One method is to use a small volume of dilute hydrochloric acid (15% wt/wt HCl acid) as a pre-flush to the main treatment. Typical volumes of acid ahead of the main treatment are of the order of 1,000 to 1,500 L of acid. Any acid soluble materials, in the near wellbore area, are removed and an improved connection between the wellbore and the reservoir is created. However, acid pre-treatments are not routinely required, and many stimulation treatments are performed without pre-treatment. If stimulation is undertaken in deep gas reservoirs, a dilute acid is commonly used as a pre-stimulation treatment. This is primarily to reduce friction pressure for future pumping operations by improving access through the perforations to the reservoir. It is carried out after completion of the well casing and ‘well screen’ perforations, but prior to stimulation.

3.3.7.4 Minifrac

A Minifrac is a small volume injection of clean fluid (such as friction reduced water or linear gel) into the perforated or jetted holes for the purpose of ascertaining design related parameters such as NWBP, frac gradient, treatment rate, treatment pressures and fluid leakoff signatures. These parameters can influence a design change in the main treatment and in cases where high NWBP is encountered, warrant an acid pre-treatment.

3.3.7.5 Corrosion Inhibitor

Weak acids are corrosive to metals and the corrosion rate increases with higher temperatures. On any acid treatment, a corrosion inhibitor is added to protect against any corrosion of the casing during the pumping operation. This ensures that the well integrity is maintained by applying a protective coating on the surface of the casing. The concentration of the corrosion inhibitor is based on lab testing with the same material at downhole temperature conditions for a given period of time. Typical corrosion inhibitor concentrations used are 2% by volume or 20 L inhibitor per m^3 of acid blend.

The acid is mixed into a surface tank prior to pumping. The mixing procedure is controlled while mixing all the chemicals from bunded containers. The order of mixing is to add the fresh water to the tank, add the additives including the corrosion inhibitor and then the concentrated acid (32% hydrochloric acid, HCl). The total blend will be the required volume of acid at a concentration of 15% HCl. This acid blend is pumped directly into the well using a single high pressure pump.

3.3.7.6 Pad Volume Injection

The stimulation process is initiated by pumping a designed volume of the stimulation fluid without proppant, referred to as the “pad”. This fluid is carefully prepared using the equipment described in Section 3.3.6. Prior to pumping into the well, the base gel is prepared and tested using specific QA/QC procedures. The main polymer used for Cooper Basin stimulation is a guar derivative (Figure 34) which is combined with bore water in the pre-gel blender, providing the base gel viscosity. Programmed and automated control systems are used to maintain the fluid properties during the pumping of the treatment. Fluid sampling occurs during the treatment to ensure that the fluid maintains the desired properties.

The purpose of the pad volume is to create the fracture area required to receive the designed proppant volume. Once the pad volume is pumped, and without shutting down the pumps, the proppant is added to the downhole blender and proportioned into the stimulation fluid. The concentration of proppant increases through each stage as designed within the stimulation simulator. The stimulation fluid with proppant is referred to as “slurry” and the proppant concentration is measured up to the maximum designed concentration in kg/m^3.

The pad fluid comprises a mix of water (typically 99.5% by volume) and is usually comprised of groundwater obtained from nearby water bores or formation water. A mix of water and guar gum, together with a number of additives such as crosslinkers, buffers, and breakers, make up the crosslinked stimulation fluid.

Figure 34: Example of a Typical Slurry Gum Constituent: Guar Gum

Illustrated in its native form, seed form, splits and powder

**Note: Guar gum is a vegetable product which is ground into a powder and used to create a viscous liquid for stimulation. Source: Economides and Martin, 2007

The gum (Figure 35) is allowed to hydrate in a baffled tank, referred to as the Hydration Unit, for several minutes prior to being pumped to the downhole blender. The base gel viscosity of the fluid is typically in the region of 30 to 40 centipoise (cp), depending on the specific fluid designed.

Subsequently, additives including cross-linkers, buffers, breakers, and surfactants are added at the downhole blender to provide a suitable fluid for transporting proppant into the hydraulic fracture.

At this point, the guar gum and associated ingredients comprise approximately 0.050% by volume of the pad volume. The viscosity of the crosslinked fluid will vary with time and temperature, but typical designs will provide a fluid with viscosities in the several hundreds of centipoise (Figure 35). This viscosity is required to propagate the fracture and to transport proppant well into the created fracture. Following the treatment, this fluid viscosity will break back to close to water viscosity due to added breakers and the bottom hole temperature.

Figure 35: Example of Typical Stages of Gum (Guar) Cross-linking to Achieve 300 cp.

Source: Economides and Martin, 2007

The pump rate or rate of injection on a stimulation treatment is based on the design factors discussed in Section 3.2.2 and will vary depending on the reservoir. Typical Cooper Basin injection rates range from 15 bbl/min (2.4 m^3/min) to 35 bbl/min (5.6 m^3/min). Surface treating pressures can range from 5,000 psi (35,000 kPa) to 11,000 psi (76,000 kPa).

At the initial stage of injection, the pressure will increase until a breakdown of the formation occurs. This is evident by a drop in the injection pressure and signals that the stimulation has been initiated. Pumping of the pad volume will continue at the designed rate, in order to promote the designed fracture geometry. Once the pad volume is pumped, the injection of the slurry stages begins without interruption to the treatment.

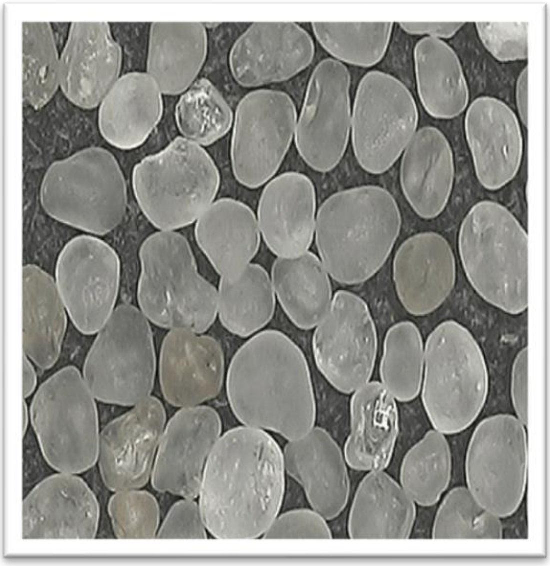
3.3.7.7 Slurry Volume Injection

Following the injection of the pad volume, the proppant stages are pumped according to the design. Proppant addition begins at low concentrations and is staged up to the final designed concentration which is specific to the formation being fracture stimulated. Typical proppant concentrations will range from 0.5 lb/gal (60 kg/m^3) to 8 lb/gal (1000 kg/m^3).

Proppants used in stimulation range from graded quartz sand to higher strength ceramic proppants (refer to Figure 36 and Figure 37). The strength of these materials increases based on the material, with ceramic being much stronger than quartz sand. Ceramic proppant is most often used in the Cooper Basin due to the high effective closure stresses. Proppant grain size varies and is also chosen based on the required conductivity for the specific fracture design. Each size and type of proppant has a number of specifications that must be met for consistency with API conditions.

Figure 36: (Left) Typical 20-40 Grade Sand used in Stimulation

Figure 37: (Right) Typical Sand-Guar Gum Fluid Mix



Source: Economides and Martin, 2007

Once the final slurry stage is pumped on surface, the final flush stage is pumped. The flush stage is a linear gel fluid (non-crosslinked) and is used simply to displace the last stage of slurry down to the perforations. This leaves the wellbore volume free of any proppant and has all proppant placed within the fracture. It is just as important not to over displace the proppant away from the wellbore. Once this flush or displacement volume has been pumped, the high pressure pumps are shut down and the main stimulation treatment is considered complete.

Breaker compounds are added at progressively increasing concentrations throughout the pad and slurry stages. The breaker comprises an oxidizing compound or enzyme that breaks the crosslink sites, as well as the long chain polymers. The end result is a fluid with lower viscosity that can be easily flowed back from the fracture to assist with clean-up. The “break time” is designed to coincide with the known pump time at reservoir conditions plus some additional time to ensure the treatment is pumped to completion. An unbroken fluid will restrict the ability for the fracture to clean up and hydrocarbon production will be impaired.

The duration of the stimulation treatment is dependent on the specified volumes to be pumped and the rate at which the treatment is pumped.

The above procedure is carried out for each target zone (pay zone) in the reservoir formations. In the case of Santos’ oil reservoirs, this typically equates to one target zone per well. In the case of gas reservoirs, the number of sands or fracture stages can range from 1 stage to 10 stages in a single well, depending on the reservoirs contacted during the drill.

A typical Cooper Basin stimulation treatment may use from 40,000 gallons (150 m^3) to 100,000 gallons (400 m^3) of water for the main stimulation treatment. The required volume is dependent on the size of the treatment required for the particular formation to be stimulated. The amounts of proppant required typically range from 40,000 lb (18 tonne) to 200,000 lb (90 tonne) and, again, is dependent on the specific formations being stimulated.

3.3.7.8 Flush Volume

As discussed above, a flush stage or displacement stage is pumped at the end of the treatment to ensure that all of the proppant is within the fracture and not within the wellbore. On occasion, proppant placement is restricted due to near wellbore width restrictions. If this restriction completely blocks the entry of proppant, the pressure rises quickly and terminates the treatment. This termination is referred to as a “screenout” and requires the wellbore to be cleaned out to enable production of the well.

3.3.7.9 Flowback

The fluid used to create the fracture and place the proppant will restrict the ability of the well to clean up and produce hydrocarbons. As mentioned, the use of breakers and reservoir temperature will assist with viscosity reduction. With the fluid viscosity reduced to near water (1 cp), the well is allowed to flowback to reduce the amount of leak off into the formation. Often recovered fluid volumes are in the range of 30% to 60% of the total volume pumped. This is usually enough to allow the well to flow on its own energy or with assistance from artificial lift.

Light condensate entrained in the flowback fluid is often removed with a vacuum truck and taken to a nearby oil facility. The clean-up of conventional oil zones is often bypassed due to the fact that artificial lift systems are installed as part of the final completions program. These lift systems include typical installation beam pumps which can lift both the oil and fluid out of the well.

Flowback fluids are removed from site and transported to and disposed to a dedicated flowback fluid pond located in Naccowlah.

After the well has been equipped with all the required completion and gathering equipment, the well is put on production. Production continues for the life of the well, with produced water (groundwater, condensation and frac fluid) over that period ranging less than 1 ML up to 30 ML for gas wells, increasing to a maximum of approximately 340 ML for oil wells. This flow is likely to flush all the available (mobile) components of the original stimulation fluid which may remain in the formation *after* flowback.

3.3.7.10 Stimulation Treatment Monitoring

As described in Section 3.3.4, the stimulation for each reservoir layer is modelled using an industry accepted stimulation simulator. Based on the final pumping schedule from the optimized design, a predicted fracture geometry and expected pressures are available.

During the treatment key parameters such as surface, bottom hole and annular treatment pressures, proppant concentrations, volume of injected fluid and fluid additives are monitored live from the Frac Van as well as at Santos' offices. The modelled pressures are compared with the actual pressures. The overall pressure response can provide useful information in evaluating the fracture growth and containment. A contained fracture will exhibit a pressure profile different from an uncontained fracture. The mechanical properties of the interbedded sandstones, shales coals mean that horizontal propagation of the fracture network dominates. Treatment parameters are used with the stimulation model, following the treatment, to achieve a history match and predict the actual fracture geometry.

Live monitoring allows for potential problems (surface or downhole) to be identified and corrected quickly. In the event that a problem develops on the surface (e.g. leak in line, pumps shut down), the use of live monitoring as a control measure for early detection can prevent the problem from escalating. An example of live monitoring applied to downhole conditions is if pressure communication is seen between the annulus of the well and inside of the well, the well's integrity may have been breached and the treatment is stopped immediately.

Santos has trialled in South Australia the use of advanced monitoring techniques such as micro-seismic monitoring, which can be used to evaluate fracture azimuth and fracture half length. This additional information can be used to further calibrate the stimulation model predictions. The additional cost of this technology precludes the use on every treatment and will be evaluated as the technology is better understood.

Microseismic monitoring involves the use of a string of sensitive receivers (“geophones”) in one or more nearby wells to detect and locate in 3D space the releases of energy associated with the propagation of the hydraulically-induced fractures. Figure 38 shows an example of a side-view of the locatable microseismic events that were detected during the multi-stage fracture stimulation of Cowralli-10 (in South Australia), with the positions of the events colour-coded by frac stage. The viewpoint for the figure is at approximately the same depth as the upper frac stages (shown in red, mid-blue and grey), and it can be seen that the fracture propagation is predominantly horizontal, with the coals being effective at confining the vertical propagation of the fractures. All of the locatable microseismic events for each frac stage were contained within the formation that was being stimulated. Figure 39 shows a map view of the locatable microseismic events; these are shown in red, and the ellipses around each well show the expected (modelled) fracture-extents. The modelling and actual results show good agreement, although in practice the fractures seem to have propagated horizontally slightly less far than expected. The technique has limitations, in that it requires at least one pre-existing nearby well (within approximately 500 - 700 m) to use for the monitoring, and it is also expensive, meaning that the use of the technique is necessarily selective.

The use of radioactive tracers (as impregnated beads) involves incorporating a different short half-life radioactive isotope into the proppant slurry for each stage, and then monitoring for the distribution of each of these isotopes along the wellbore after the stimulation treatment. However, there are presently no plans to use radioactive materials in SWQ, should this alter Santos will comply with all applicable legislative requirements concerning their use, storage and disposal.

