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BIOREGIONAL ASSESSMENTS

CSIRO

Geology of the Cooper GBA region

Technical appendix for the Geological and Bioregional Assessment: Stage 2

2020

A scientific collaboration between the Department of Agriculture, Water and the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia

The Geological and Bioregional Assessment Program

The Geological and Bioregional Assessment Program will provide independent scientific advice on the potential impacts from development of selected unconventional hydrocarbon plays on water and the environment. The geological and environmental data and tools produced by the Program will assist governments, industry, landowners and the community to help inform decision making and enhance the coordinated management of potential impacts.

The Program is funded by the Australian Government Department of the Environment and Energy. The Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia are collaborating to undertake geological and bioregional assessments. For more information, visit http://www.bioregionalassessments.gov.au.

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Authorship is listed in relative order of contribution.

On 1 February 2020 the Department of the Environment and Energy and the Department of Agriculture merged to form the Department of Agriculture, Water and the Environment. Work for this document was carried out under the then Department of the Environment and Energy. Therefore, references to both departments are retained in this report.

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Cover photograph

Cooper Creek in flood, 4 km east of Windorah, March 2018.
Credit: Geological and Bioregional Assessment Program, Russell Crosbie (CSIRO)
Element number: GBA-COO-2-343

Executive summary

This appendix provides a regional geological analysis and conceptualisation of the Cooper Geological and Bioregional Assessment (GBA) region. It delivers information critical for the shale, tight and deep coal gas prospectivity assessment outlined in the petroleum prospectivity technical appendix (Lech et al., 2020), and for input into assessing the potential impacts on groundwater and surface water assets detailed in the hydrogeology (Evans et al., 2020) and hydraulic fracturing (Kear and Kasperczyk, 2020) technical appendices.

The Cooper Basin is a Carboniferous to Triassic intracratonic basin in north-eastern South Australia and south-western Queensland. It has a total area of approximately 130,000 km^2, of which about three quarters lies within Queensland and the remainder lies within South Australia.

Section 2 provides a comprehensive inventory and review of existing open data and information for the Cooper GBA region relevant for the prospectivity assessment (Lech et al., 2020) and hydrogeological characterisation (Evans et al., 2020). It includes discussion of the datasets incorporated in the data inventory. A broad range of datasets were utilised to develop a three-dimensional conceptualisation of the geological basin. These include: geographic and cultural datasets that detail the location and nature of administrative boundaries, infrastructure and topography; and geological datasets such as surface geology and geological provinces, well and seismic data and geophysical data. A range of public domain publications, reports and data packages for the Cooper Basin are also utilised to characterise the basin architecture and evolution.

Section 3 reviews the Cooper Basin's geological setting and the GBA region's basin evolution from pre-Permian basement to creation of the Cooper, Eromanga and Lake Eyre basins. Section 4 reviews the main structural elements of the Cooper Basin and how these relate to the basin's stratigraphy and evolution.

The base of the Cooper Basin succession lies at depths of up to 4500 m, and reaches thicknesses in excess of 2400 m. In the south-west, the Cooper Basin unconformably overlies lower Paleozoic sediments of the Warburton Basin, and includes three major troughs (Patchawarra, Nappamerri and Tenappera troughs). The depocentres include a thick succession of Permian to Triassic sediments (the Gidgealpa and Nappamerri groups) deposited in fluvio-glacial to fluvio-lacustrine and deltaic environments. The north-eastern Cooper Basin overlies Devonian sediments associated with the Adavale Basin. Here the Permian succession is thinner than in the south-west, and the major depocentres, including the Windorah Trough and Ullenbury Depression, are generally less well defined.

The Cooper Basin is entirely and disconformably overlain by the Jurassic–Cretaceous Eromanga Basin. In the Cooper GBA region the Eromanga Basin includes two major depocentres, the Central Eromanga Depocentre and the Poolowanna Trough, and is in excess of 2500 m thick. Deposition within the Eromanga Basin was relatively continuous and widespread and was controlled by subsidence due to plate tectonic events along the eastern margins of the Australian Plate. The Eromanga Basin is comprised of a stratigraphic succession of terrestrial and marine origin. It includes a basal succession of terrestrial sedimentary rocks, followed by a middle marine succession, then finally an upper terrestrial succession.

The Lake Eyre Basin is a Cenozoic sedimentary succession overlying the Eromanga Basin, covering parts of northern and eastern South Australia, south-eastern Northern Territory, western Queensland and north-western New South Wales. The Lake Eyre Basin is subdivided into sub-basins, with the northern part of the Callabonna Sub-basin overlying the Cooper Basin. Here the basin is up to 300 m thick and contains sediments deposited from the Paleocene through to the Quaternary. Deposition within the Lake Eyre Basin is recognised to have occurred in three phases, punctuated by periods of tectonic activity and deep weathering.

This technical appendix provides the conceptual framework to better understand the potential connectivity between the Cooper Basin and overlying aquifers of the Great Artesian Basin and to help understand potential impacts of shale, tight and deep coal gas development on water and water-dependent assets.

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- Internal Peer Review Group: Geoscience Australia: Robert Langford, Ron Hackney and David Robinson
- Technical Peer Review Group: Andrew Boulton, Peter McCabe, Catherine Moore and Jenny Stauber
- State Government Science Technical Review: This group includes scientists from the Queensland and South Australian governments.

Abbreviations and acronyms

Abbreviation/acronym	Definition
CO_2	Carbon dioxide
CSG	Coal seam gas
DEM	Digital elevation model
DMITRE	Department for Manufacturing, Innovation, Trade, Resources and Energy
GBA	Geological and Bioregional Assessment
GMI	Gidgealpa–Merrimelia–Innamincka
IMEA	Impact Modes and Effects Analysis
JNP	Jackson–Naccowlah–Pepita
Ma	Million years before the present
NGMA	National Geoscience Mapping Accord
NSW	New South Wales
QLD	Queensland
SA	South Australia
TMI	Total magnetic intensity
TOC	Total organic carbon
WMS	Web Map Server

Units

Unit	Description
km	Kilometre
km^2	Kilometre squared
m	Metre
m^2	Metre squared
Ma	Millions of years before the present
Myr	Million years
mgal	Milligal
nT	Nanotesla

The Geological and Bioregional Assessment Program

The $35.4 million Geological and Bioregional Assessment (GBA) Program is assessing the potential environmental impacts of shale and tight gas development to inform regulatory frameworks and appropriate management approaches. The geological and environmental knowledge, data and tools produced by the Program will assist governments, industry, landowners and the community by informing decision making and enabling the coordinated management of potential impacts.

In consultation with state and territory governments and industry, three geological basins were selected based on prioritisation and ranking in Stage 1: Cooper Basin, Isa Superbasin and Beetaloo Sub-basin. In Stage 2, geological, hydrological and ecological data were used to define 'GBA regions': the Cooper GBA region in Queensland, SA and NSW; the Isa GBA region in Queensland; and the Beetaloo GBA region in NT. In early 2018, deep coal gas was added to the assessment for the Cooper GBA region, as this play is actively being explored by industry.

The GBA Program will assess the potential impacts of selected shale and tight gas development on water and the environment and provide independent scientific advice to governments, landowners, the community, business and investors to inform decision making. Geoscience Australia and CSIRO are conducting the assessments. The Program is managed by the Department of the Environment and Energy and supported by the Bureau of Meteorology.

The GBA Program aims to:

- inform government and industry and encourage exploration to bring new gas supplies to the East Coast Gas Market within five to ten years
- increase understanding of the potential impacts on water and the environment posed by development of shale, tight and deep coal gas resources
- increase the efficiency of assessment and ongoing regulation, particularly through improved reporting and data provision/management approaches
- improve community understanding of the industry.

The GBA Program commenced in July 2017 and comprises three stages:

- **Stage 1 Rapid regional basin prioritisation** identified and prioritised geological basins with the greatest potential to deliver shale and/or tight gas to the East Coast Gas Market within the next five to ten years.
- **Stage 2 Geological and environmental baseline assessments** is compiling and analysing available data for the three selected regions to form a baseline and identify gaps to guide collection of additional baseline data where needed. This analysis includes a geological basin assessment to define structural and stratigraphic characteristics and an environmental data synthesis.
- **Stage 3 Impact analysis and management** will analyse the potential impacts to water resources and matters of environmental significance to inform and support Commonwealth and State management and compliance activities.

The PDF of this report and the supporting technical appendices are available at https://www.bioregionalassessments.gov.au/geological-and-bioregional-assessment-program.

About this report

Presented in this technical appendix is a description of the geology for the Cooper GBA region. It provides detailed information regarding the geological setting, tectonic evolution, depositional environments and structural and stratigraphic framework. The structure and focus of the synthesis report and technical appendices reflect the needs of government, industry, landowners and community groups.

Technical appendices

Other technical appendices that support the geological and environmental baseline assessment for the Cooper GBA region are:

- Lech ME, Wang L, Hall LS, Bailey A, Palu T, Owens R, Skeers N, Woods M, Dehelean A, Orr M, Cathro D and Evenden C (2020) Shale, tight and deep coal gas prospectivity of the Cooper Basin.
- Evans TJ, Martinez J, Lai ÉCS, Raiber M, Radke BM, Sundaram B, Ransley TR, Dehelean A, Skeers N, Woods M, Evenden C and Dunn B (2020) Hydrogeology of the Cooper GBA region.
- O'Grady AP, Herr A, MacFarlane CM, Merrin LE and Pavey C (2020) Protected matters for the Cooper GBA region.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D and Kookana R (2020) Qualitative environmental risk assessment of drilling and hydraulic fracturing chemicals for the Cooper GBA region.
- Kear J and Kasperczyk D (2020) Hydraulic fracturing and well integrity for the GBA regions.

All maps for the Cooper GBA region use the Map Grid of Australia (MGA) projection (zone 54) and the Geocentric Datum of Australia 1994 (GDA 1994).

1 Summary

Table 1 Summary table for the Cooper Basin

Jurisdiction		Queensland, South Australia
Area (km²)		Approximately 130,000 km²
Maximum sediment thickness		Max basin depth: >4500 km; Cooper Basin thickness: up to 2500 m
Age range		Late Carboniferous to Middle Triassic
Basin	**Overlies**	Warburton Basin, Warrabin and Barrolka troughs (Adavale Basin equivalent)
	Underlies	Eromanga Basin, Lake Eyre Basin
	Adjacent basins	Galilee Basin, Darling Basin, Adavale Basin
Basin type		Intracratonic
Depositional setting		Glacial, braided to meandering fluvial to floodplain, deltaic and lacustrine environments
Regional structure		Contractional and extensional events, producing faulted anticlines, ridges and basin depocentres
Seismic line km		>81,000 line km of two-dimensional seismic; >10,000 km² of three-dimensional seismic
Number of wells		>3000

1.1 Introduction

This technical appendix provides regional geological analysis and conceptualisation of the Cooper Basin in the context of shale, tight and deep coal gas prospectivity and development. It provides baseline datasets and information which were used for undertaking shale, tight and deep coal prospectivity analyses in the petroleum prospectivity technical appendix (Lech et al., 2020). This is a critical input in order to understand the potential impacts on water resources and water-dependent assets. A summary is provided in Table 1.