Figure 38: Lateral View of the Locatable Microseismic Events during Monitoring of Multi-Stage Fracture Stimulation of Cowralli-10 (SA)

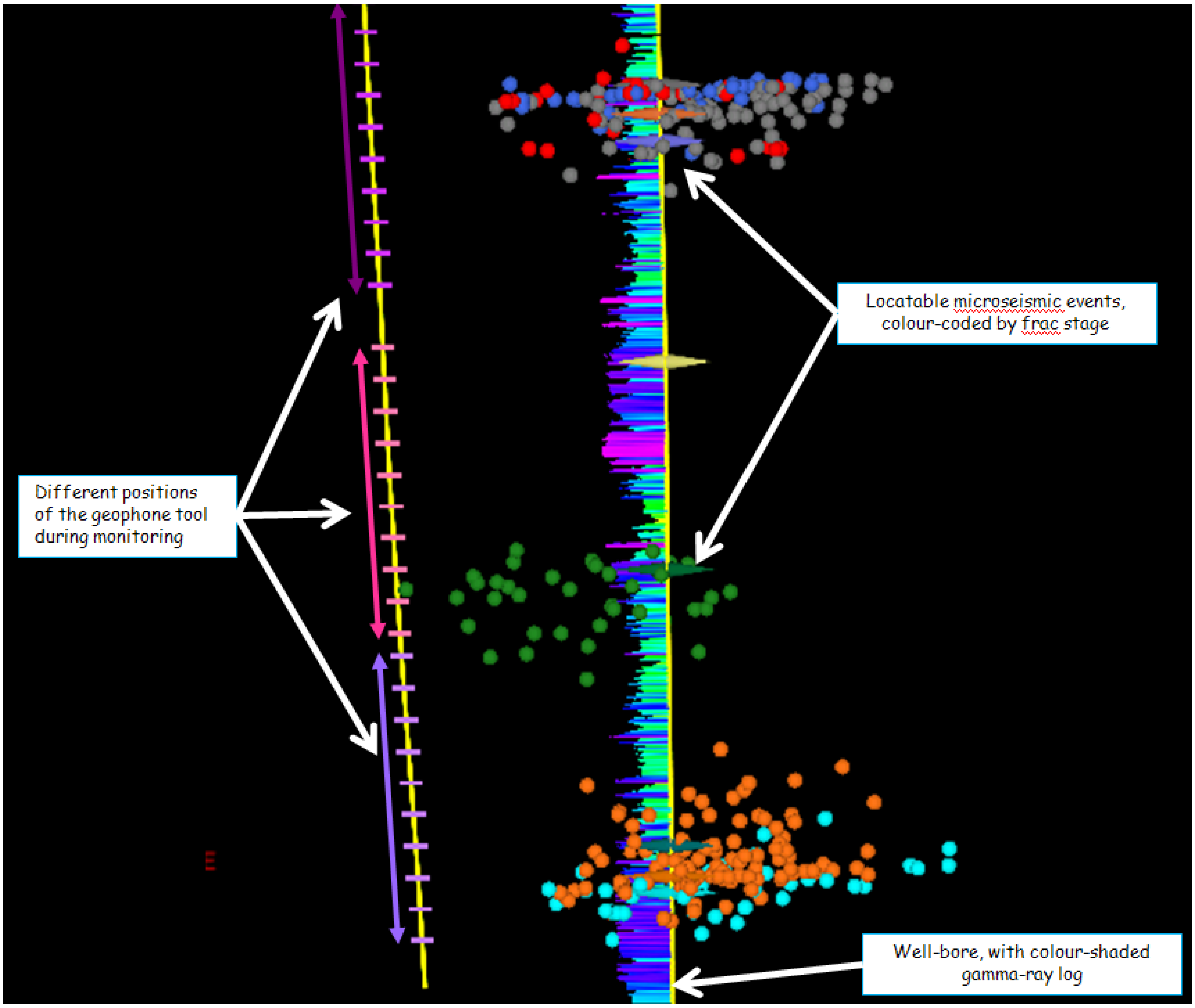
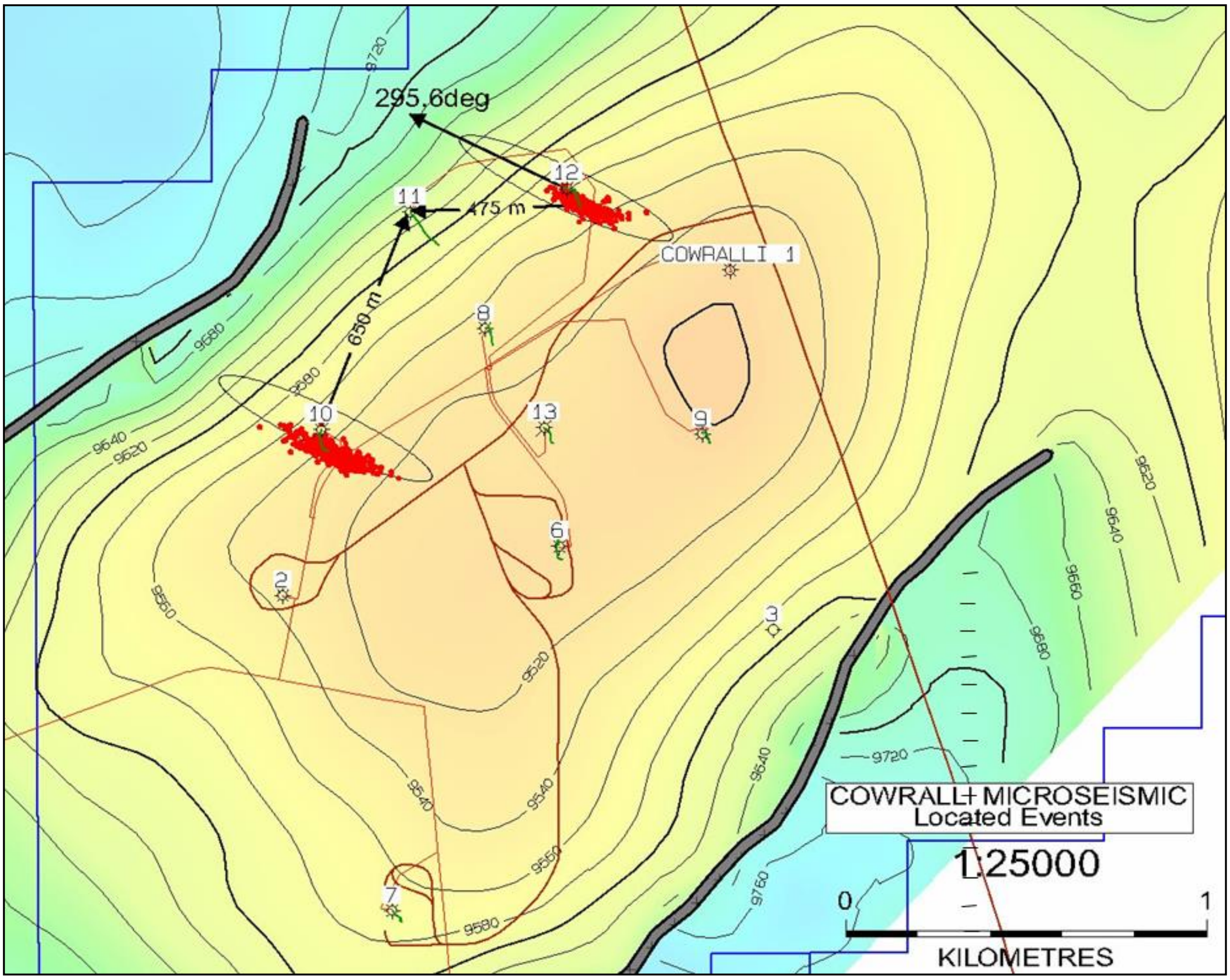


Figure 39: Map View of the Locatable Microseismic Events During Monitoring of Multi-stage Fracture Stimulation of Cowralli-10 and Cowralli-12 (SA)



3.3.7.11 *Timing of Stimulation Process*

The stimulation of a typical conventional oil well takes two to three days to complete a treatment. The stimulation of a deep gas well with multiple stages can require anywhere from five to ten days to complete the stimulation operation. The flowback period can extend from three to ten days depending on the reservoir and clean up profile.

At the end of the clean-up phase, Santos completions engineers install the production tubing and associated completion equipment such as packers, nipple profiles, tubing hanger, and the production tree.

3.4 Program for Wells to be Stimulated

3.4.1 Frequency of Stimulation

Selected wells will be stimulated prior to being brought into production, involving the various tasks described previously. At the time of writing, Santos has indicated that approximately 67 wells are proposed for stimulation in SWQ. The potential wells scheduled for stimulation are expected to occur over the period 2020 to 2022. However, the program of wells is *indicative* only and prone to change.

During the life of the well, the formation may be re-stimulated at a later date, which would essentially be a repeat of the initial stimulation process.

3.4.2 Distribution of Completed and Scheduled Stimulation Locations

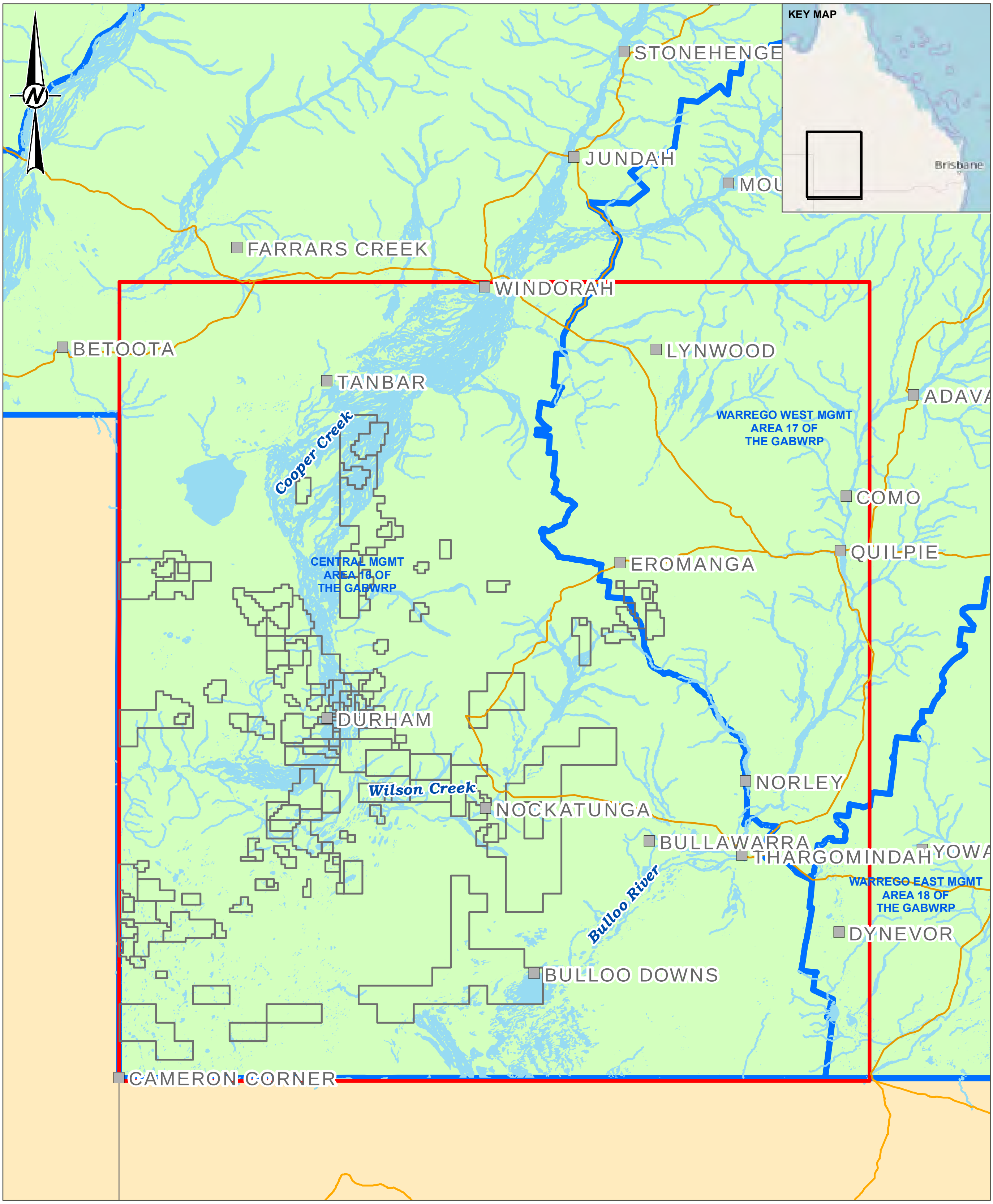
Oil and gas wells that have been stimulated to date are listed in Figure 40 and presented in APPENDIX E. Since 1987, a total of 376 wells have been stimulated in SWQ. Golder understands that have been no recorded incidents associated with these activities. Indicative wells that are scheduled for fracturing until 2022 are presented in APPENDIX F.

According to information provided by Santos, the well spacing varies between the oil and gas well heads, from 400 m in the oil fields, up to tens of kilometres in the gas fields. Santos is moving toward “Pad” wells, where multiple deviated wells emanate from a single wellsite. Proposed deviated gas wells for the Santos project are listed in APPENDIX E and include “DEV” in the well name. These are generally shown as clusters within tenements (e.g. Baryulah Gas, PL131).

It should be noted that for a variety of reasons (including but not limited to future production performance and access-related issues such as the flooding of the Cooper Creek system), the geographic distribution of the forward fracturing programme is frequently reviewed and is subject to change, although the overall number of fracture stimulations is likely to remain similar to that outlined here.

Queensland legislation regarding notice of intent and reporting of activities allows for flexibility to change the program of wells to be fractured. According to the Petroleum and Gas regulations, 2004 (PGGD-03, s35, and subsections s35A and S46A) the holder of a petroleum tenure must lodge a notice prior to activity commencement with the (now) Department of Natural Resources and Mines and Energy (DNRME, formerly Department of Natural Resources and Mines), followed by a notice of completion after activities have ended. These notices must be distributed to the landholder and land occupier. A detailed stimulation activities completion report must then be lodged no later than two months after activities have been carried out including a stimulation fluid statement and if any material environmental harm has occurred (relevant to the definitions of the EPA 1994).

Santos proposes to copy DES on the notification of stimulation operations on the same timescales as required by the above DNRME legislation. Adjustments to the locations or schedule of future stimulation activities will be managed in the context of the outcomes of this risk assessment.



LEGEND

- Historical Stimulation Locations
- Town/Locality
- Highway/Major Road
- River/Creek
- Groundwater Management Area
- Santos Tenements
- Study Area

0 KILOMETERS 100

1:2,750,000 GCS GDA 1994

NOTE(S)

REFERENCE(S)

1. BASE INFORMATION COPYRIGHT MAPINFO AUSTRALIA PTY LTD
2. ATP/PL TENURE SUPPLIED BY SANTOS, NOVEMBER 2019
3. GROUNDWATER MANAGEMENT AREA SOURCED DEPARTMENT OF NATURAL RESOURCES & WATER, QLD GOVERNMENT 2008

CLIENT
SANTOS

PROJECT
HYDRAULIC FRACTURING RISK ASSESSMENT – SANTOS SOUTHWEST QUEENSLAND TENEMENTS

TITLE
HISTORICAL HYDRAULIC FRACTURING LOCATIONS IN SW QLD

CONSULTANT

GOLDER

DD-MM-YYYY	19-03-2020
DESIGNED	KB
PREPARED	KB
REVIEWED	CB
APPROVED	CB

PROJECT NO.	CONTROL	REV.	FIGURE
127666004	011-R	2	40

3.5 Location of Landholders Active Bores

The locations of licensed water bores relative to the Santos tenement boundaries are discussed in Section 2.5.8 and are presented in Figure 40. The results of the WBBA completed (as of December 2012 (updated 2020), Section 2.5.8) identified eight active private bores and one additional bore being within potential impact zones. The vertical proximity of the target petroleum formations to aquifers utilised for private or commercial/industrial water supply is discussed in Section 2.6.

The proximity of the identified water supply bores to the proposed stimulation locations is presented in APPENDIX F and the distances are listed in Table 11 (refer to Sections 0 and 2.6.2 for the stratigraphic thickness ranges separating hydrocarbon-bearing formations from aquifers).

The active landholder bores in the oil fields in the east of the project range from approximately 3 to 10 km from the closest proposed oil well. The upper-most formation proposed for stimulation is the Wyandra Sandstone (Upper Cadna-Owie). The closest bore, Mt Margaret No 14, targets the shallower Winton formation for stock purposes. At this location the vertical separation between the Winton Formation and the Wyandra Sandstone is at least 750 m, including the low permeability mudstones of the Wallumbilla and Toolebuc Formation and the Allaru Mudstone (Section 0).