1.2 Basin location and extent

The Cooper Basin is located in north-eastern South Australia and south-western Queensland (Figure 1). The total area of the Cooper Basin is approximately 130,000 km², of which about two-thirds lies within Queensland and the remainder lies within north-eastern South Australia.

2 Data inventory

2.1 Introduction

A review of existing open file geological, petroleum and environmental data and information was undertaken for the Cooper GBA region, as follows.

- Relevant datasets compiled for the original Bioregional Assessment Program (Australian Government, 2018) and Stage 1 of the Geological and Bioregional Assessments Program (Hall et al., 2018) were identified and checked for currency.
- Additional geological and petroleum datasets were identified for use in the Geological and Bioregional Assessments Stage 2.
- The need for additional data compilation will be assessed again during Stage 3.

Where possible, the most recent data has been used. In some cases, an older dataset provides better spatial coverage and consistency, licensing conditions or applicability. The datasets considered as part of this assessment were limited to those that were considered appropriate and were publically available at the time of draft preparation (May 2018). To enable sufficient time for analysis, datasets were downloaded or acquired in April or May, 2018.

Data and ancillary materials are available from the Geological and Bioregional Assessments website, https://www.bioregionalassessments.gov.au/geological-and-bioregional-assessment-program. Datasets incorporated in the data inventory are discussed below.

2.2 Cultural, hydrography and relief

2.2.1 Administrative boundaries and infrastructure

All administrative boundaries and infrastructure (road and rail; Figure 1) are sourced from the Australian Topographic Base Map (Web Mercator) Web Map Server (WMS) (Geoscience Australia, 2015). This web map service is a seamless national dataset coverage for the whole of Australia and includes cultural, hydrography and relief themes. The map is a representation of the GA 1:250,000 topographic specification and portrays a detailed graphic representation of features that appear on the Earth's surface.

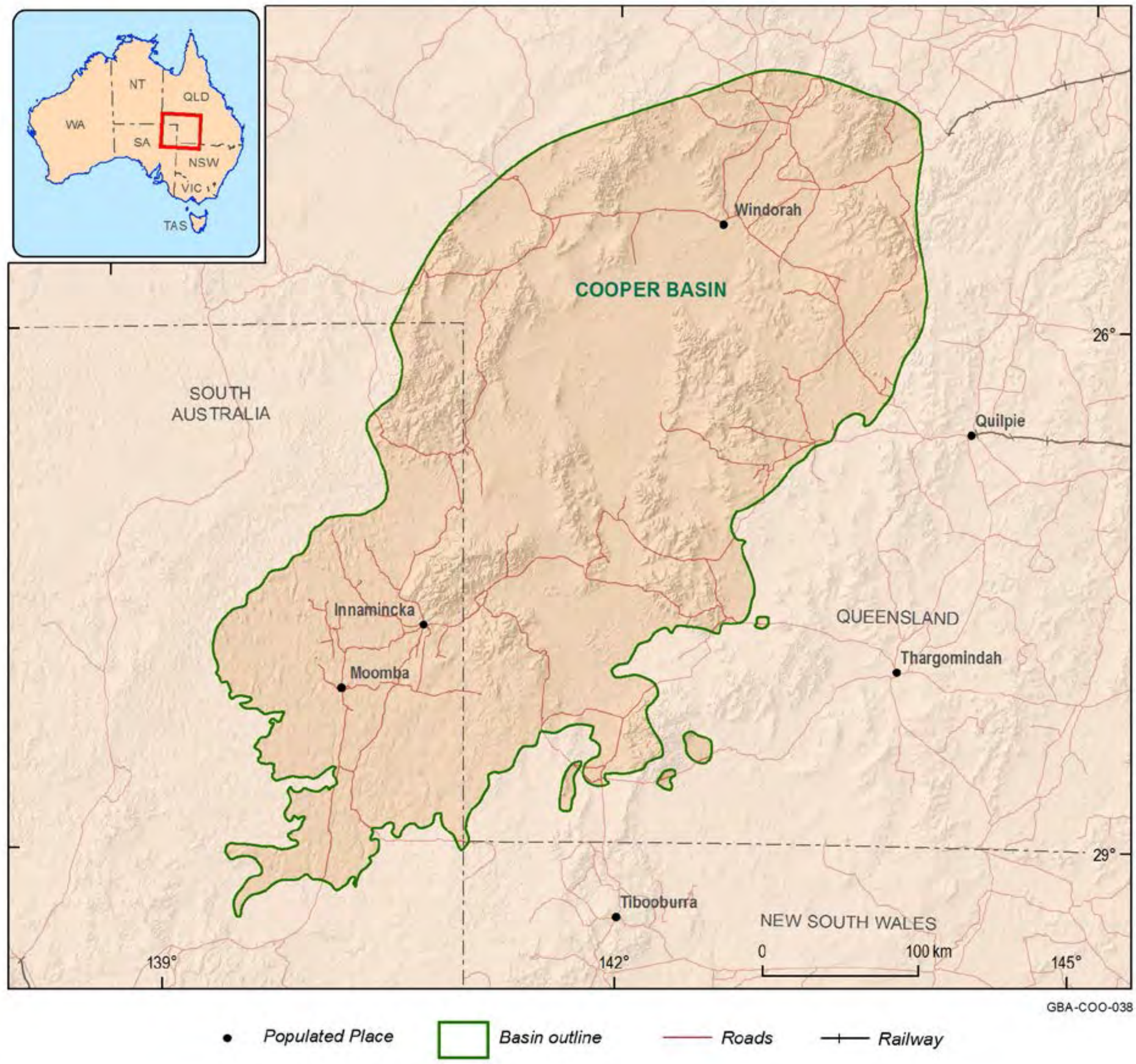

Figure 1 Administrative boundaries with road and rail infrastructure

Data: Cooper Basin outline from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008); Roads from Geoscience Australia (2017)
Element: GBA-COO-038

2.2.1.1 National oil and gas infrastructure

The National Oil and Gas Infrastructure datasets (Petrosys Pty Ltd, 2019) present the spatial locations of onshore oil and gas pipelines for the transmission of oil and gas within mainland Australia. They also present the location of oil and gas platforms and infrastructure facilities for the extraction, processing and/or storage of oil and natural gas. Pipeline and processing facilities for the Cooper Basin are shown in Figure 2.

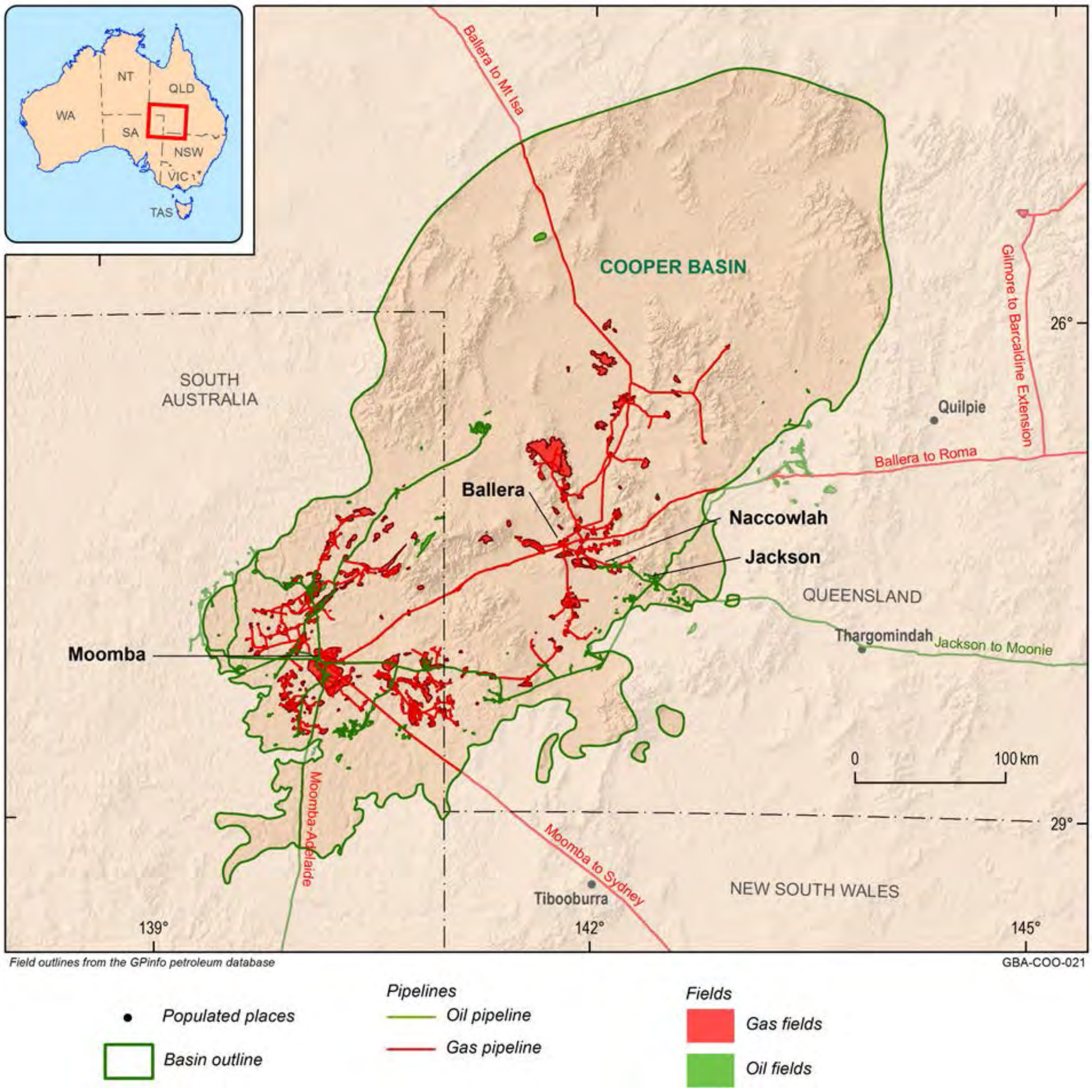

Figure 2 Gas processing facilities (labelled fields) and oil and gas pipelines

Data: Field outlines and pipeline routes from the GPinfo petroleum database, a Petrosys Pty Ltd product (Petrosys Pty Ltd, 2019); Cooper Basin outline from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)
Element: GBA-COO-021

2.2.2 Topographic and remote sensing data

By using the spatial patterns and spectral properties of radiation measured from surface rocks and regolith, remote sensing data like aerial photography, satellite imagery and radiometric data are used for geological mapping and boundary definition. As the primary purpose of the geological analysis in this study is an assessment of shale, tight and deep coal gas prospectivity of the Cooper Basin under the cover of the Lake Eyre and Eromanga basins, remotely sensed data from these sources have not been directly used. However, remotely sensed data have been used in previous studies for refining the surface geology of the Cooper GBA region. Remotely sensed data is also used for the mapping and assessment of surface geomorphology and soils, which are useful for an assessment of potential environmental risks of unconventional gas extraction. Remote sensing datasets are detailed in the hydrogeology technical appendix (Evans et al., 2020).