The active landholder bores within, or near, the gas fields in the west of the project range from approximately 25 to 90 km from the closest proposed stimulation location. The upper-most target proposed for stimulation are formations within the Nappamerri Group. The closest bore was the Whim Well however this well is not in operation. The Coothero Bore which targets the Hooray Sandstone for stock water is the closest operational bore. The Coothero Bore and is located more approximately 44 km from the closest proposed location for gas production, and more than 80 km from the closest location proposed for oil production from the Hooray Sandstone. The Coothero Bore is monitored by Santos as part of the UWIR monitoring program.

Table 11: Distance of Active Landholder Bores in the Study Area to the Closest Proposed Stimulation Location

Bore Name	DEHP RN	Distance	Target Aquifer
Mt Margaret No 14	9096	3 km	Winton Formation
Walla Wallan Bore 5	6373	5 km	(no data)
Mt Margaret No 20	10565	3 km	(no data)
Cherry Cherry Bore	6369	10 km	(no data)
Tarbat Job No 1947	12036	8 km	Winton Formation
Palara Bore	6057	12 km	(no data)
Grahams Bore	14955	87 km	Glendower Formation
Moon Road Field Bore	0**	81 km	-**
Coothero Bore*	23569	44 km	Hooray Sandstone

* Potentially within the impact zone as described in Section 2.5.8
** Bore not observed in database records. Referred to as “Moon Field Road Bore” in WBBA.

4.0 CONCLUSIONS

4.1 Environmental Setting

Santos operates conventional gas and oil fields across petroleum tenements within an approximately 30,000 km^2 portion of Southwest Queensland. The operations are divided into three sub-areas of interest: *Western, Central* and *Eastern Project Areas*. At the time of preparation of this report the three project areas were no longer in effect, with the project area (Figure 1) now referred to as "SWQ". The terrain in the study area is generally characterised by low undulating topography (hills and ridges) between the drainage channel systems of the Cooper Creek. The area is sparsely developed, and generally comprises rural communities and homesteads that are largely engaged in pastoralism.

It is within the stratigraphy that comprises the Eromanga Basin and the underlying Cooper Basin that oil and gas reservoirs are located which contain the proposed target formations for hydraulic fracturing. A detailed description of key geological and hydrogeological features is provided in the text, including geological models for the study area, target hydrocarbon-bearing sandstone formations (oil in the Eromanga Basin formations at depths ranging from 700 to 1,200 m below ground level (mbgl); and gas in the Cooper Basin formations at depths of 1,500 to greater than 2,000 mbgl), their hydraulic characteristics, adjacent aquifers and aquitards, structural features including faults and fracture characteristics (and their potential to behave as barriers or conduits), regional and local seismicity characteristics, aquifer environmental values and the location of groundwater users.

In terms of the environmental setting, this stimulation risk assessment (SRA) document has provided specific information which addresses the requirements anticipated of the EA conditions regarding stimulation that will apply to new areas proposed for production.

This version of the SRA updates a 2012 version (127666004-011-R-Rev0, December 2012). Updated content includes reference to the updated Environment Authority (EA) Blueprint conditions (December, 2019), updated tenements (as of January 2020), historical well stimulation events and potential future stimulation dates. Background information, such as the geological setting, hydrogeology, environmental values and stimulation process, etc has not changed in this version of the HFRA.

Specific inclusions addressing consent conditions are located within the logical flow of the description of the existing environment in the Santos SWQ petroleum field areas, with the specific information located as follows:

- a geological model of the field to be stimulated including geological names, descriptions and depths of the target producing reservoir(s) (Sections 2.4 and 0);
- naturally occurring geological faults (Sections 2.4.3.5 and 2.4.5);
- seismic history of the region (e.g. earth tremors, earthquakes) (Section 2.4.5);
- proximity of overlying and underlying aquifers (Section 2.6);
- description of the depths that aquifers with environmental value(s) occur, both above and below the target producing reservoir (Section 2.6);
- description of overlying and underlying formations in respect of porosity, permeability, hydraulic conductivity, faulting and fracture propensity (Sections 2.4.4 and 2.5.5);
- consideration of barriers or known direct connections between the target producing formation and the overlying and underlying aquifers (Section 0);
- the environmental values of groundwater in the area (Section 2.6);
- locations of landholders' active groundwater bores (Section 2.5.7); and
- groundwater transmissivity**,** flow rate, hydraulic conductivity and direction(s) of flow (Sections 2.5.3, 2.5.4 and 2.5.5);

Based on understanding of the environmental setting, this qualitative risk assessment considered the key environmental values as follows:

Groundwater environmental values:

- Town water supply;
- Stock and domestic water supply;
- Sandstone aquifers of the GAB; and
- Groundwater Dependant Ecosystems (GDEs).

Surface water environmental values:

- Protection of aquatic ecosystems;
- Recreation and aesthetics: primary recreation with direct contact, and visual appreciation with no contact; and
- Cultural and spiritual values.

Terrestrial environmental values:

- Protection of flora and fauna, particularly small mammals, reptiles and birds.

The report considered the applicable environmental values in the context of the proposed fracturing activities within the study area.

4.2 Stimulation Process Description

A detailed description of the stimulation process was provided in Section 3.0; with an emphasis on the safeguards inherent in the planning and implementation of fracturing events to ensure that the stimulation fluid and proppant are delivered (and maintained) within the target formation. The specific information required in the EA consent conditions can be found in the following sections:

- practices and procedures to ensure that the stimulation activity(ies) is designed to be contained within the target gas producing formation (Sections 3.3.4 and 3.3.7);
- provide details of where, when and how often stimulation is to be undertaken on the tenures covered by this environmental authority (Section 3.4);
- a description of the well mechanical integrity testing program (Section 3.2.2);
- process control and assessment techniques to be applied for determining extent of stimulation activity(ies) (e.g. microseismic measurements, radioactive tracers, modelling etc.) (Sections 3.3.4 and 3.3.7); and
- a process description of the stimulation activity to be applied, including equipment and a comparison to best international practice (Sections 3.2.1 and 3.3).

4.3 Summary

Based on the available geological information for the study area, the following key points are noted:

- The DEHP database and the interim results of the WBBA program indicate that groundwater supply development in the vicinity of Santos' tenements is limited to the Glendower and Winton Formations, and to a lesser extent the Hooray Sandstone. The minimum vertical offset between the Glendowner and Winton Formations and the shallowest hydrocarbon reservoirs (oil reservoirs of the Cadna-Owie Formation) is 400 to 800 m, which includes the low permeability formations of the Wallumbilla Formation and Allaru Mudstone, which form a thick, competent and regionally extensive seal between the Cadna-Owie Formation and the shallower aquifers. The vertical offset to gas reservious is much greater (1,000 m to 1,800 m).

- Within formations that host both aquifers and hydrocarbon reservoirs (e.g. Hooray Sandstone), the water-bearing zones are separated from hydrocarbon reservoirs by intra-formational seals. However, there is not enough information available to discretise the internal stratigraphy of these formations. Where petroleum activities (including fracturing) occur within a formation that hosts both aquifers and hydrocarbon reservoirs, the lateral distance of the water supply bores accessing the aquifer to Santos' tenements was considered.
- The closest beneficial use bore to the Santos tenements targeting the Hooray Sandstone in the DEHP database records is the Coothero Bore, is at least 25 km from the closest tenement proposed for stimulation and more than 80 km from the closest tenement with activities proposed at a similar.

Based on the available site setting information for the study area, the following key points are noted:

- Cooper Creek is largely influenced by surface water flows and evaporation, with negligible contribution from groundwater. Waterholes and billabongs occur throughout the Cooper Creek floodplain and channel complex, some of which coincide directly with Santos tenements.
- Three of the identified wetlands (Cooper Creek – Wilson River Junction, Bulloo Lake and Cooper Creek Swamps – Nappa Merri) are within boundaries of Santos' tenements. It should be noted that hydraulic fracturing activities may be completed within any tenement boundary over the life of the Project.
- The Cooper Creek catchment and downstream Lake Eyre are popular recreational fishing destinations. Popular fishing spots include Bulloo River at Thargomindah, Wilson River at Nockatunga and Cooper Creek flows (episodically).

Based on the provided Santos stimulation process information, the following key points are noted:

- Buffers to are assigned during establishment of well leases between petroleum operations and potential "environmentally sensitive areas" identified though database review and site-specific ecological assessment where warranted.
- The procedures employed by Santos' and its contractors follow a design philosophy predicated on the guidance, specifications and recommended practices of the American Petroleum Institute (API), considered to represent international best practice.
- The procedures employed by Santos' and its contractors for mechanical integrity and surveillance follow a design philosophy with international best practice. Practices for ensuring well mechanical integrity consist of a robust surveillance plan.
- OH&S procedures are implemented during stimulation operations to prevent workers from direct contact with chemicals during spills and when handling flowback water or sediments. Golder understands that there has not been a recordable spill since hydraulic fracturing commenced in 1987.
- Santos operational procedures monitor fracture design to stay within the target formation.
- Santos implement spill containment procedures during operations to prevent migration of and exposure to chemicals.

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Signature Page

Golder Associates Pty Ltd

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NC/CB/ro

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APPENDIX A

Limitations

The document ("Report") to which this page is attached and which this page forms a part of, has been issued by Golder Associates Pty Ltd ("Golder") subject to the important limitations and other qualifications set out below.

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Having regard to the matters referred to in the previous paragraphs on this page in particular, carrying out the Services has allowed Golder to form no more than an opinion as to the actual conditions at any relevant location. That opinion is necessarily constrained by the extent of the information collected by Golder or otherwise made available to Golder. Further, the passage of time may affect the accuracy, applicability or usefulness of the opinions, assessments or other information in this Report. This Report is based upon the information and other circumstances that existed and were known to Golder when the Services were performed and this Report was prepared. Golder has not considered the effect of any possible future developments including physical changes to any relevant location or changes to any laws or regulations relevant to such location.

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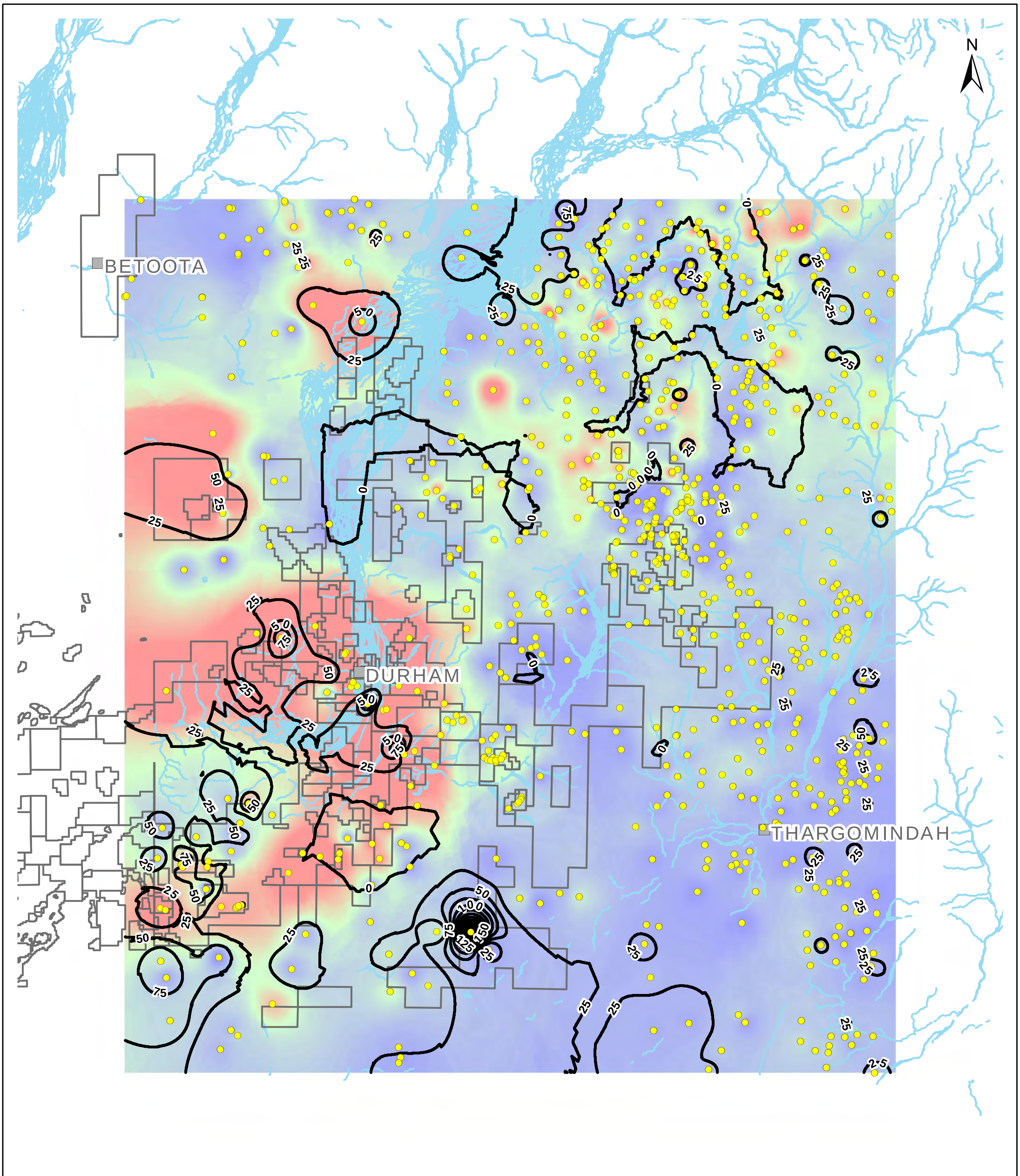
APPENDIX B

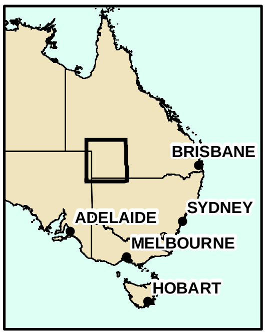
Geological Contour Plans



SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

GEOLOGICAL CONTOUR MAP: WINTON FORMATION



LEGEND

- Geology Data Point
- Town/Locality
- Depth to Winton Formation (m)
- River/Creek
- Santos Operated Permits

Thickness of Winton Formation (m)