2.2.2.1 Digital elevation data

The GEODATA 9-second Digital Elevation Model (DEM-9S) Version 3 is a grid of ground level elevation points covering the whole of Australia with a grid spacing of 9 seconds in longitude and latitude (approximately 250 metres) in the GDA94 coordinate system (Figure 3) (Hutchinson et al., 2008).

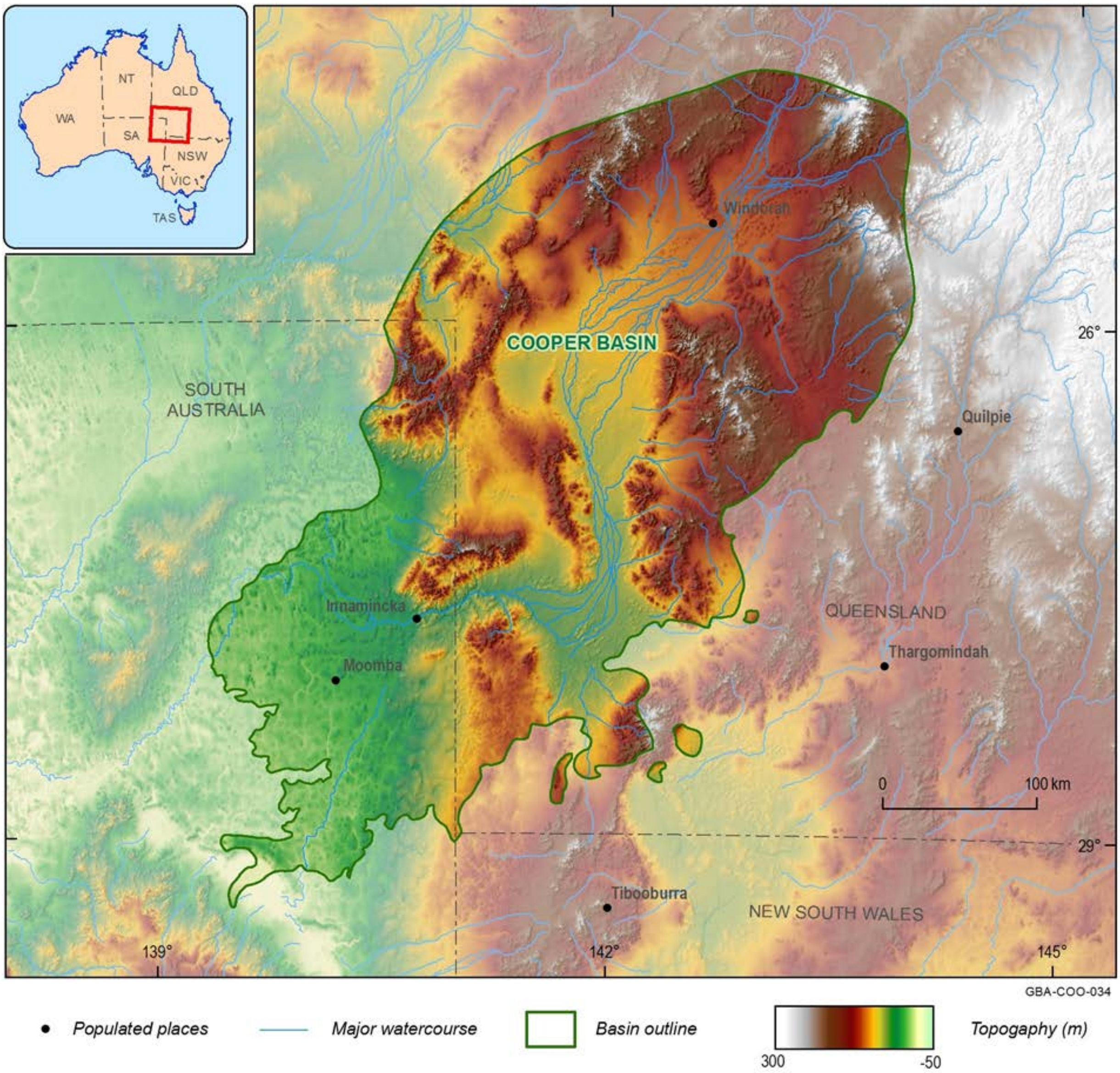

Figure 3 Cooper Basin surface topography

Data: Cooper Basin outline from Raymond et al. (2018); Digital elevation model from Hutchinson et al. (2008), watercourses from Geoscience Australia (1997)
Element: GBA-COO-034

2.3 Geological datasets

As a result of approximately 60 years of continuous exploration, the Cooper Basin has the largest dataset of any onshore sedimentary basin in Australia (Carr et al., 2016). However, while there is good data coverage across large areas of the Cooper Basin, some frontier areas remain poorly constrained, including the eastern Nappamerri Trough and the depocentres in the north-eastern basin.

2.3.1 Surface geology

The surface geology maps used in this study (Figure 4) are sourced from either the Surface Geology of Australia 1:1M scale dataset, 2012 edition (Raymond et al., 2012a), or 1:2.5M, 2012 edition (Raymond et al., 2012b). These are seamless national coverages of outcrop and surficial geology, which show areas of outcropping bedrock geology and unconsolidated or poorly consolidated regolith material covering bedrock. Geological units are represented as polygon and line geometries, and are attributed with information regarding stratigraphic nomenclature and hierarchy, age, lithology, and primary data source. The dataset also contains geological contacts, structural features such as faults and shears, and miscellaneous supporting lines. Figure 5 presents the index of the spatial extents of all 1:250,000 scale geological maps of Australia from the Geoscience Australia's Web Map Service (Geoscience Australia, 2016). The service contains information on the edition, publication date, and map publisher, and has links to map images.

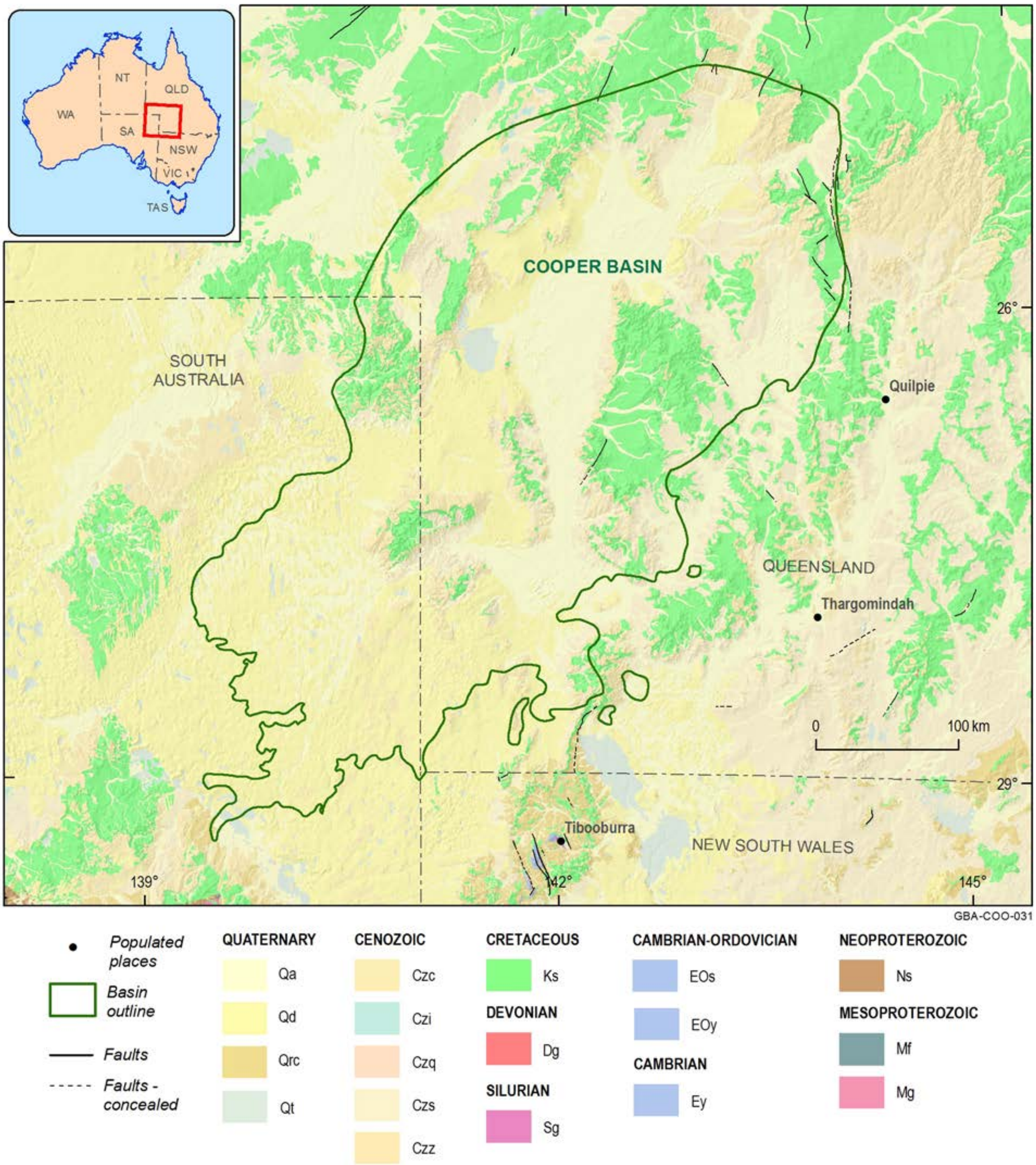

Figure 4 Cooper GBA region surface geology at 1:1M scale

Data: Surface geology from Raymond et al. (2012a); Cooper Basin outline from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)
Element: GBA-COO-031