High : 970

Low : 1

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) **1:2,500,000**

Coordinate System: GCS GDA 1994

PROJECT:	**127666004**
DATE:	**27/09/2012**
DRAWN:	**FA**
CHECKED:	**RS**

APPENDIX C1

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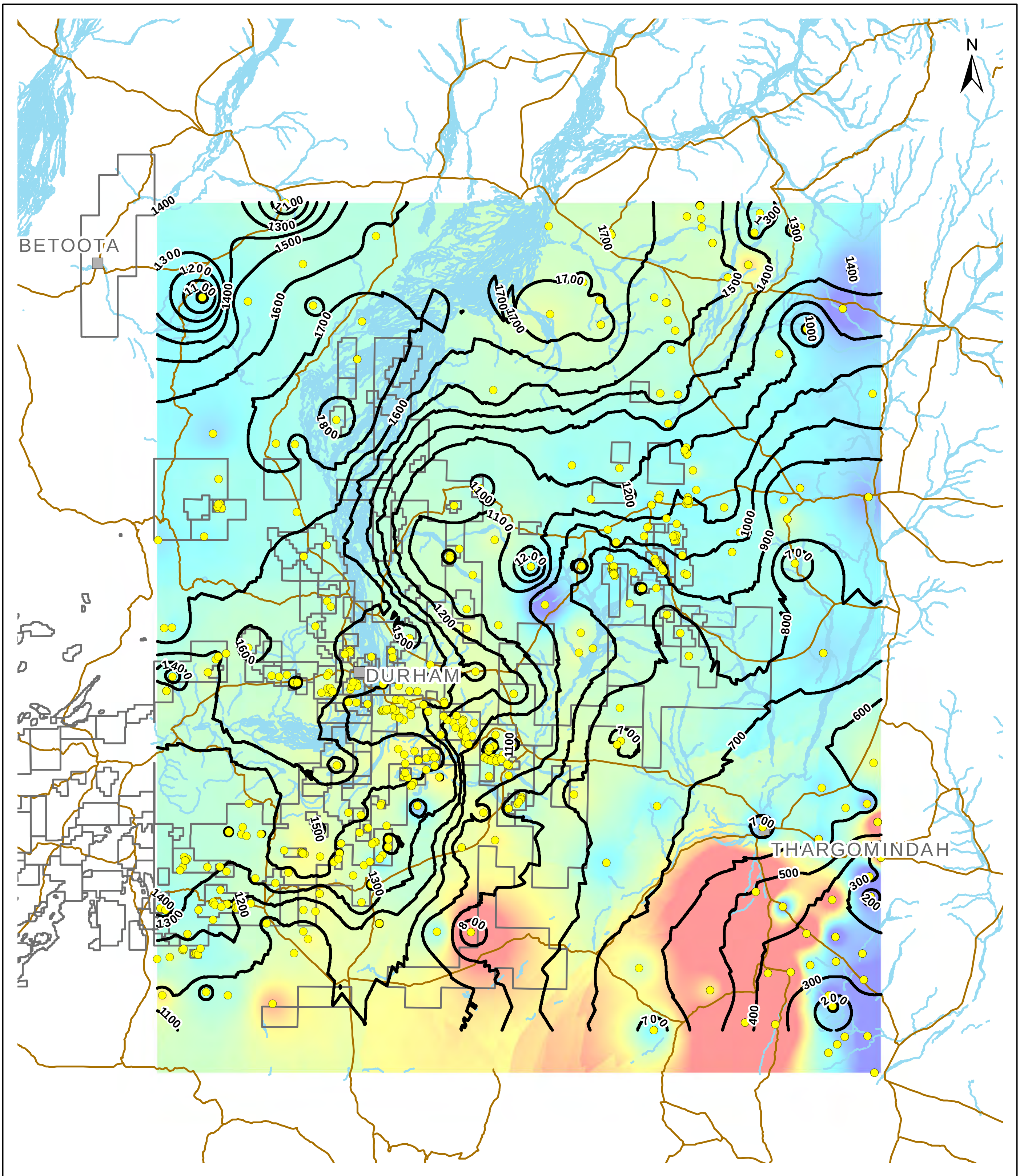
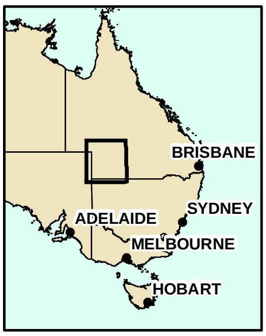


SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

GEOLOGICAL CONTOUR MAP: HOORAY FORMATION



LEGEND

- Geology Data Point
- Town/Locality
- Depth to Hooray Sandstone (m)
- Highway / Major Road
- River/Creek
- Santos Operated Permits

Thickness of Hooray Sandstone (m)

High : 595

Low : 1.8

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) **1:2,500,000**

Coordinate System: GCS GDA 1994

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APPENDIX C2

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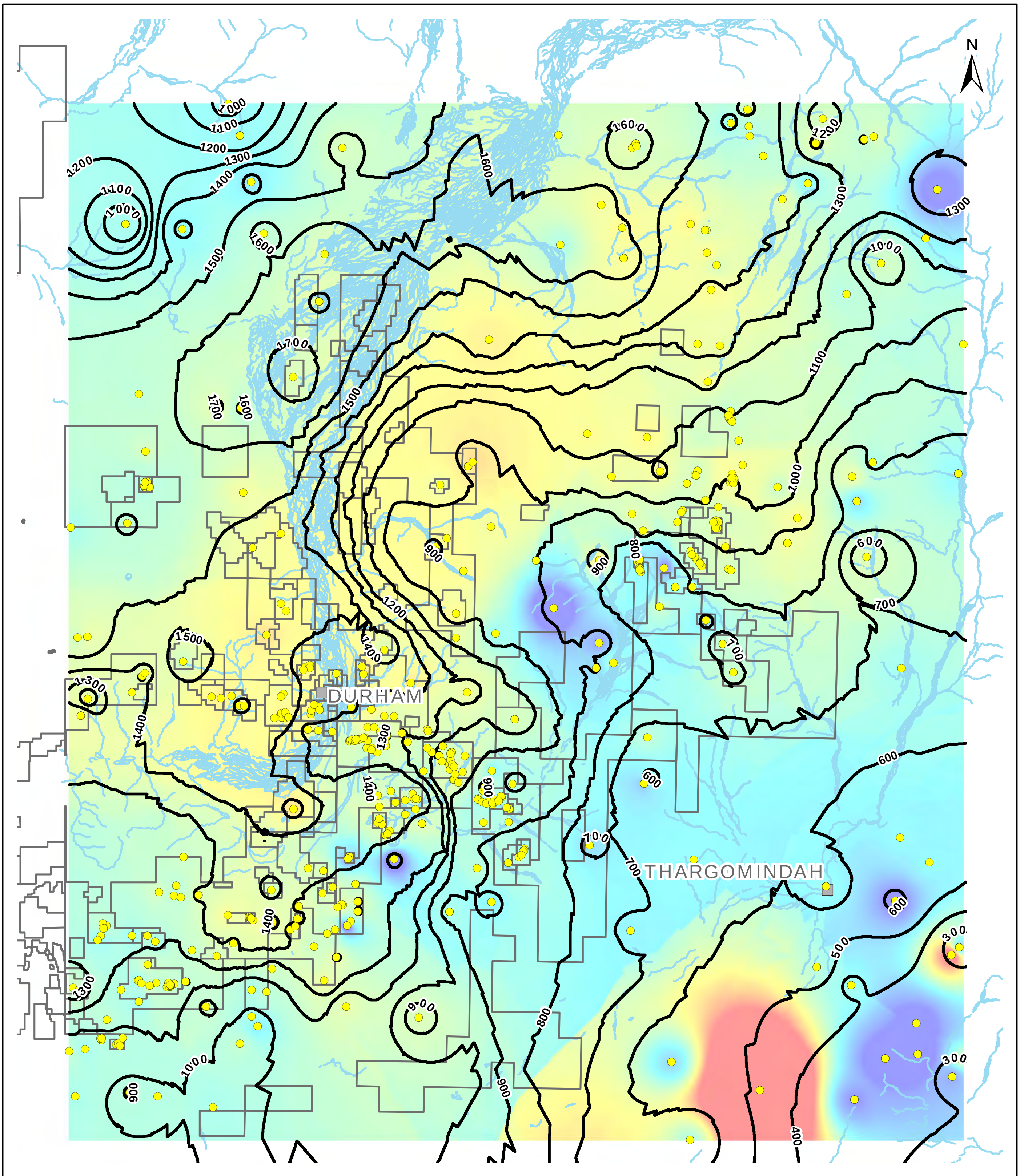
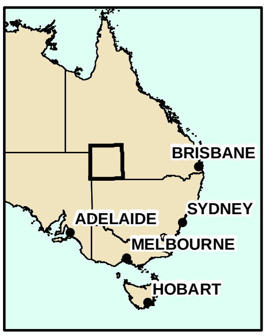


SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

GEOLOGICAL CONTOUR MAP: CADNA OWIE FORMATION



LEGEND

- Geology Data Point
- Town/Locality
- Depth to Cadna Owie (m)
- River/Creek
- Santos Operated Permits

Thickness of Cadna Owie Formation (m)

High : 390

Low : 18

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) **1:2,000,000**

Coordinate System: GCS GDA 1994

PROJECT:	**127666004**
DATE:	**27/09/2012**
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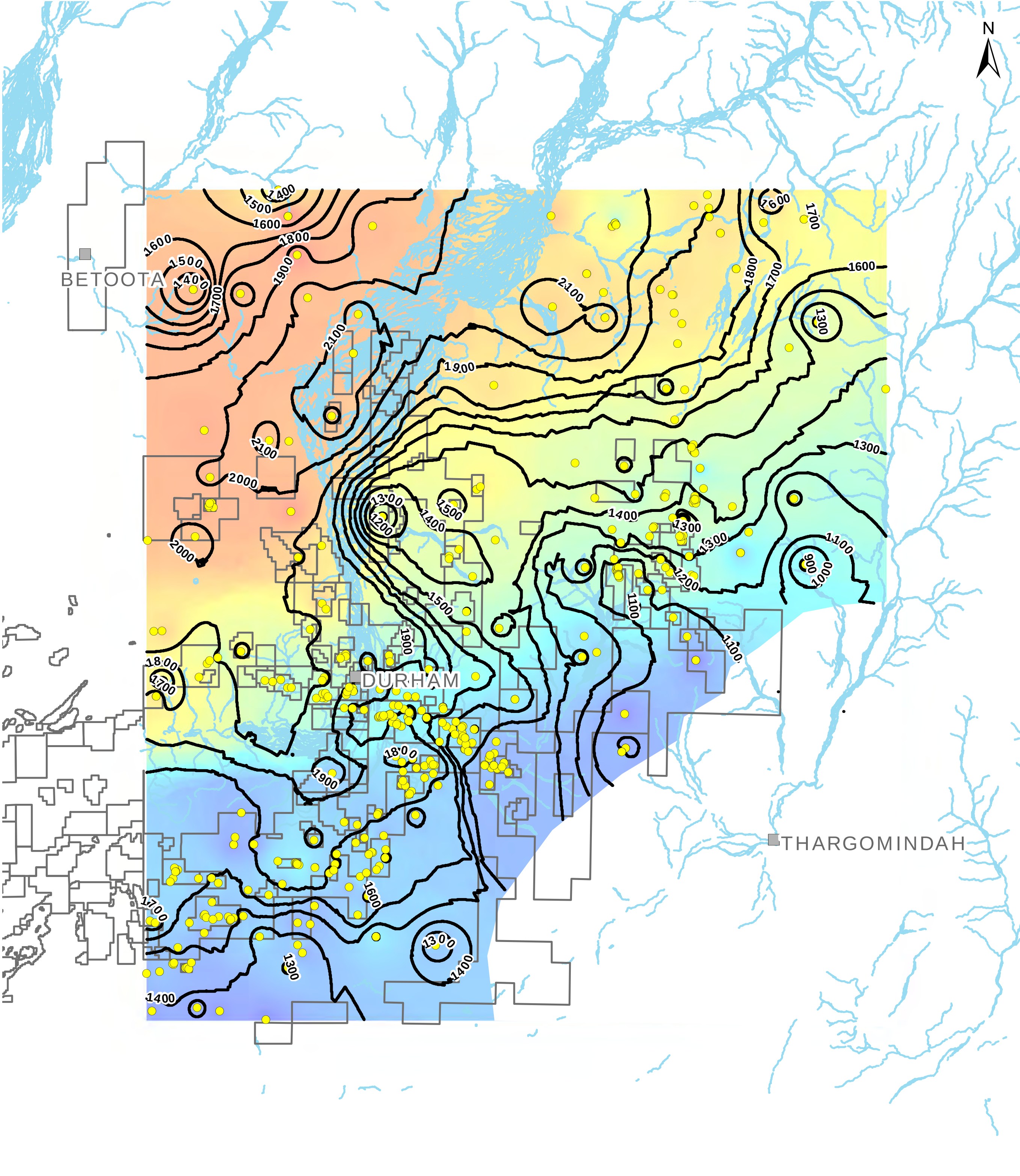
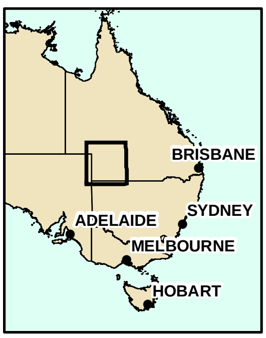


SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

GEOLOGICAL CONTOUR MAP: HUTTON SANDSTONE



LEGEND

- Geology Data Point
- Town/Locality
- Depth to Hutton Sandstone (m)
- River/Creek
- Santos Operated Permits

Thickness of Hutton Sandstone (m)

High : 241

Low : 2.

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) **1:2,500,000**

Coordinate System: GCS GDA 1994

PROJECT:	**127666004**
DATE:	**27/09/2012**
DRAWN:	**FA**
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APPENDIX C4

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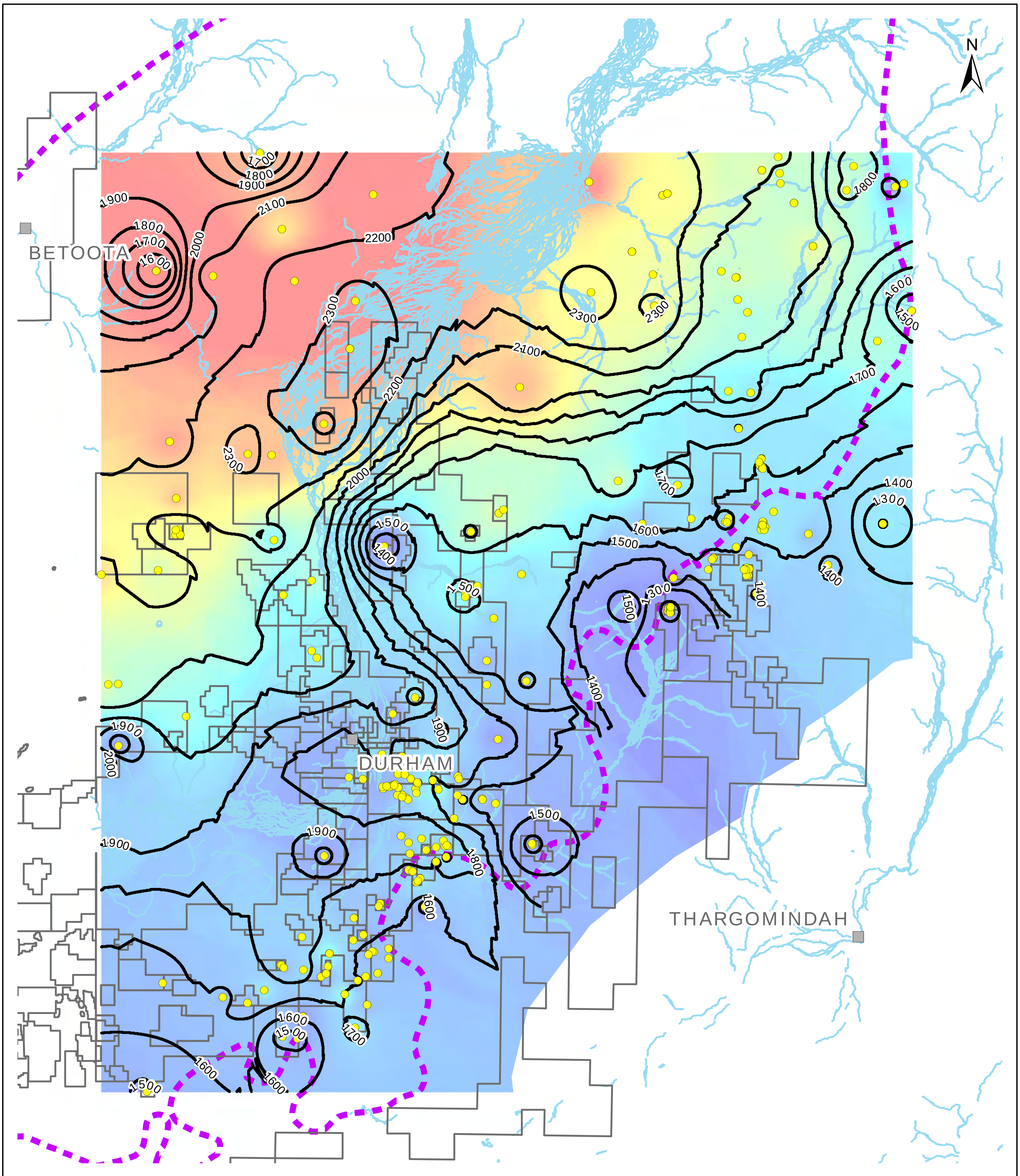
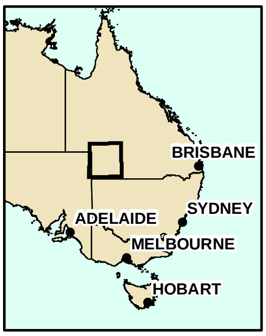


SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

GEOLOGICAL CONTOUR MAP: POOLOWANNA FORMATION



LEGEND

- Geological Data Point
- Town/Locality
- Depth to Poolowanna Formation (m)
- River/Creek
- Santos Operated Permits
- Cooper Basin

Thickness of Poolowanna Formation (m)

170

3

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) **1:2,000,000**

Coordinate System: GCS GDA 1994

PROJECT:	**127666004**
DATE:	**27/09/2012**
DRAWN:	**FA**
CHECKED:	**RS**

APPENDIX C5

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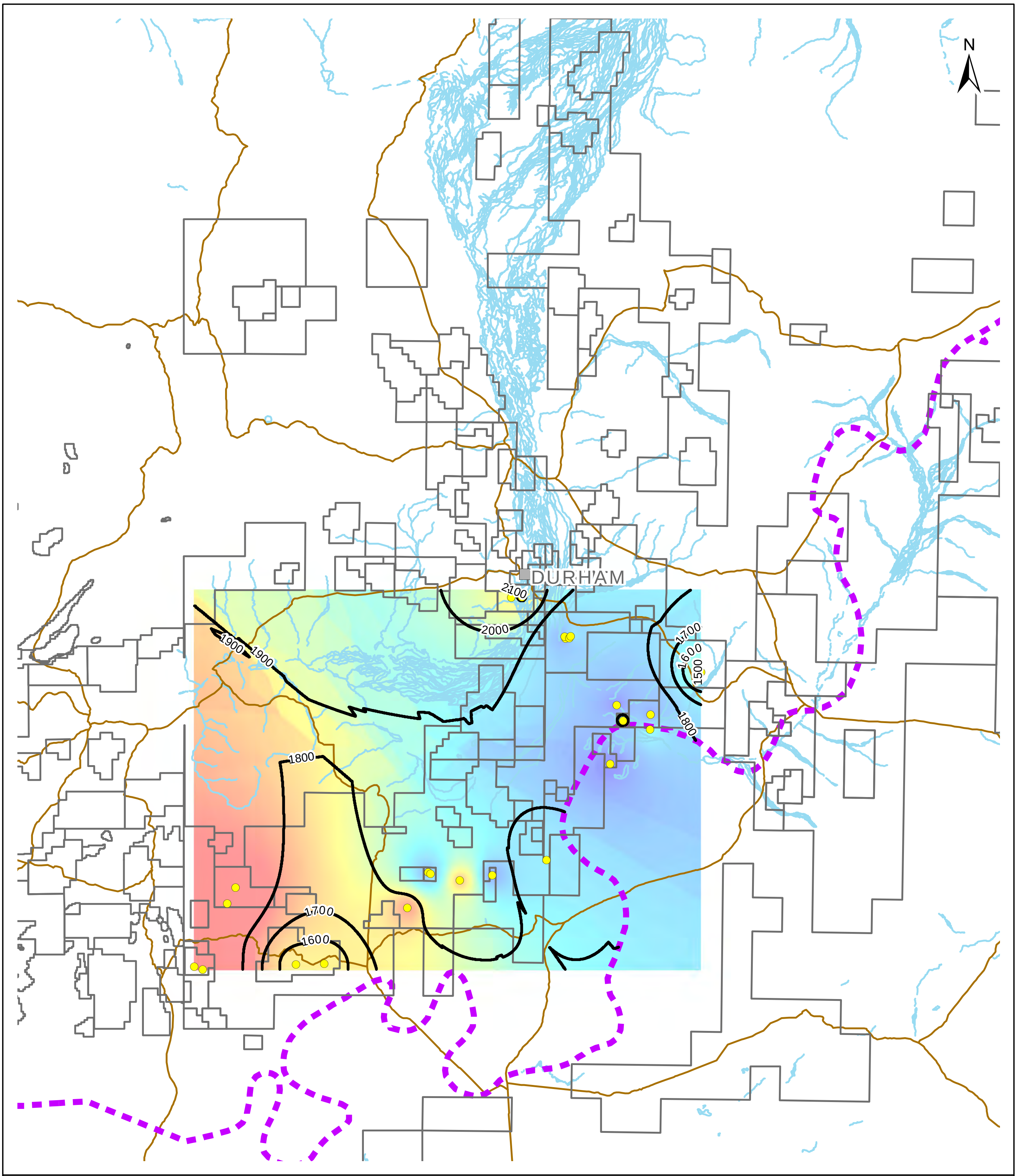

SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

GEOLOGICAL CONTOUR MAP: TOOLACHEE FORMATION

LEGEND

- Geology Data Point
- Town/Locality
- Depth to Toolachee Formation (m)
- Highway / Major Road
- River/Creek
- Santos Operated Permits
- Cooper Basin

Thickness of Toolachee Formation (m)

160

7

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) **1:1,500,000**

Coordinate System: GCS GDA 1994

PROJECT:	**127666004**
DATE:	**27/09/2012**
DRAWN:	**FA**
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APPENDIX C6

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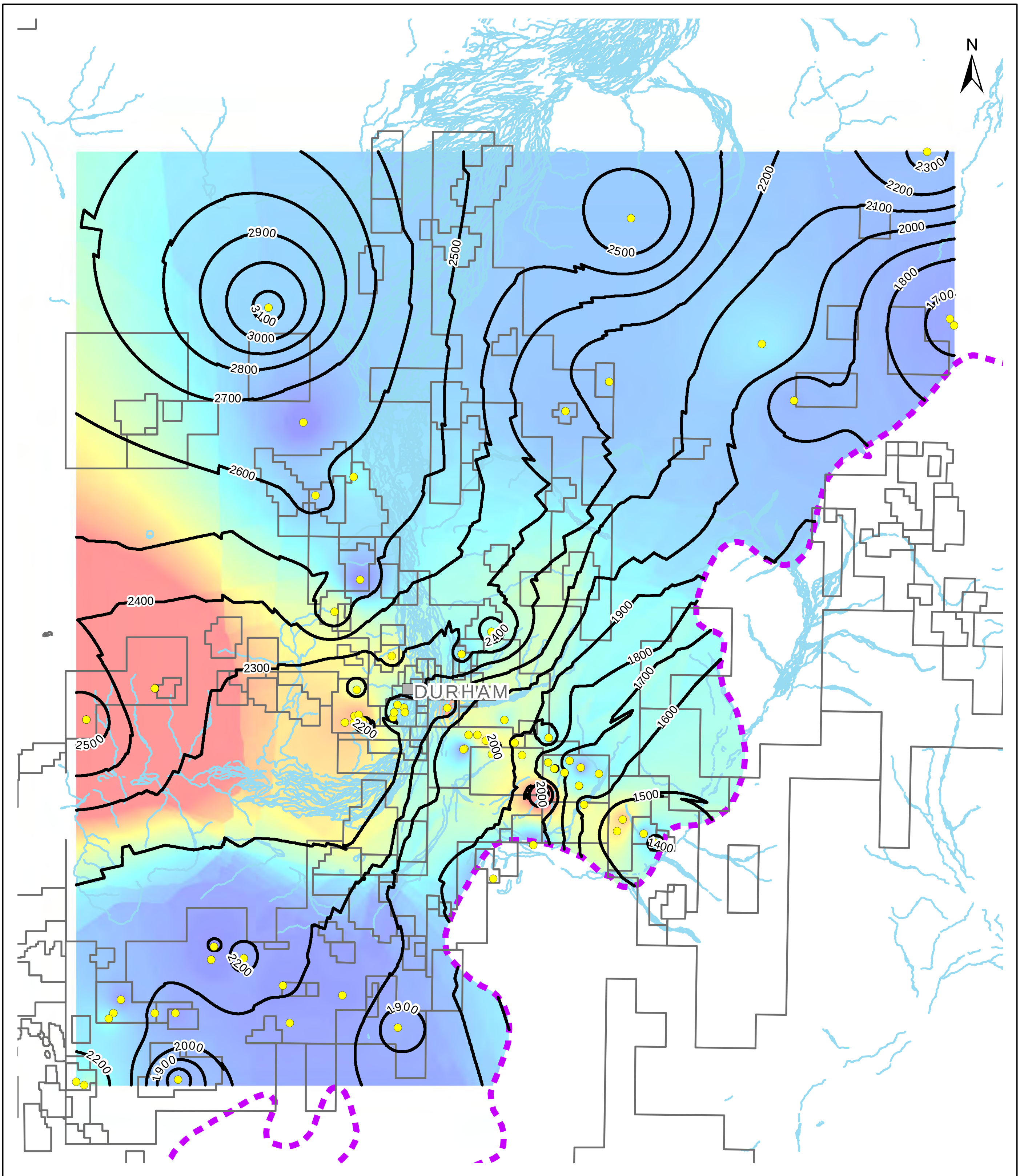

SWQ HYDRAULIC FRACTURING ASSESSMENT

SANTOS

GEOLOGICAL CONTOUR MAP: PATCHAWARRA FORMATION

LEGEND

- Geology Data Point
- Town/Locality
- Depth to Patchawarra Formation (m)
- River/Creek
- Santos Operated Permits
- Cooper Basin

Thickness of Patchawarra Formation (m)

745

Low : 7.5

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) 1:1,500,000

Coordinate System: GCS GDA 1994

PROJECT:	127666004
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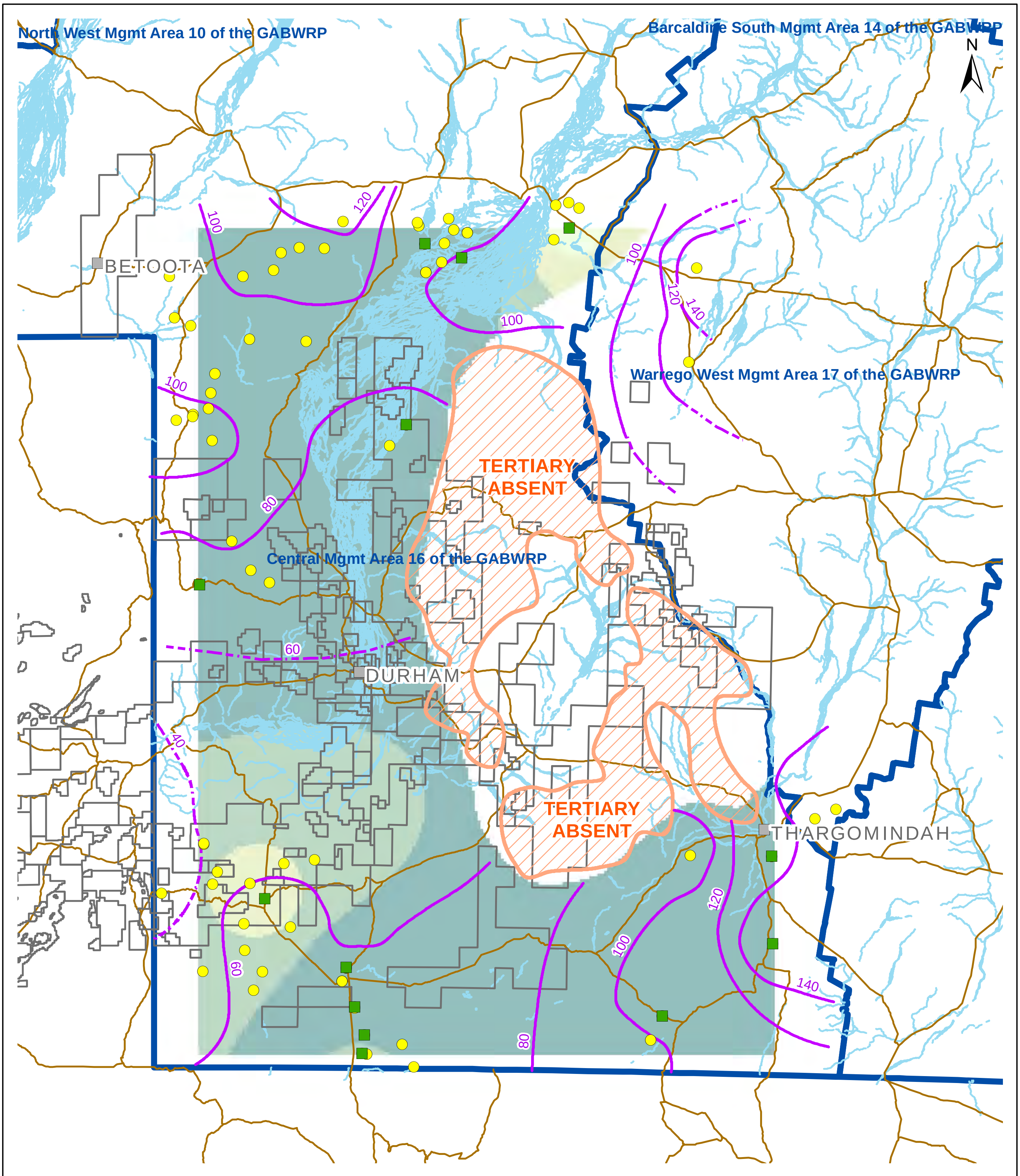
APPENDIX C

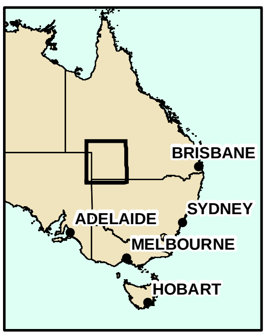
Hydrogeological Contour Plans



SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

HYDROGEOLOGICAL MAP: TERTIARY FORMATION



LEGEND

- Town/Locality
- Water Level and Electrical Conductivity Data Point
- Water Level Data Point
- Piezometric Isoline (mAHD) 20 m Interval
- Inferred Piezometric Isoline (mAHD) 20 m Interval
- Highway / Major Road
- River/Creek
- Santos Operated Permits
- Groundwater Management Area