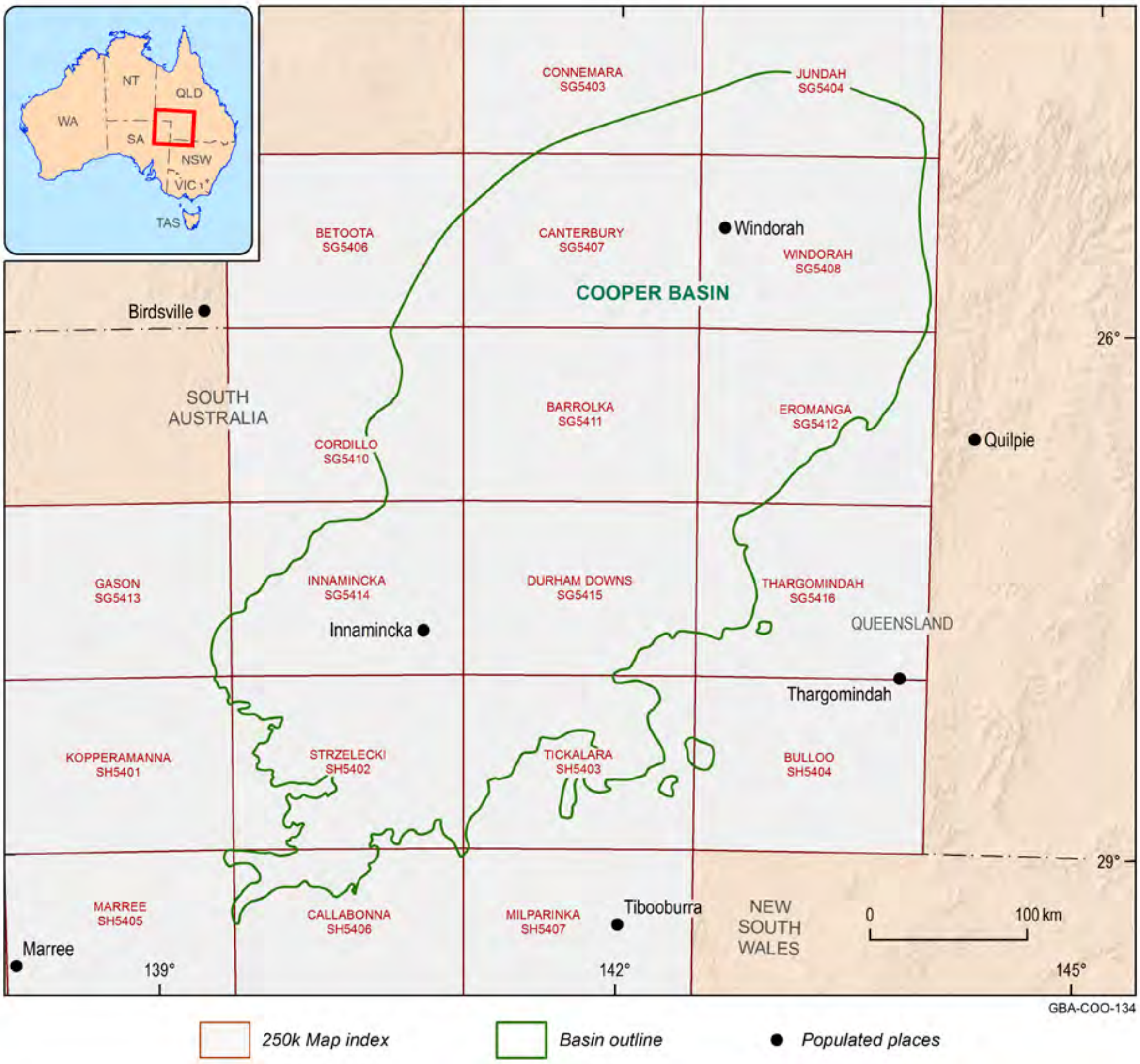

Figure 5 Index of the scanned 1:250,000 scale geological map sheets

Source: Geoscience Australia (2016); Cooper Basin outline from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)

Element: GBA-COO-134

2.3.2 Geological provinces

Geological province boundaries, including sedimentary basin outlines, are sourced from the Australian Geological Provinces dataset (Figure 6) (Raymond et al., 2018). These outlines provide a clipping and analytical extent for the various other datasets considered in this stage.

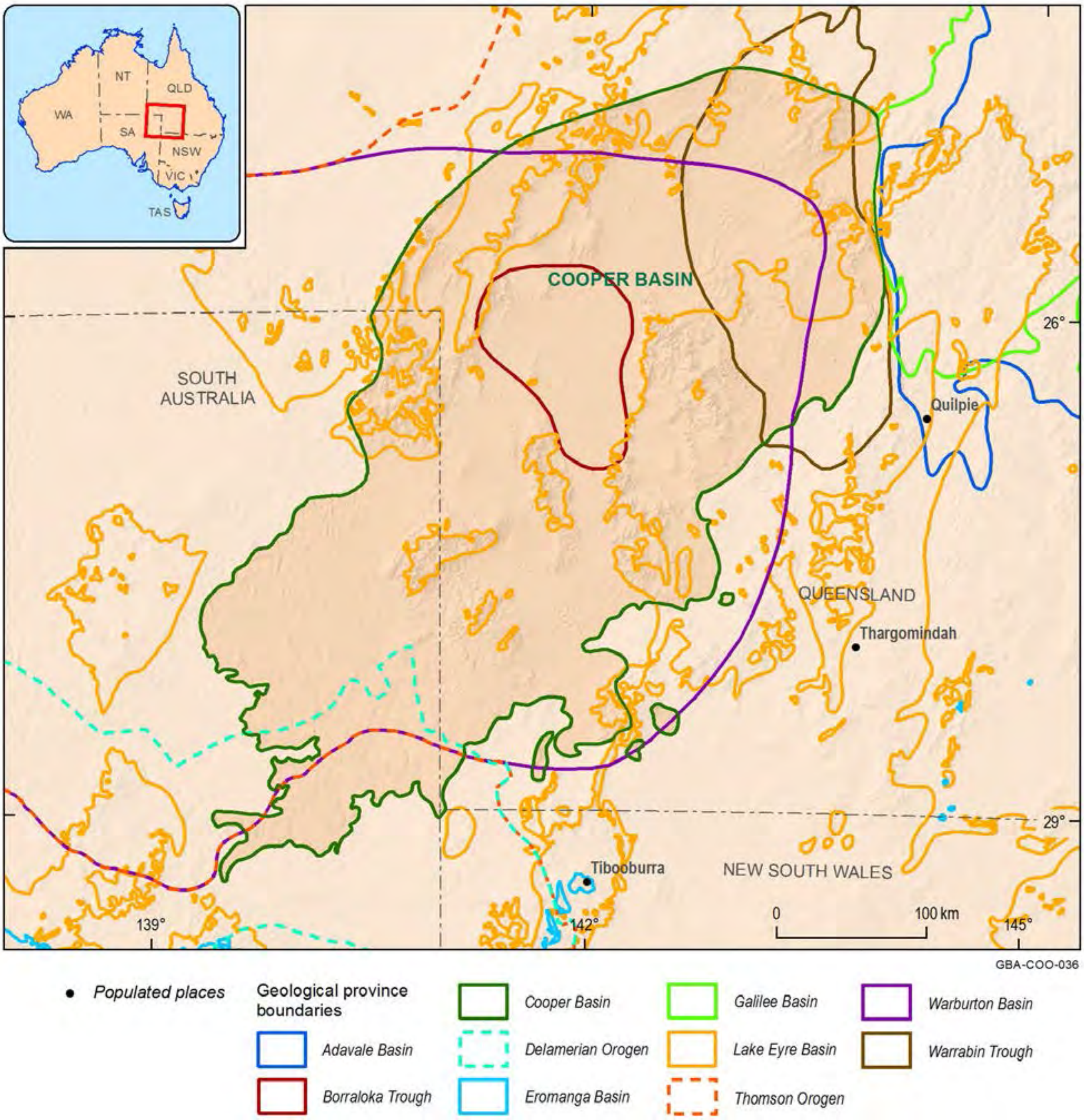

Figure 6 Cooper Basin outline and surrounding province boundaries

Data: Cooper Basin outline and surrounding provinces from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)
Element: GBA-COO-036

2.3.3 Well data

2.3.3.1 Well header data

A standardised set of well header data is available from Geoscience Australia's boreholes database (Geoscience Australia, 2018). The borehole data include mineral drillholes, petroleum wells and water bores along with a variety of other types.

2.3.3.2 Formation tops and wireline log data

Formation tops and public domain wireline log data were sourced from the state survey databases, as follows:

- Queensland Petroleum Exploration Data (QPED) (Queensland Government, 2018) and;
- Petroleum Exploration and Production System–South Australia (PEPS–SA) (Department of State Development (SA), 2018).

A complete set of standardised formation tops for key horizons (current to 2015) were generated to create the geological model published in Hall et al. (2015). Formation tops from the state databases were combined into a single database with formation names standardised to ensure consistency across the state border. Preferred names are consistent with the Geoscience Australia Stratigraphic Units Database (Geoscience Australia and Australian Stratigraphy Commission, 2012). The formation tops database included approximately 1760 wells with tops intersecting the Cooper Basin section. This formation top set was then simplified to only capture the tops of the structure surfaces included in the three-dimensional geological model. Basic quality checks were applied to the formation picks to ensure all depth and thickness values were geologically reasonable, but no further interpretation was undertaken.

The distribution of wells in the Cooper GBA region, classified according to their depth of penetration, is shown in Figure 7. The location of key wells used in this study to characterise the shale, tight and deep coal gas plays are shown in Figure 8.