Electrical Conductivity (µS/cm)

- 0 - 3000
- 3,000 - 4,500
- 4,500 - 6,000
- 6,000 - 7,500
- 7,500 - 9000

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) 1:2,500,000

Coordinate System: GCS GDA 1994

PROJECT:	**127666004**
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APPENDIX D1

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3. Groundwater Management Area supplied by the State of Queensland (Department of Natural Resources & Water), 2008
4. Golder Associates 2012a Cooper Basin UWIR Report

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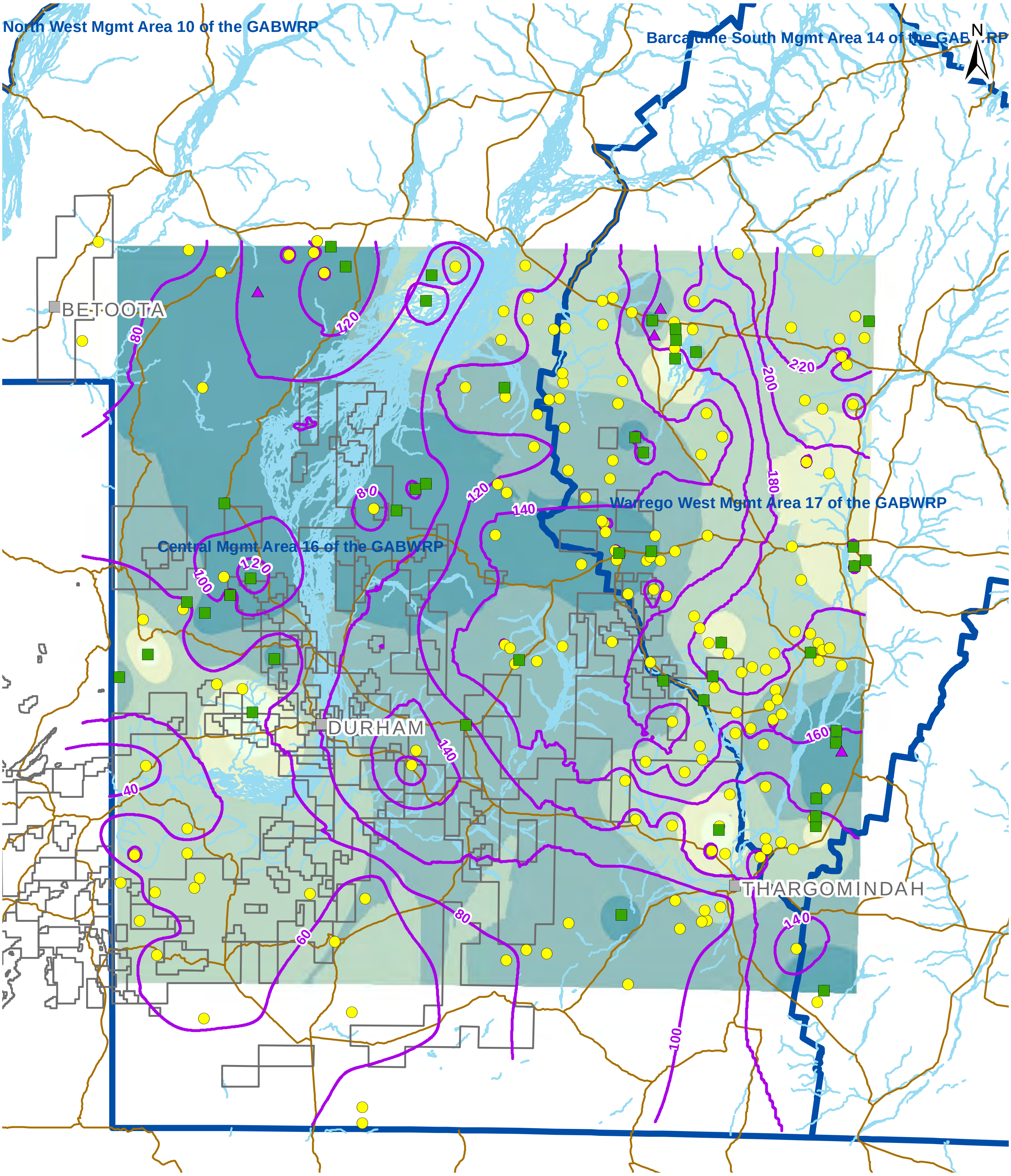
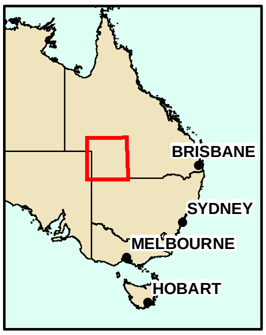


SWQ HYDRAULIC FRACTURING RISK ASSESSMENT

SANTOS

HYDROGEOLOGICAL MAP: WINTON FORMATION



LEGEND

- Town/Locality
- Water Level and Electrical Conductivity Data Point
- Electrical Conductivity Data Point
- Water Level Data Point
- Inferred Piezometric Isoline (m AHD) 20 m interval
- River/Creek
- Highway / Major Road
- Santos Operated Permits
- Groundwater Management Area

Electrical Conductivity (µS/cm)

- 0 - 3,000
- 3,000 - 4,500
- 4,500 - 6,000
- 6,000 - 7,500
- 7,500 - 15000

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) 1:2,500,000

Coordinate System: GCS GDA 1994

PROJECT:	**127666004**
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APPENDIX D2

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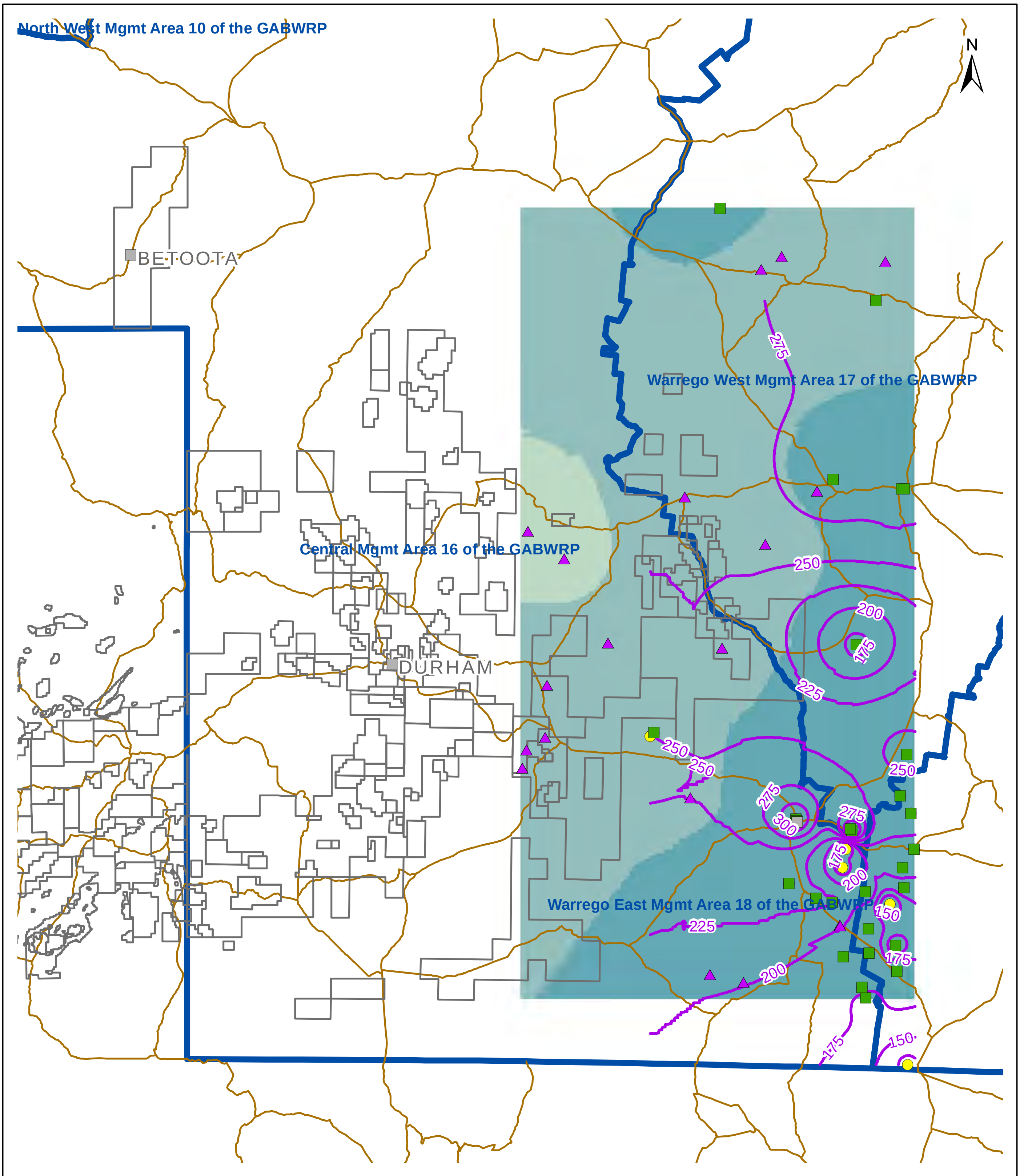
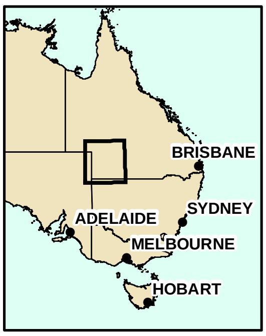


SWQ HYDRAULIC FRACTURING
RISK ASSESSMENT

SANTOS

HYDROGEOLOGICAL MAP: HOORAY SANDSTONE



LEGEND

- Town/Locality
- Water Level and Electrical Conductivity Data Point
- Electrical Conductivity Data Point
- Water Level Data Point
- Inferred Piezometric Isoline (metres AHD - Interval 25 metres)
- Highway / Major Road
- Santos Operated Permits
- Groundwater Management Area

Electrical Conductivity (µS/cm)

- 0 - 1,500
- 1,500 - 3,000
- 3,000 - 4,500

0 5 10 20 30 40 50 Kilometres

SCALE (at A3) 1:2,500,000

Coordinate System: GCS GDA 1994

PROJECT: **127666004**
DATE: **27/09/2012**
DRAWN: **FA**
CHECKED: **RS**

APPENDIX D3

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APPENDIX D

Santos Hydraulic Stimulation - Schematic Well Lease Setup

Figure D1: Conventional Oil Well Lease Set-up (Batch Mixing)