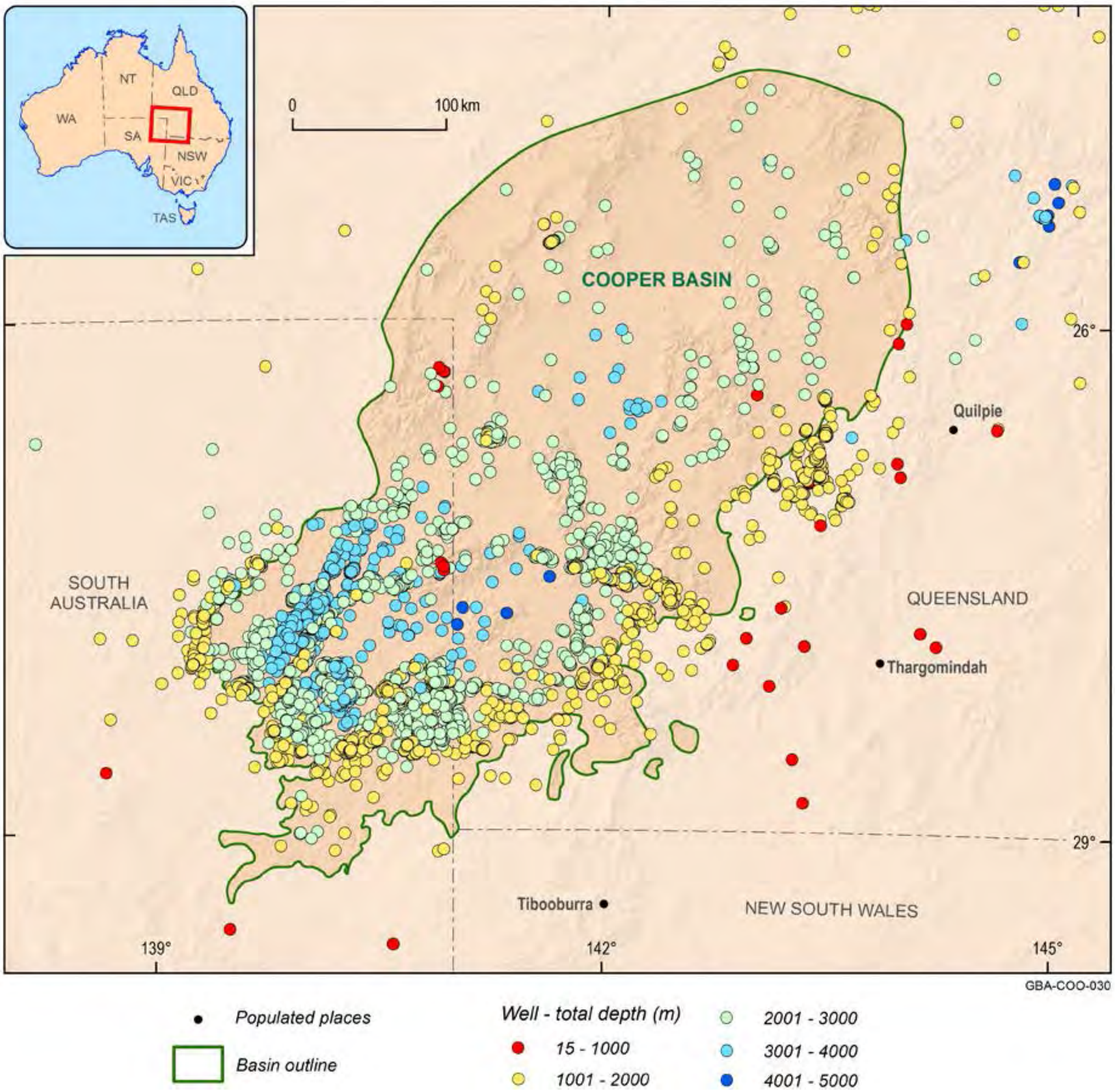

Figure 7 Distribution of wells and bores in the Cooper GBA region, classified according to their depth of penetration

Data: Wells from Queensland Government (2018) and Department of State Development (SA) (2018); Cooper Basin outline from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)
Element: GBA-COO-030

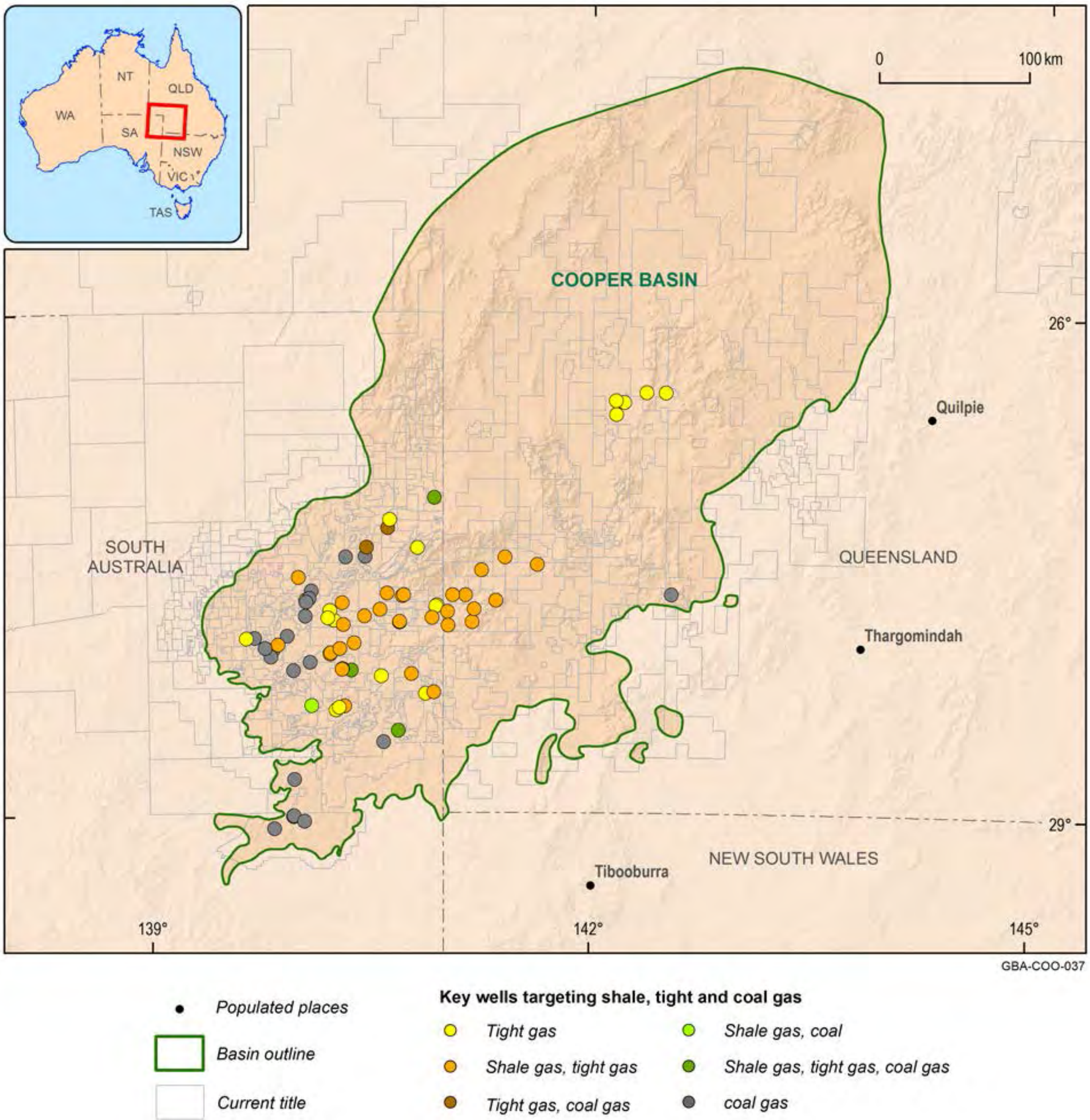

Figure 8 Distribution of key wells used to characterise reservoirs for the shale, tight and deep coal gas plays assessed in this study

Source: Wells targeting shale, tight and deep coal gas plays are compiled from Department for Energy and Mining (SA) (2018), Business Queensland - Queensland Government (2017) and company websites (e.g. Real Energy, 2014, 2018; Beach Energy, 2018; Senex Energy Ltd, 2013; Beach Energy, 2015).
Data: Cooper Basin outline from Raymond et al. (2018); Wells from Queensland Government (2018) and Department of State Development (SA) (2018); Permit outlines (titles) provided from GPinfo petroleum database, a Petrosys Pty Ltd product (Petrosys Pty Ltd, 2019); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)
Element: GBA-COO-037

2.3.4 Geophysical data

Geophysical data are available over the basin, including seismic, gravity and magnetics (discussed below) and airborne electromagnetics (see hydrogeology technical appendix (Evans et al., 2020)). These datasets provide valuable insight into the subsurface architecture of the stacked Eromanga, Cooper, and Warburton basins.

2.3.4.1 Seismic data

The Cooper Basin has an extensive coverage of seismic data collected from the 1960s until the present (Figure 9). More than 81,000 line-kilometres of two-dimensional and 10,000 km^2 of three-dimensional seismic have been acquired (Carr et al., 2016; Department of Natural Resources, 2017c, 2017a, 2017b; Department for Energy and Mining (SA), 2017a, 2017b). Over time, improvements in seismic technologies have greatly enhanced the understanding of subtle structural features and plays within the basin.

Both two-dimensional seismic navigation and three-dimensional seismic areas for Queensland and South Australia were sourced directly from the state websites. Navigation data for deep crustal seismic was also included within the inventory, where available. SEGY can be obtained directly from QLD and SA State government agencies referenced above.

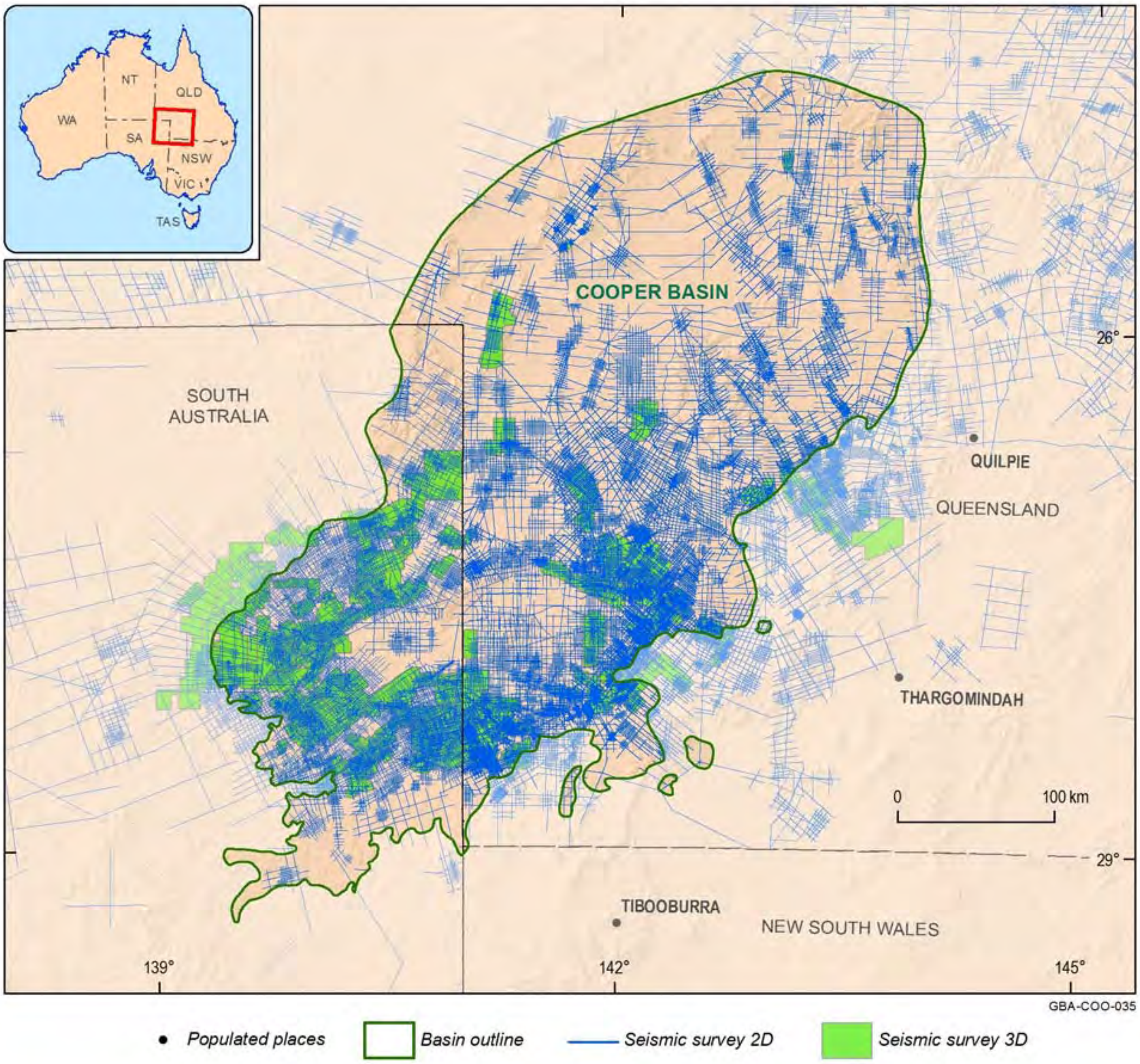

Figure 9 Cooper Basin seismic data coverage (two-dimensional and three-dimensional)

Data: Department of Natural Resources (2017c, 2017a, 2017b); Department for Energy and Mining (SA) (2017a, 2017b); Cooper Basin outline from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)
Element: GBA-COO-035

2.3.4.2 Gravity

The Australian National Gravity Database contains data from more than 900,000 point gravity observations on the Australian mainland, over the continental margins, on the Australian Antarctic Territory, and other external territories of Australia. These data have been collected from nearly 1000 gravity surveys dating back to 1937 (Wynne and Bacchin, 2009). A full coverage of ground based gravity is available over the Cooper Basin at generally greater than 4 km station spacing (Figure 10).

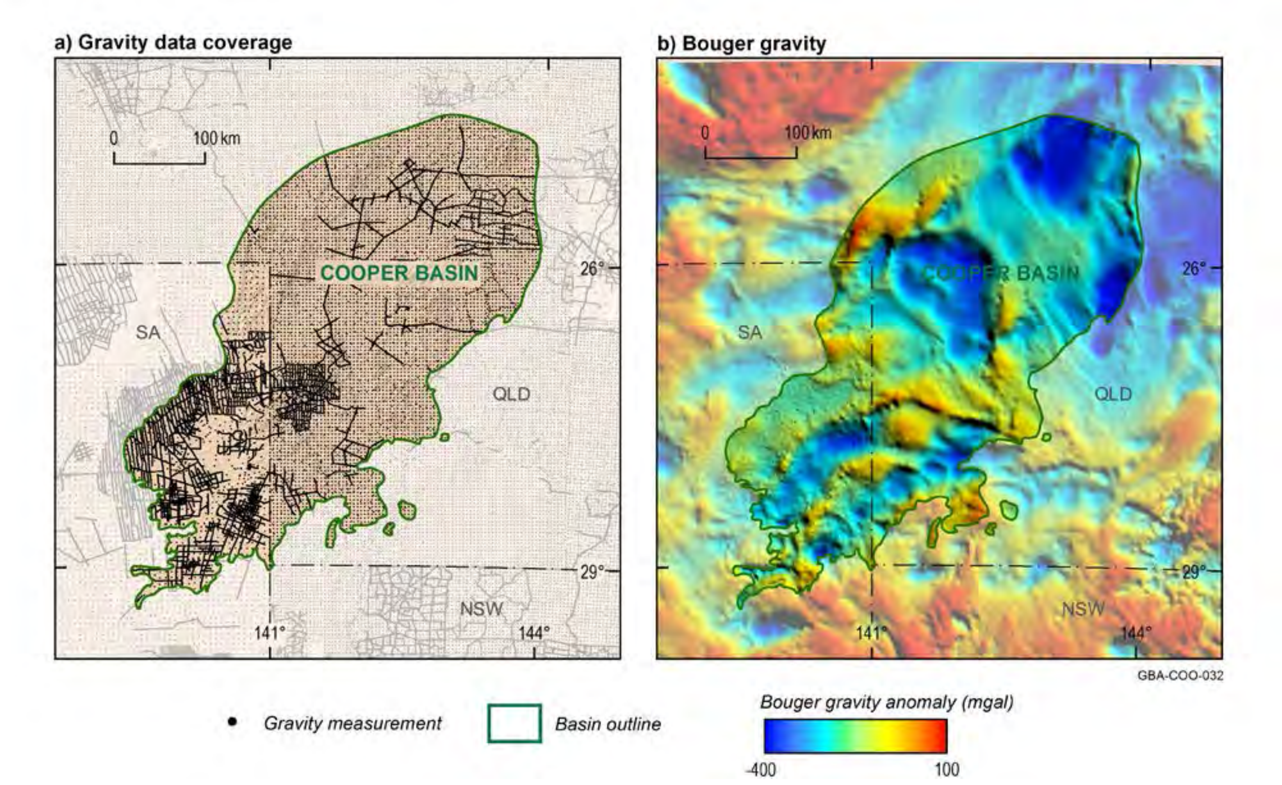

Figure 10 a) Distribution of point gravity data observations; b) Regional Bouguer gravity coverage

Data: a) Australian National Gravity Database (Wynne and Bacchin, 2009); b) Nakamura (2016); Cooper Basin outline from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)
Element: GBA-COO-032

2.3.4.3 Magnetics

The 6th edition of the Total Magnetic Intensity (TMI) anomaly grid of Australia with Variable Reduction to Pole covers all of Australia with a grid cell spacing of approximately 3 seconds of arc (approximately 80 m; Figure 11; (Milligan and Nakamura, 2017)). Details of the specifications of individual airborne surveys can be found in the Fourteenth Edition of the Index of Airborne Geophysical Surveys (Percival, 2014). Airborne magnetic data is available across most of the Cooper Basin with line spacings of 500 m or less (Figure 11).

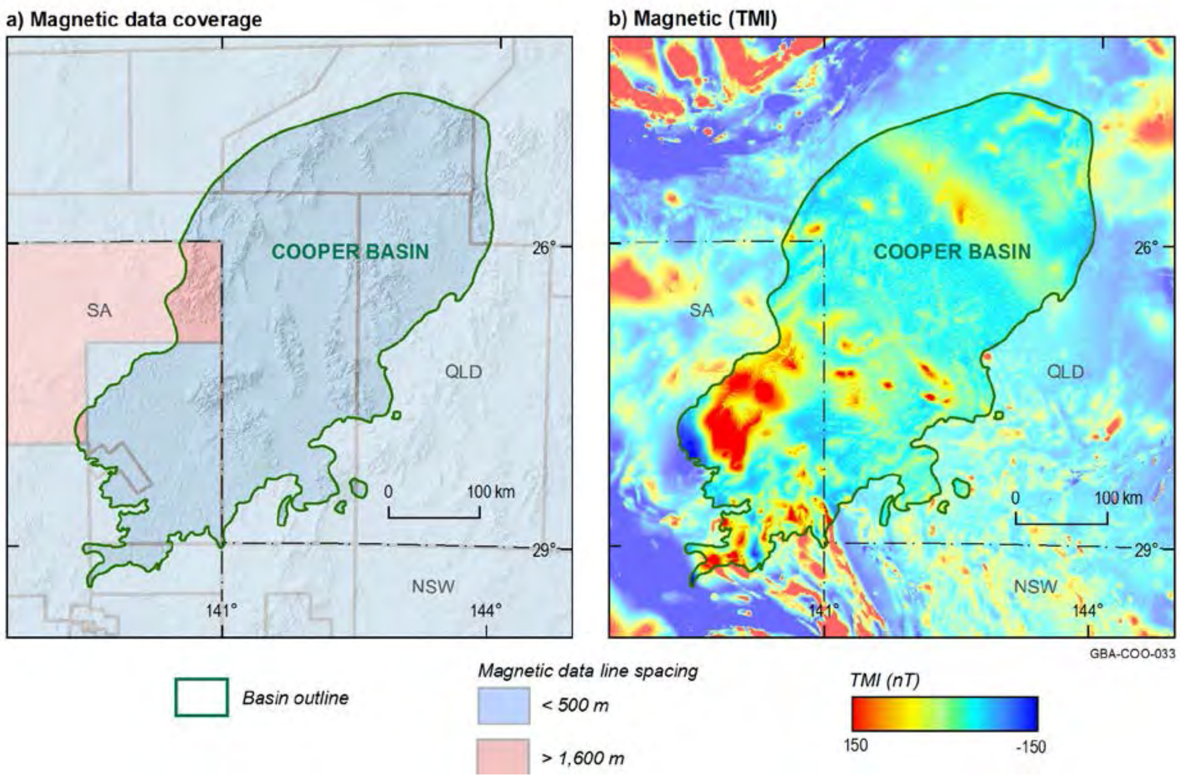

Figure 11 a) Distribution of magnetic survey by resolution; b) Regional TMI (Total Magnetic Intensity) data coverage

Data: a) ARGUS (Airborne Geophysical Surveys) metadata database (Richardson, 2018); b) Milligan and Nakamura (2017); Cooper Basin outline from Raymond et al. (2018); Hill-shade derived from 9-second DEM from Hutchinson et al. (2008)
Element: GBA-COO-033

2.4 Published studies

Previous regional studies of the Cooper Basin geology and petroleum prospectivity include Gravestock et al. (1998) for the South Australian region, Draper (2002) for the Queensland region, and Hall et al. (2015), which focused on the entire basin.

As part of the National Geoscience Mapping Accord (NGMA) strategy conducted in the 1990s, the Cooper-Eromanga Basins Project was undertaken to develop a hydrocarbon generation model for the basins as a whole. The Cooper-Eromanga Basins Project was undertaken co-operatively by the Queensland, South Australian, Commonwealth, New South Wales and Northern Territory Governments. The study was a major advance, integrating and standardising the seismic coverage for the Cooper Basin. The project also produced a comprehensive organic geochemistry database and a basin-wide burial, thermal maturation and hydrocarbon generation model (Deighton et al., 2003).

Other studies of note in the Cooper-Eromanga basins include Toupin et al. (1997) and Gallagher and Lambeck (1989).

The source rocks and petroleum reservoirs of the Cooper and Eromanga basins have been comprehensively studied, for example: Moore and Pitt (1984); Summons et al. (2002); Hunt et al. (1989); Deighton and Hill (1998); Deighton et al. (2003); Boreham and Summons (1999). Further information on the regional petroleum systems is available in the petroleum prospectivity technical appendix (Lech et al., 2020).

An outline of the exploration history and current permit operators can be found in the petroleum prospectivity technical appendix (Lech et al., 2020).