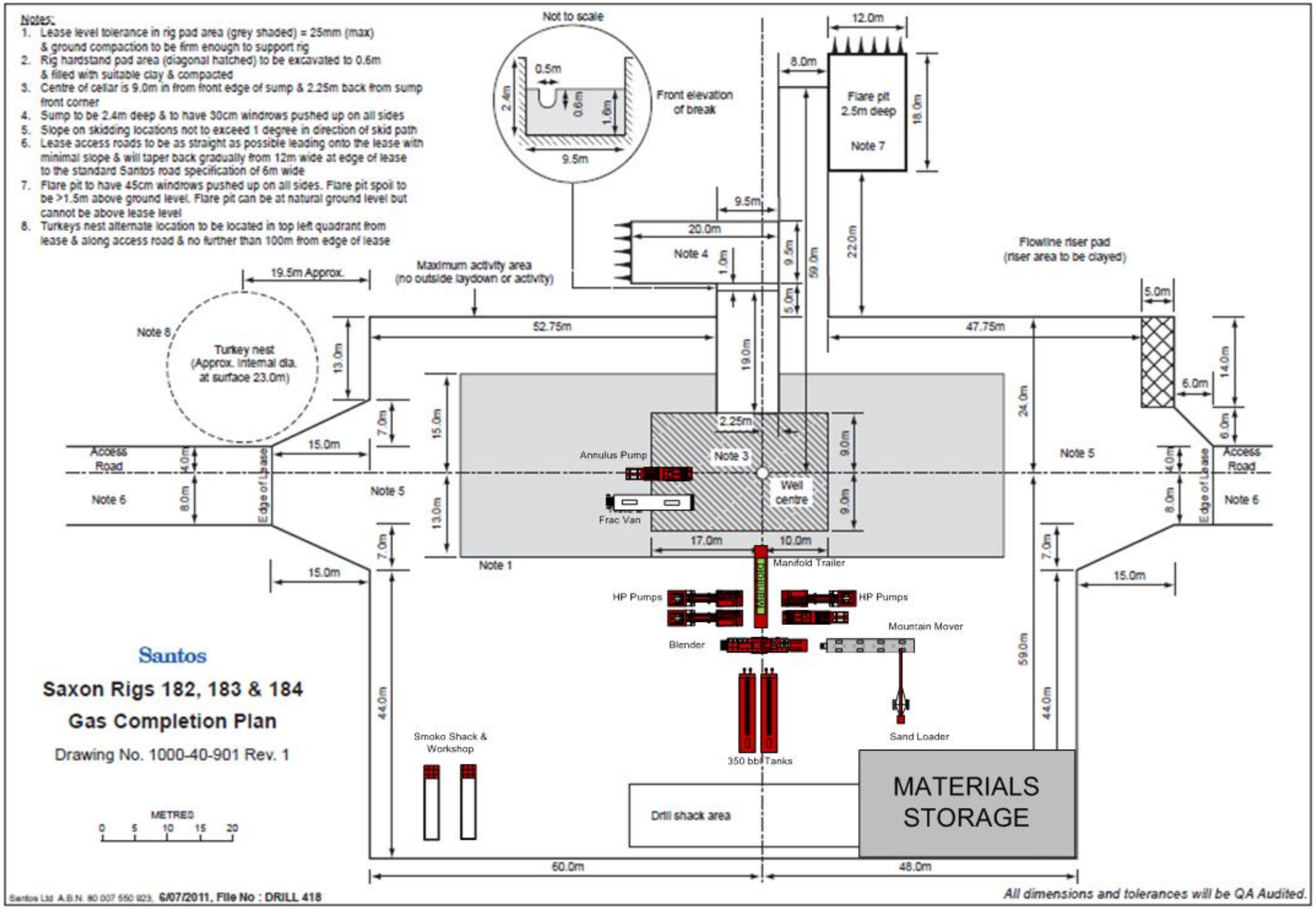


Figure D2: Conventional Gas Well Lease Set Up

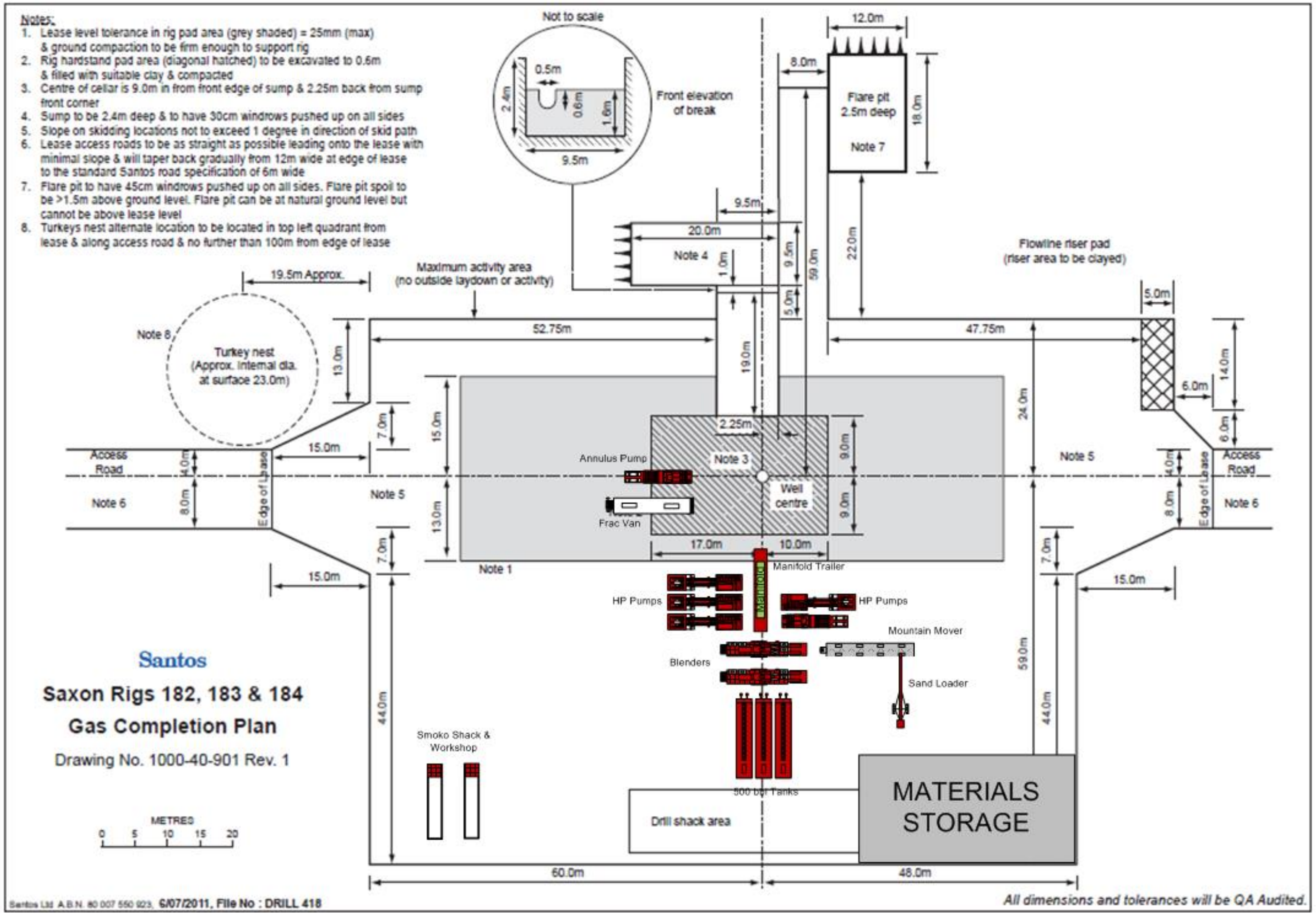
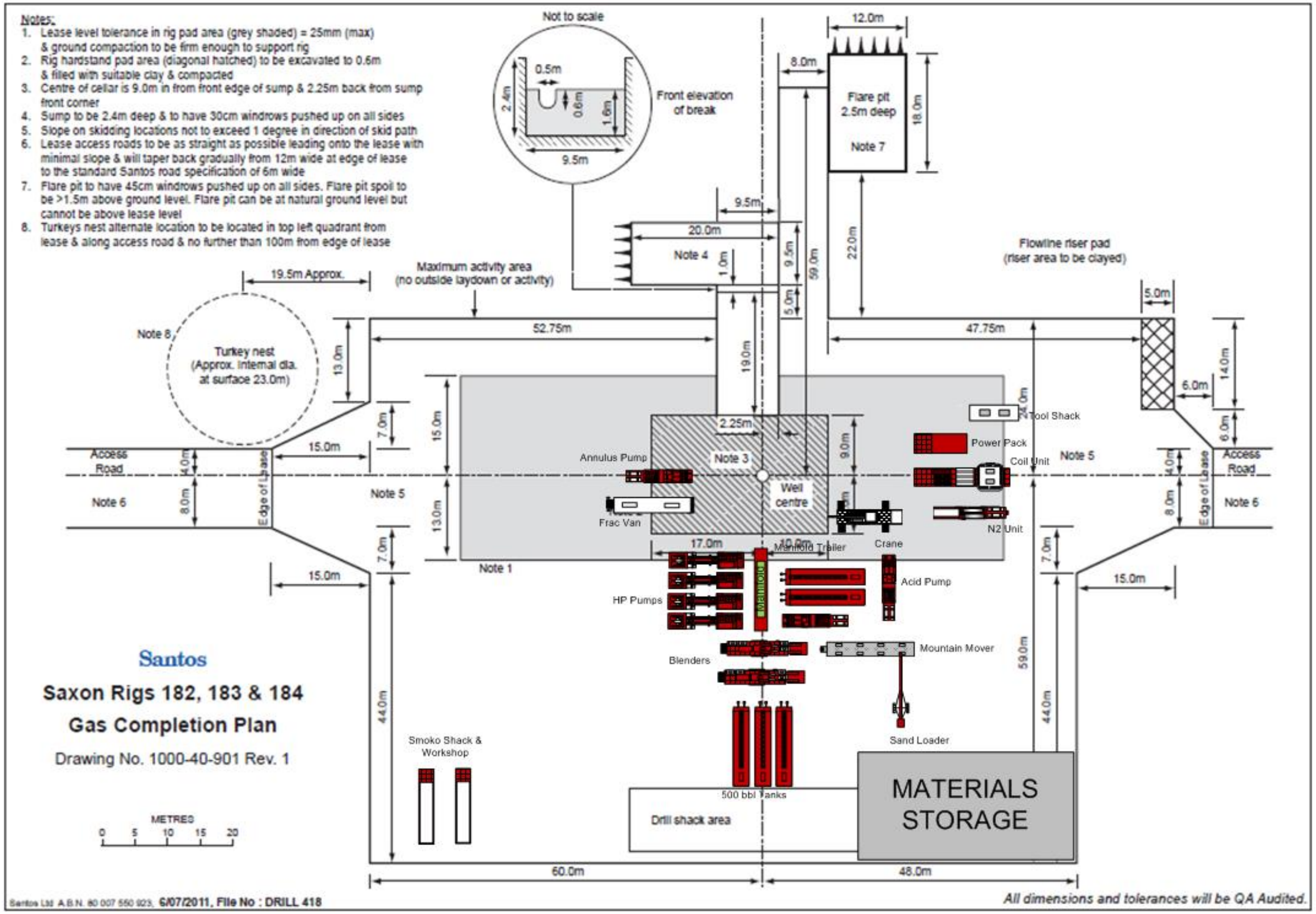


Figure D3: Deep Gas Well Lease Set Up (Coil Tubing Assisted Stimulation)



APPENDIX E

Historical Well Hydraulic Stimulations in SWQ

Appendix E - Historical Well Hydraulic Fracturing Events in SW Queensland

Name	Latitude	Longitude	Date Fractured
Challum 1	-27.393	141.574	Sep-1987
Brumby 2	-28.381	140.959	Jun-1989
Wilson 4	-27.566	142.426	Jul-1989
Brumby 1	-28.409	140.991	Aug-1991
Epsilon 2	-28.142	141.133	Dec-1991
Epsilon 1	-28.145	141.154	Apr-1992
Thungo 2	-27.735	142.577	Jan-1993
Patroclus 1	-28.111	141.681	Dec-1994
Stokes 1	-28.345	141.029	Mar-1997
Yanda 8	-27.452	141.821	Jun-1997
Challum 3	-27.388	141.537	Oct-1998
Coolah 2	-26.956	141.835	Nov-1998
Challum 13	-27.373	141.571	May-1999
Wolgolla 2	-28.193	141.334	May-2002
Dartmoor 1	-27.687	142.540	Sep-2002
Thungo 7	-27.722	142.582	Sep-2002
Juno 5	-27.697	141.829	Oct-2002
Thungo 7	-27.722	142.582	Oct-2002
Juno 5	-27.697	141.829	Oct-2002
Juno 2	-27.688	141.829	Oct-2002
Juno 5	-27.697	141.829	Oct-2002
Coonaberry 1	-26.851	142.104	Oct-2002
Ramses 1	-26.764	142.102	Nov-2002
Moon 1	-28.227	141.042	Nov-2002
Ipundu North 2	-26.911	143.307	Jan-2004
Talgeberry 2	-26.948	143.430	Jan-2004
Talgeberry 8	-26.952	143.432	Jan-2004
Challum 24	-27.381	141.598	Jan-2004
Challum 22	-27.408	141.650	Jan-2004
Karmona 3	-27.304	141.883	Jan-2004
Ipundu North 11	-26.917	143.310	Jan-2004
Ipundu North 11	-26.917	143.310	Jan-2004

Name	Latitude	Longitude	Date Fractured
Thungo 8	-27.719	142.585	Jan-2004
Ipundu North 2	-26.911	143.307	Feb-2004
Mulberry 1	-26.892	143.402	Feb-2004
Roti West 1	-27.367	142.143	Mar-2004
Gimboola West 1	-26.872	143.403	Oct-2004
Winninia 1	-27.856	141.836	Nov-2004
Winninia North 2	-27.828	141.894	Nov-2004
Baryulah 6	-27.753	141.869	Dec-2004
Baryulah 6	-27.753	141.869	Dec-2004
Baryulah 6	-27.753	141.869	Dec-2004
Baryulah 6	-27.753	141.869	Dec-2004
Baryulah 6	-27.753	141.869	Dec-2004
Baryulah 6	-27.753	141.869	Dec-2004
Winninia North 3	-27.826	141.879	Jan-2005
Winninia North 3	-27.826	141.879	Jan-2005
Winninia North 3	-27.826	141.879	Jan-2005
Winninia North 3	-27.826	141.879	Jan-2005
Winninia North 3	-27.826	141.879	Jan-2005
Endeavour 1	-26.789	143.382	Feb-2005
Endeavour 2	-26.796	143.379	Feb-2005
Talgeberry 7	-26.944	143.430	Feb-2005
Talgeberry 7	-26.944	143.430	Feb-2005
Cranstoun 1	-26.814	143.387	Apr-2005
Takyah 1	-27.010	143.301	Apr-2005
Takyah 1	-27.010	143.301	Apr-2005
Mulberry 2	-26.891	143.397	May-2005
Mulberry 3	-26.895	143.409	May-2005
Ipundu North 9	-26.918	143.305	May-2005
Ipundu North 4	-26.914	143.306	May-2005
Mulberry 4	-26.890	143.405	Jun-2005
Ipundu North 9	-26.918	143.305	Jun-2005
Ipundu North 4	-26.914	143.306	Jul-2005
Ipundu North 4	-26.914	143.306	Jul-2005

Name	Latitude	Longitude	Date Fractured
Iliad 1	-28.294	141.366	Aug-2005
Iliad 2	-28.294	141.355	Aug-2005
Jackson 45	-27.578	142.414	Aug-2005
Ipundu 12	-26.936	143.332	Aug-2005
Ipundu 12	-26.936	143.332	Aug-2005
Tartulla 6	-27.207	142.139	Oct-2005
Psyche 4	-27.929	141.810	Oct-2005
Barylah 8	-27.738	141.834	Nov-2005
Barylah 8	-27.738	141.834	Nov-2005
Barylah 8	-27.738	141.834	Nov-2005
Barylah 8	-27.738	141.834	Nov-2005
Barylah 7	-27.750	141.857	Nov-2005
Barylah 7	-27.750	141.857	Nov-2005
Barylah 7	-27.750	141.857	Nov-2005
Barylah 7	-27.750	141.857	Nov-2005
Talgeberry 6	-26.945	143.420	Nov-2005
Ipundu 4A	-26.936	143.333	Nov-2005
Ipundu 4A	-26.936	143.333	Nov-2005
Wellington 5	-27.739	141.865	Nov-2005
Thoar 3	-28.025	141.775	Nov-2005
Barylah 9	-27.759	141.847	Dec-2005
Barylah 9	-27.759	141.847	Dec-2005
Barylah 9	-27.759	141.847	Dec-2005
Barylah 9	-27.759	141.847	Dec-2005
Wellington 5	-27.739	141.865	Dec-2005
Juno 4	-27.687	141.837	Dec-2005
Juno 4	-27.687	141.837	Dec-2005
Juno 4	-27.687	141.837	Dec-2005
Juno 4	-27.687	141.837	Dec-2005
Juno 4	-27.687	141.837	Dec-2005
Juno 4	-27.687	141.837	Dec-2005
Psyche 3	-27.942	141.824	Dec-2005
Durham Downs North 2	-27.054	141.821	Jan-2006

Name	Latitude	Longitude	Date Fractured
Baryulah 10	-27.756	141.878	Jan-2006
Baryulah 10	-27.756	141.878	Jan-2006
Baryulah 10	-27.756	141.878	Jan-2006
Baryulah 10	-27.756	141.878	Jan-2006
Winna 4	-27.725	142.540	Jan-2006
Talgeberry 4	-26.945	143.435	Jan-2006
Talgeberry 4	-26.945	143.435	Jan-2006
Tickalara 10	-28.344	141.378	Feb-2006
Iliad 3	-28.293	141.364	Feb-2006
Tickalara 3	-28.341	141.384	Mar-2006
Sigma 1	-28.335	141.340	Mar-2006
Sigma 2	-28.340	141.341	Mar-2006
Mulberry 6	-26.894	143.399	Mar-2006
Dululu 1	-28.326	141.440	Mar-2006
Yanda 16	-27.449	141.826	Apr-2006
Tickalara 3	-28.341	141.384	Apr-2006
Mulberry 8	-26.899	143.399	Apr-2006
Yanda 16	-27.449	141.826	Apr-2006
Mulberry 9	-26.899	143.406	May-2006
Mulberry 10A	-26.902	143.414	May-2006
Chancett 1	-26.856	143.406	May-2006
Mulberry 14	-26.899	143.411	May-2006
Mulberry 16	-26.888	143.399	May-2006
Gimboola 3	-26.880	143.412	May-2006
Epsilon 3	-28.161	141.137	Jun-2006
Toby 1	-26.685	142.368	Jun-2006
Mulberry 15	-26.888	143.393	Jun-2006
Kercummurra 1	-27.108	142.433	Jul-2006
Endeavour 8	-26.800	143.377	Jul-2006
Mulberry 17	-26.899	143.388	Jul-2006
Gimboola 2	-26.880	143.418	Jul-2006
Mulberry 12	-26.884	143.392	Jul-2006
Gimboola 4a	-26.875	143.412	Aug-2006