2.4.1 Interpreted seismic horizons

Several vintages of open file interpreted seismic horizon data have been released for the Cooper Basin as follows (Table 2):

- Structural surfaces and isopachs of significant seismic horizons in depth and two-way travel time current to 2001 for South Australia only (Department for Manufacturing Innovation Trade Resources and Energy (DMITRE) (SA), 2001).
- Structural surfaces in depth and two-way travel time to the top of the Cadna-owie Formation, Permian succession and Warburton Basin, current to 2001 for all of the Cooper Basin (NGMA (National Geoscience Mapping Accord), 2001).
- Structural surfaces in depth and two-way travel time to the top of the Cadna-owie Formation, Permian succession and Warburton Basin, current to 2009 for South Australia only (Department for Manufacturing, 2009). Additional updates to the Base Eromanga Basin and Top Cadna-owie Formation surfaces, in depth, were provided in 2012 for South Australia (Department of State Development, 2012).

Additional seismic horizon maps are available from selected recent well completion reports, including. Boston 1, Encounter 1 and Gaschnitz 1 (Beach Energy, 2013b, 2011; Santos–Delhi–Origin, 2012).

Table 2 Cooper-Eromanga Basin seismic horizons interpreted in previous public domain studies

Horizon Name	Description	Area – Vintage
a	Top Winton Formation at the base of the Tertiary	SA - 2001
c	Top Cadna-owie Formation	SA – 2009, 2012; QLD - 2001
h	Top Hutton Sandstone	SA - 2001
j	Base Eromanga Basin (also referred to as Top Cooper Basin)	SA – 2001, 2012
n	Top Nappamerri Group	SA - 2001
p	Top, or near top, of Permian sediments (Toolachee Formation)	SA - 2009; QLD - 2001
r / ru	Top Daralingie unconformity and correlative unconformities	SA - 2001
rss	Top Daralingie Sandstone sediments	SA - 2001
v	Top Patchawarra Formation	SA - 2001
wx	Top Glacial sediments	SA - 2001
z	The top of what is traditionally considered 'basement', usually the top of the Warburton Basin	SA - 2009; QLD - 2001

Data: Department of State Development (2012); NGMA (National Geoscience Mapping Accord) (2001); Department for Manufacturing (2009)

2.4.2 Regional three-dimensional geological model of the Cooper Basin

Hall et al. (2016) published a regional three-dimensional model framework for the Cooper Basin, based on existing interpretations (e.g. Department for Manufacturing Innovation Trade Resources and Energy (DMITRE) (SA), 2001; NGMA (National Geoscience Mapping Accord), 2001; Department for Manufacturing, 2009) with the following updates and modifications:

- Updated structural surfaces consistent with new open file well data (up to May 2015).
- Revised seismic interpretation in selected areas.
- Better integration of existing interpretations across the state border.
- Addition of structural surfaces and isopachs for the Daralingie and Epsilon formations and the Roseneath and Murteree shales.

A perspective view of this model is shown in Figure 12.

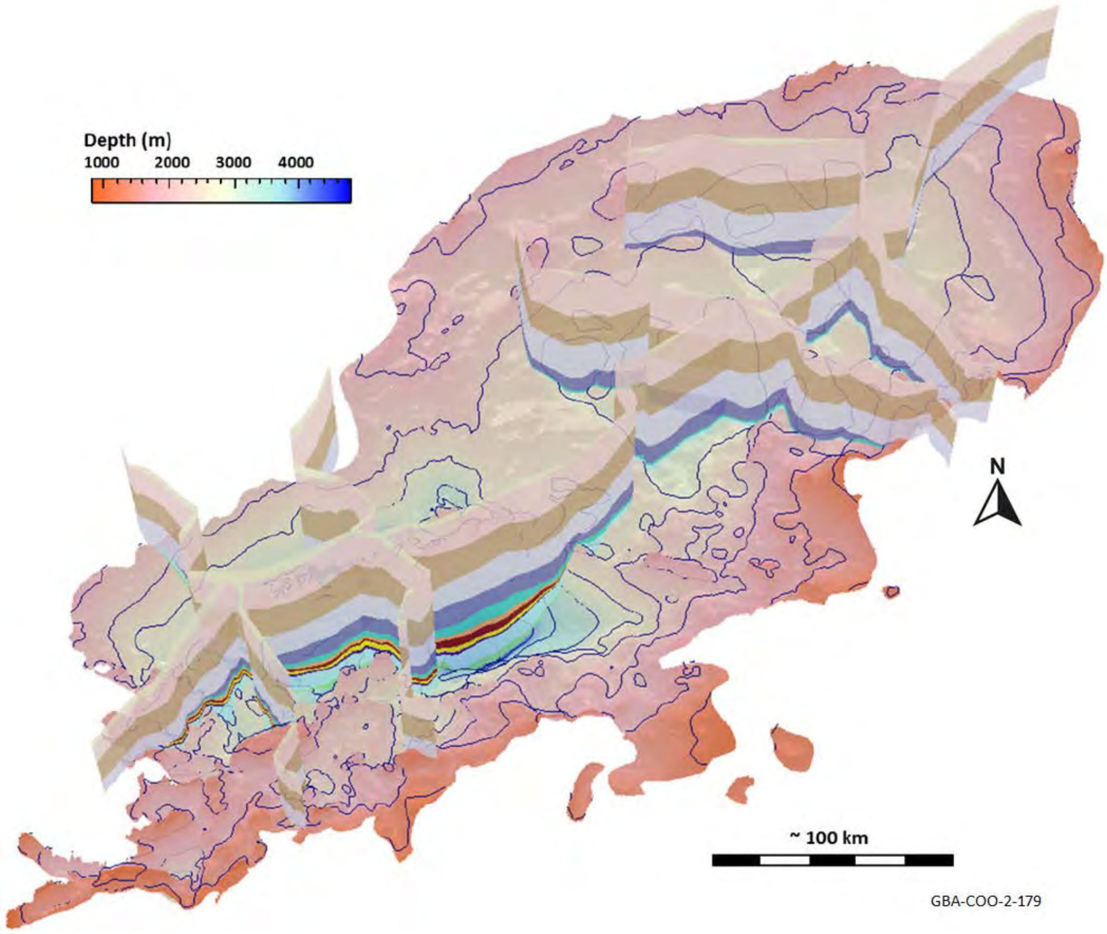

Figure 12 Oblique view of the regional three-dimensional geological model of the Cooper Basin, looking north

The structural surface shown is top “pre-Permian” basement clipped to the Cooper Basin outline (Raymond et al., 2018). Cross-sections running north-east to south-west through the basin and broadly east–west across the basin help to understand the thickness and distribution of the sedimentary units within the basin. For more detailed information on the cross-sections shown, refer to Figure 26, Figure 27 and Figure 28
Source: Hall et al. (2015)
Data: Hall et al. (2016); Hall and Palu (2016)
Element: GBA-COO-2-179

2.4.3 Other third party public domain data packages

Other 3rd party public domain reports and data packages have been released for the Cooper Basin, which are relevant to characterising the regional basin architecture.

Meixner and Holgate (2009) and Meixner et al. (2012) produced a three-dimensional model of the Cooper Basin region using geologically constrained inversions of Bouguer gravity data. The model was used to predict temperatures and their uncertainty throughout the basin down to 4–5 km depth, to aid geothermal exploration. The model also delineates regions of low density within the basement of the Cooper and Eromanga basins that are inferred to be granitic bodies. This helps to delineate the distribution of the high-heat-producing granites, including the granodiorite of the Big Lake Suite at the base of the Cooper and Eromanga basins.

As part of the Great Artesian Basin Water Resource Assessment (Ransley and Smerdon, 2012), a three-dimensional model of the Great Artesian Basin was published with an accompanying report (Nelson et al., 2012). This model provides useful constraints on the regional geometry and stratigraphy of the overlying Eromanga Basin. An additional review of the Cooper Basin and associated data listings have also been compiled as part of the more recent groundwater-focussed bioregional assessment study for the region (Smith et al., 2015b; Smith et al., 2015a; Smith et al., 2016).

Additional datasets and supplementary information can be found on the Queensland and South Australia government websites:

- Department of Premier and Cabinet, South Australia Petroleum website http://petroleum.statedevelopment.sa.gov.au/
- Queensland Government, Mining and Resources website https://www.business.qld.gov.au/industry/mining/geoscience-data-information

3 Basin geology

3.1 Geological setting

The Cooper Basin, located in north-eastern South Australia and south-western Queensland (Figure 13), formed in an intraplate setting far to the west of the active convergent plate margin in eastern Australia. The basin represents a large Carboniferous (Pennsylvanian) to Triassic depocentre, which was terminated at the end of the Middle Triassic by widespread contractional deformation, regional uplift and erosion. The north-eastern limit of the basin is marked by the Canaway Ridge (Figure 13), which separates it from the coeval southern Galilee Basin. The total area of the Cooper Basin is approximately 130,000 km^2, of which about three quarters lies within Queensland and the remainder lies within north-eastern South Australia (Figure 13, Figure 14).

The Cooper Basin unconformably overlies lower Paleozoic sediments of the Warburton Basin, however in the north-eastern part of the basin it also overlies Devonian sediments associated with the Adavale Basin. Basement to the Cooper Basin (below the Adavale and Warburton basins) consists of the Thomson Orogen, the northern extension of Delamerian Orogen and the northern Gawler Craton. The Cooper Basin is entirely and disconformably overlain by the Jurassic–Cretaceous Eromanga Basin, which in turn is unconformably overlain by the Cenozoic Lake Eyre Basin (Ransley and Smerdon, 2012; Cook et al., 2013; Cook and Jell, 2013; Raymond et al., 2018; Gravestock et al., 1998). The Patchawarra Trough in South Australia and the Windorah Trough in Queensland are, in part, overlain by isolated Late Triassic units, which are transitional between the Cooper Basin and the Eromanga Basin (Hall et al., 2015).

The Cooper Basin is divided into north-eastern and south-western areas, which show different structural and sedimentary histories, and are separated by a series of north-west to south-east trending ridges, known as the Jackson–Naccowlah–Pepita (JNP) Trend (Heath, 1989; McKellar, 2013). The three major troughs in the south-west (Patchawarra, Nappamerri and Tenappera troughs) are separated by the Gidgealpa–Merrimelia–Innamincka (GMI) and Murteree ridges, which align approximately north-east to south-west, and are parallel to the main depositional axis of the basin (Figure 13, Figure 14) (Gravestock and Jensen-Schmidt, 1998). In the north-eastern Cooper Basin, the Permian succession is thinner than in the south-west, and the major depocentres, including the Windorah Trough and Ullenbury Depression, are generally less well defined (Draper, 2002; McKellar, 2013).