Name	Latitude	Longitude	Date Fractured
Endeavour 9	-26.781	143.391	Aug-2006
Endeavour 7	-26.795	143.382	Aug-2006
Talgeberry 12	-26.941	143.433	Aug-2006
Talgeberry 13	-26.940	143.427	Aug-2006
Minni Ritchi 1	-26.825	143.375	Aug-2006
Cranstoun 3	-26.817	143.390	Sep-2006
Talgeberry 9	-26.948	143.424	Sep-2006
Talgeberry 11	-26.948	143.436	Sep-2006
Patroclus 1	-28.111	141.681	Sep-2006
Patroclus 1	-28.111	141.681	Sep-2006
Orientos 2	-28.048	141.428	Oct-2006
Talgeberry 14	-26.946	143.441	Oct-2006
Endeavour 18	-26.800	143.370	Oct-2006
Kooyong 1	-26.809	143.355	Oct-2006
Endeavour 19	-26.806	143.370	Oct-2006
Mulberry 19	-26.899	143.393	Oct-2006
Mulberry 22	-26.904	143.405	Oct-2006
Mulberry 21	-26.904	143.400	Oct-2006
Mulberry 23	-26.910	143.399	Oct-2006
Endeavour 5	-26.789	143.377	Oct-2006
Mulberry 5	-26.894	143.405	Oct-2006
Endeavour 16	-26.795	143.370	Nov-2006
Endeavour 13	-26.789	143.370	Nov-2006
Barrolka 9	-26.862	141.758	Nov-2006
Barrolka 9	-26.862	141.758	Nov-2006
Yanda 19	-27.459	141.793	Nov-2006
Durham Downs 4	-27.077	141.786	Nov-2006
Winninia North 1	-27.814	141.888	Nov-2006
Yanda 20	-27.453	141.796	Nov-2006
Yanda 19	-27.459	141.793	Nov-2006
Baryulah 12	-27.740	141.847	Nov-2006
Endeavour 15	-26.795	143.376	Nov-2006
Baryulah 12	-27.740	141.847	Dec-2006

Name	Latitude	Longitude	Date Fractured
Barylah 12	-27.740	141.847	Dec-2006
Barylah 12	-27.740	141.847	Dec-2006
Barylah 12	-27.740	141.847	Dec-2006
Barylah 12	-27.740	141.847	Dec-2006
Barylah 11	-27.753	141.843	Dec-2006
Yanda 20	-27.453	141.796	Dec-2006
Barylah 11	-27.753	141.843	Dec-2006
Barylah 11	-27.753	141.843	Dec-2006
Barylah 11	-27.753	141.843	Dec-2006
Yanda 24	-27.458	141.808	Dec-2006
Barylah 11	-27.753	141.843	Dec-2006
Yanda 21	-27.449	141.804	Dec-2006
Barylah 11	-27.753	141.843	Dec-2006
Theta 1	-27.979	141.745	Jan-2007
Yanda 22	-27.446	141.814	Jan-2007
Theta 1	-27.979	141.745	Jan-2007
Kooroopa North 1	-27.001	143.230	Feb-2007
Kooroopa North 2	-26.996	143.218	Feb-2007
Jackson 28	-27.583	142.413	Feb-2007
Endeavour 34	-26.803	143.373	Mar-2007
Endeavour 33	-26.803	143.367	Mar-2007
Endeavour 26	-26.783	143.388	Mar-2007
Mulberry 11	-26.894	143.393	Mar-2007
Thungo 9	-27.725	142.583	May-2007
Thungo 13	-27.734	142.581	May-2007
Dilkera North 1	-27.739	142.641	May-2007
Thungo 10	-27.728	142.583	May-2007
Thungo 11	-27.729	142.573	May-2007
Endeavour 28	-26.789	143.388	May-2007
Mulberry 29	-26.893	143.388	May-2007
Mulberry 42	-26.888	143.381	May-2007
Mulberry 44	-26.899	143.382	May-2007
Mulberry 26	-26.886	143.389	May-2007

Name	Latitude	Longitude	Date Fractured
Endeavour 39	-26.806	143.364	May-2007
Endeavour 25	-26.783	143.381	May-2007
Endeavour 35	-26.787	143.373	May-2007
Talgeberry 5	-26.936	143.435	May-2007
Mulberry 27	-26.888	143.387	May-2007
Currambar 1	-27.753	142.666	Jun-2007
Muthero 6	-27.712	142.615	Jun-2007
Muthero 7	-27.712	142.612	Jun-2007
Endeavour 29	-26.793	143.367	Jun-2007
Mulberry 35	-26.913	143.403	Jun-2007
Yanda 25	-27.460	141.799	Jun-2007
Takyah 2	-27.011	143.282	Jul-2007
Kooroopa 3	-27.024	143.236	Jul-2007
Coonaberry 2	-26.842	142.109	Aug-2007
Coonaberry 2	-26.842	142.109	Aug-2007
Challum West 1	-27.358	141.503	Aug-2007
Lepard 1	-27.827	141.732	Aug-2007
Lepard 1	-27.827	141.732	Aug-2007
Lepard 1	-27.827	141.732	Aug-2007
Lepard 1	-27.827	141.732	Aug-2007
Lepard 1	-27.827	141.732	Aug-2007
Patroclus 4	-28.116	141.689	Sep-2007
Ipundu 2	-26.926	143.321	Sep-2007
Ipundu 14	-26.937	143.337	Sep-2007
Mulberry 33	-26.896	143.402	Oct-2007
Mulberry 34	-26.896	143.402	Oct-2007
Mulberry 31	-26.896	143.402	Oct-2007
Mulberry 32	-26.896	143.402	Oct-2007
Talgeberry 18	-26.945	143.427	Oct-2007
Talgeberry 22	-26.940	143.438	Oct-2007
Dilkera 2	-27.744	142.629	Jan-2008
Jackson 17	-27.598	142.419	Mar-2008
Mama 1	0.000	0.000	Aug-2008

Name	Latitude	Longitude	Date Fractured
Yanda 15	-27.452	141.807	Sep-2008
Durham Downs North 1	-27.054	141.810	Oct-2008
Tartulla 8	-27.195	142.151	Oct-2008
Ramses 2	-26.755	142.106	Nov-2008
Iliad 4	-28.294	141.370	Nov-2008
Iliad 6	-28.297	141.365	Nov-2008
Galex 2	-27.453	141.852	Nov-2008
Yawa 2	-27.376	141.929	Nov-2008
Vega 3	-27.719	141.864	Dec-2008
Vega 3	-27.719	141.864	Dec-2008
Vega 3	-27.719	141.864	Dec-2008
Vega 3	-27.719	141.864	Dec-2008
Vega 3	-27.719	141.864	Dec-2008
Vega 3	-27.719	141.864	Dec-2008
Vega 3	-27.719	141.864	Dec-2008
Iliad 5	-28.296	141.353	Sep-2009
Baryulah 4	-27.752	141.873	Sep-2009
Baryulah 4	-27.752	141.873	Sep-2009
Baryulah 4	-27.752	141.873	Sep-2009
Baryulah 4	-27.752	141.873	Oct-2009
Baryulah 4	-27.752	141.873	Oct-2009
Baryulah 5	-27.755	141.865	Oct-2009
Baryulah 5	-27.755	141.865	Oct-2009
Baryulah 5	-27.755	141.865	Oct-2009
Baryulah 5	-27.755	141.865	Oct-2009
Theta 2	-27.960	141.726	Oct-2009
Psyche 6	-27.903	141.818	Oct-2009
Okotoko West 2	-27.351	141.956	Oct-2009
Baryulah 5	-27.755	141.865	Nov-2009
Ipundu 16	-26.928	143.320	Jun-2010
Ipundu North 13	-26.916	143.302	Jun-2010
Patroclus 3	-28.114	141.687	Jun-2010
Moon 1	-28.227	141.042	Jul-2010

Name	Latitude	Longitude	Date Fractured
Moon 1	-28.227	141.042	Jul-2010
Moon 1	-28.227	141.042	Jul-2010
Moon 1	-28.227	141.042	Jul-2010
Challum 5	-27.416	141.657	- (1)
Dingera 2	-27.957	141.901	- (1)
Dilkera 3	-27.742	142.634	- (1)
Psyche 2	-27.916	141.836	- (1)
Mulberry 24	-26.910	143.417	- (1)
Psyche 2	-27.916	141.836	- (1)
Endeavour 11	-26.791	143.385	- (1)
Ramses 2	-26.755	142.106	- (1)
Genoa 2	-28.141	141.853	- (1)
Challum 23	-27.403	141.589	Mar-13
Challum 5	-27.416	141.657	Mar-13
Karmona 5	-27.312	141.89	Mar-13
Durham Downs 2	-27.104	141.811	Mar-13
Psyche 1	-27.913	141.813	Mar-13
Baryulah 15	-27.762	141.835	Mar-13
Baryulah 13	-27.755	141.883	Apr-13
Brumby 13	-28.388	141.002	Apr-13
Baryluah 14	-27.756	141.87	Apr-13
Lepard 2	-27.836	141.736	Jul-13
Psyche 7	-27.921	141.814	Jul-13
Juno 6	-27.701	141.823	Jul-13
Karmona 6	-27.303	141.901	Jul-13
Galex 2	-27.453	141.852	Aug-13
Curri 1	-27.365	141.821	Aug-13
Challum 7	-27.39	141.55	Aug-13
Raffle 1	-28.011	141.588	Aug-13
Okotoko West 3ST1	-27.354	141.963	Oct-13
Barrolka 12	-26.88	141.761	Mar-14
Barrolka 11	-26.863	141.743	Apr-14
Barrolka 13	-26.851	141.776	Apr-14

Name	Latitude	Longitude	Date Fractured
Durham Downs 1	-27.081	141.79	Apr-14
Baryulah 18	-27.74	141.844	Apr-14
Baryulah 17	-27.75	141.878	May-14
Vega 4	-27.72	141.875	Jul-14
Vega 5	-27.725	141.881	Jul-14
Kanook 1	-27.106	141.915	Jul-14
Bolah 1	-26.969	141.638	Jul-14
Toby 1	-26.685	142.368	Aug-14
Hera 3	-27.689	141.862	Aug-14
Hera 4	-27.689	141.862	Aug-14
Durham Downs 6	-27.066	141.78	Nov-14
Durham Downs 7ST1	-27.096	141.795	Nov-14
Durham Downs 8	-27.112	141.791	Nov-14
Durham Downs North 4	-27.041	141.806	Nov-14
Cook 29H	-26.692	141.291	Dec-14
Monte 1	-27.29	141.775	May-15
Beeree 1	-26.91	141.614	Jun-15
Barrolka 15	-26.894	141.762	Jun-15
Barrolka 17	-26.86	141.672	Jun-15
Barrolka 16	-26.838	141.7	Jun-15
Barrolka 14	-26.86	141.672	Jun-15
Toby 2	-26.676	142.371	Aug-15
Whanto 2	-26.523	142.186	Aug-15
Whanto 3	-26.523	142.186	Aug-15
Mt Howitt 3DW1	-26.594	142.489	Aug-15
Hebe 1	-27.73	141.958	Aug-15
Bolah 2	-26.986	141.661	Dec-15
Cuisinier 14	-26.669	141.232	Dec-15
Cuisinier 9	-26.704	141.233	Dec-15
Cuisinier 5	-26.704	141.224	Dec-15
Cuisinier 12	-26.675	141.231	Dec-15
Cuisinier 3	-26.693	141.226	Dec-15
Durham Downs North 6	-27.058	141.826	Nov-16

Name	Latitude	Longitude	Date Fractured
Whanto 3	-26.523	142.186	Aug-15
Whanto 2	-26.523	142.186	Aug-15
Whanto 4	-26.535	142.213	Nov-16
Whanto South West 1	-26.607	142.16	Nov-16
Whanto West 1	-26.526	142.157	Oct-16
Barta North 1	-26.705	141.184	Dec-16
Cuisinier 22	-26.658	141.229	Dec-16
Dilkera 3	-27.742	142.634	Dec-16
Maxwell 2	-27.886	142.695	Dec-16
Wippo East 1	-27.294	142.121	Apr-17
Roti South 1	-27.397	142.149	Apr-17
Windigo 3	-27.391	142.112	Apr-17
Galex 4	-27.455	141.856	May-17
Galex 5	-27.455	141.856	May-17
Coolah 3	-26.955	141.814	May-17
Whanto West 1	-26.526	142.157	Jul-17
Marama West 1	-26.056	142.099	Jul-17
Kaiden 1	-26.337	142.053	Aug-17
Lepard 3	-27.825	141.717	Sep-17
Wippo 1	-27.286	142.091	Oct-17
Roti 3	-27.389	142.181	Nov-17
Roti 5	-27.379	142.164	Oct-17
Roti 6	-27.379	142.164	Oct-17
Takyah 6	-27.006	143	Feb-18
Epsilon 4	-28.176	141.13	Mar-18
Mountain Goat 1	-27.407	141.145	Jul-18
Cocinero 6	-26.721	141.268	Aug-18
Shefu 1	-26.674	141.169	Aug-18
Cuisinier North 1	-26.665	141.232	Aug-18
Cuisinier 24	-26.701	141.24	Aug-18
Cocinero 2	-26.705	141.262	Aug-18
Whanto 5	-26.536	142.17	Aug-18
Coonaberry 4	-26.866	142.102	Aug-18

Name	Latitude	Longitude	Date Fractured
Cuisinier 19	-26.724	141.244	Dec-18
Cocinero 3	-26.695	141.257	Dec-18
Bearcat 1	-27.752	141.726	Mar-19
Bolah 3	-26.985	141.646	Jan-19
Bolah 4	-26.986	141.646	Feb-19
Ipundu 20	-26.924	143.311	Mar-19
Ipundu 19	-26.946	143.339	Mar-19
Cuisinier 28	-26.698	141.232	May-19
Cuisinier 27	-26.699	141.247	May-19
Cuisinier 21	-26.666	141.214	May-19
Cuisinier 15	-26.695	141.237	May-19
Barrolka 20	-26.876	141.742	May-19
Anna North 1	-27.099	141.693	May-19

(1) No record

APPENDIX F

Potential Hydraulic Stimulation Locations

Appendix F – Potential Hydraulic Fracture Locations

	Proposed Fracture Dates		
Field	**2020**	**2021**	**2022**
ANNA NORTH	0	1	0
BARROLKA	3	4	1
BASSET	1	0	0
BEARCAT	0	1	0
BOLAH	1	1	0
BOLAN EAST	0	1	0
COCINERO	0	3	0
COOLAH	0	4	0
CORRIDOR NORTH	0	1	0
COUGAR	0	1	0
CUISINIER	3	3	3
DILKERA	0	0	1
DURHAM DOWNS	1	1	0
ENDEAVOUR	0	0	2
HEMNANT	0	1	0
HERA	0	0	1
HOUBY	0	1	0
KANOOK SOUTH	0	1	0
MAYA	0	0	1
MIRANDA	1	0	0
MOOLIAMPAH	0	0	1
MOON	1	0	0
MOUNTAIN GOAT	0	1	0
PSYCHE	0	1	0
SNOWBALL	1	0	0
TARTULLA	1	0	0
THUNGO	0	0	1
TOBY	0	2	0
VEGA	0	0	1
WACKETT	2	0	0
WATSON NORTH	2	0	2

	Proposed Fracture Dates		
Field	2020	2021	2022
WOLGOLLA WEST	1	0	0
DUNADOO/ DUNADOO EAST	0	4	0
JUNO/ JUNO NORTH	0	0	1
WIPPO/WIPPO SOUTH	1	1	0

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