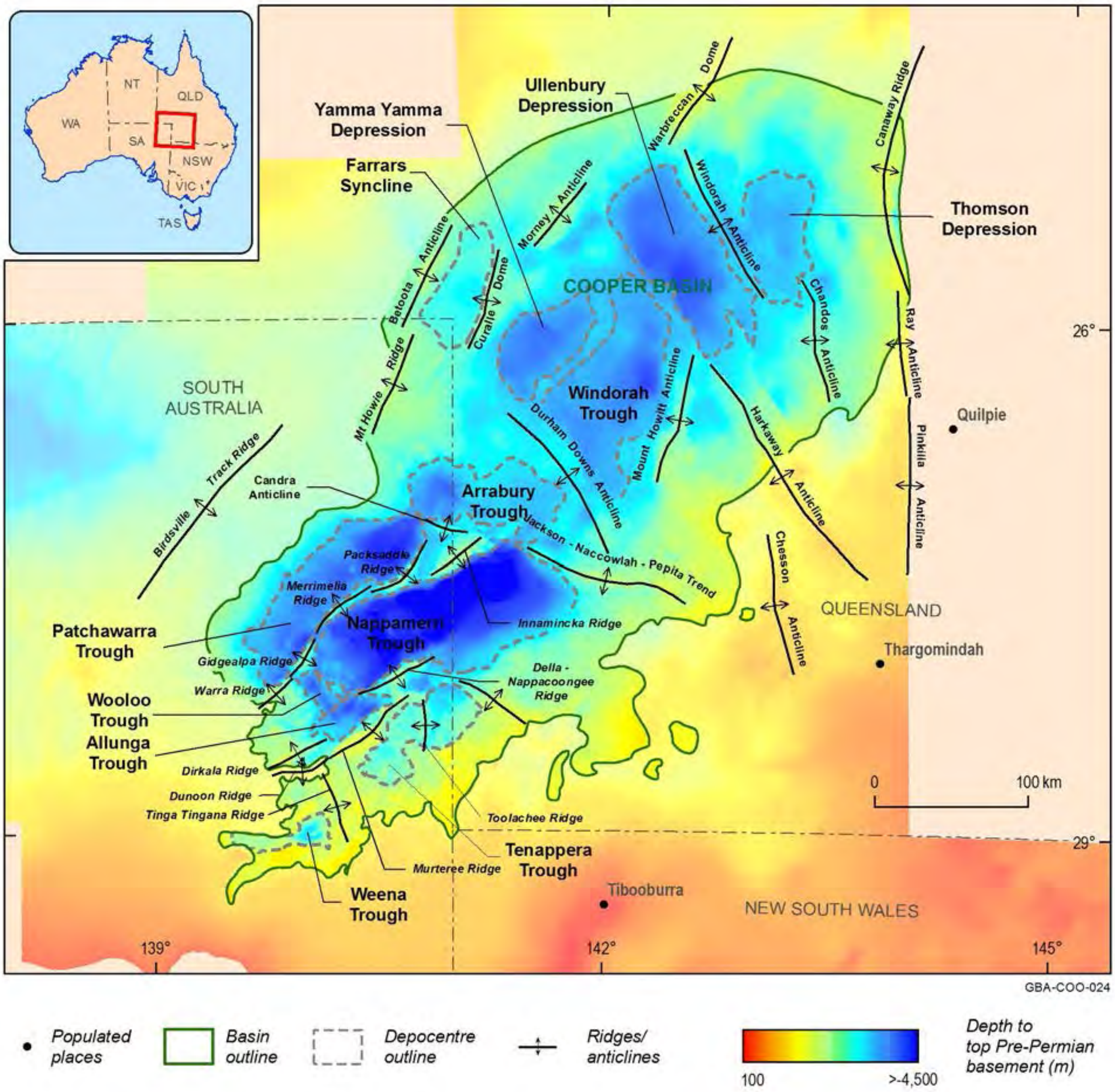

Figure 13 Cooper Basin structural elements overlain on top of the Pre-Permian basement horizon

Source: Adapted from Hall et al. (2015). Structural elements are modified from Draper (2002); Gravestock and Jensen-Schmidt (1998); McKellar (2013); and Ransley et al. (2012)
Data: Cooper Basin outline from Raymond et al. (2018); hill-shade derived from 9-second DEM (Hutchinson et al., 2008); depth to pre-Permian basement from Hall et al. (2016); structural elements from Hall et al. (2015), anticlines as regional trends only.
Element: GBA-COO-024

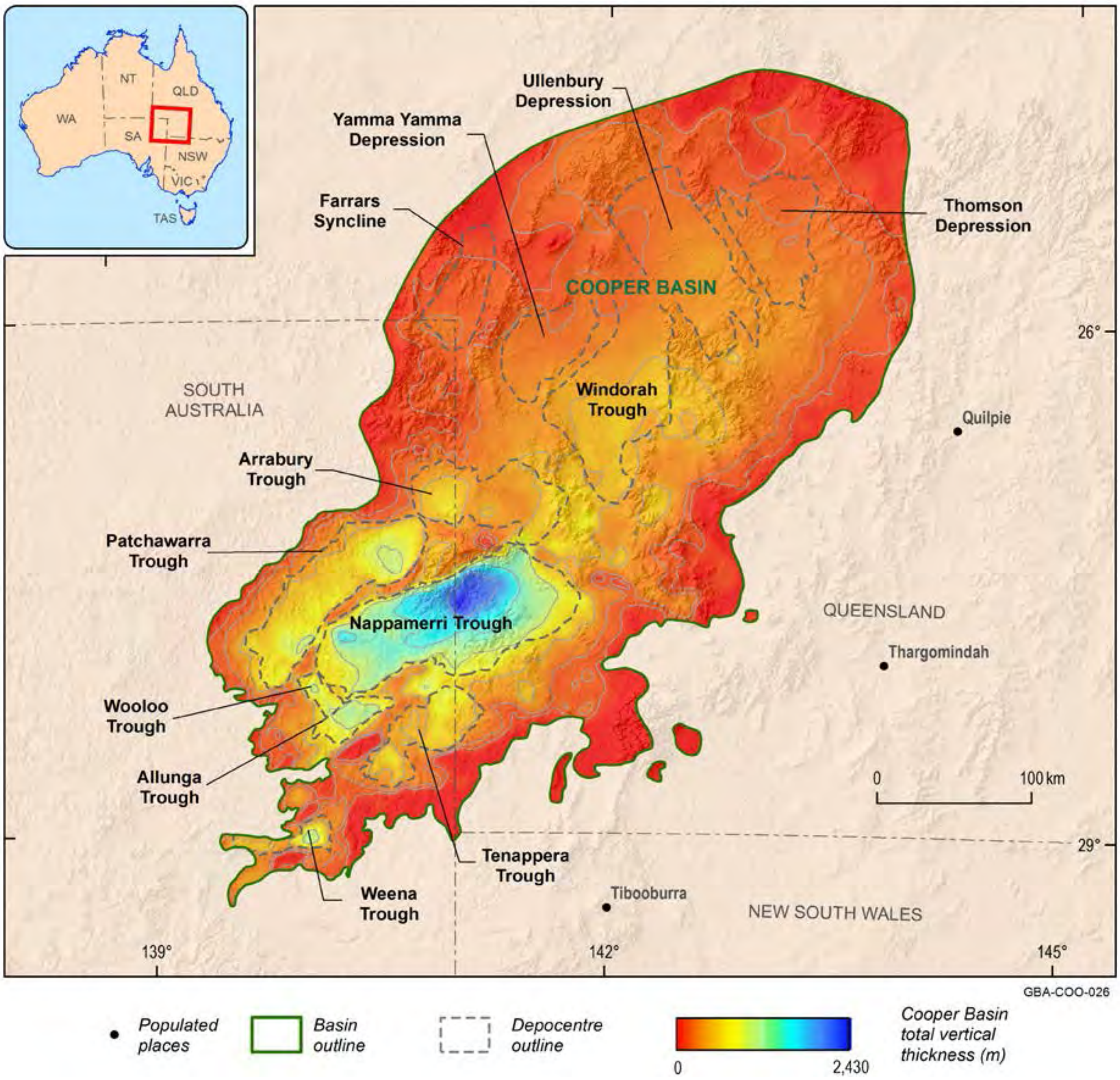

Figure 14 Structural elements of the Cooper Basin overlain on total Cooper Basin sediment thickness in metres

Source: Adapted from Hall et al. (2015). Structural elements after Draper (2002); Gravestock and Jensen-Schmidt (1998); McKellar (2013); and Ransley et al. (2012)

Data: Cooper Basin total vertical thickness is from Hall et al. (2016); the outline of the Cooper Basin is from Raymond et al. (2018). Structural elements data are from Hall et al. (2015)

Element: GBA-COO-026

3.2 Basin evolution

Pre-Permian basement to the Cooper Basin represents a series of sedimentary basins and metamorphic terranes. There is also evidence for igneous activity within the basement rocks.

Regional tectonic activity along the convergent eastern Australian plate margin (Veevers, 1984; Gallagher, 1988; Korsch et al., 2009b; Raza et al., 2009; e.g. Bryan et al., 2012) has resulted in three main stages of basin formation in the Cooper GBA region (Figure 15, Figure 17, Figure 20) (Moussavi-Harami, 1996b; Gravestock and Jensen-Schmidt, 1998; Draper, 2002; McKellar, 2013):

- Stage I: Carboniferous to Triassic Cooper Basin.
- Stage II: Jurassic to Late Cretaceous Eromanga Basin.
- Stage III: Paleogene to Neogene Lake Eyre Basin.

3.2.1 Pre-Permian Basement Evolution

The eastern part of the Cooper Basin is underlain by Cambrian–Ordovician metasedimentary rocks of the Thomson Orogen (Figure 15) (Purdy et al., 2013). The Thomson Orogen's south-western boundary remains poorly defined and its relationship with the coeval Warburton Basin to the south-east is essentially unknown (Purdy et al., 2013). The southern part of the Cooper Basin may be underlain by the North Flinders arm of the Adelaide Rift System (Meixner et al., 2012). Korsch and Doublier (2016) infer that basement below the southern Cooper Basin and Warburton Basin consists of the north-eastern Gawler Craton and the northern extension of the Delamerian Orogen.

The central and western Cooper Basin unconformably overlies sedimentary and volcanic rocks of the Cambrian–Ordovician Warburton Basin (Figure 15, Figure 16), which is discussed in detail in the following references: Roberts et al. (1990); Sun et al. (1994); Sun (1997); Gravestock and Gatehouse (1995); and Purdy et al. (2013); Draper (2013). The Warburton Basin transitions into the Thomson Orogen to the east, as greenschist-grade metasedimentary rocks (Draper, 2006; Purdy et al., 2013).

Devonian sedimentary rocks are intersected beneath the north-eastern Cooper Basin in the Warrabin and Barrolka troughs (Figure 6, Figure 15, Figure 16) (Murray, 1994; Draper et al., 2004; McKillop, 2013). These rocks are also identified on seismic data and are likely an extension of the Adavale Basin system, the main part of which lies to the east of the Cooper Basin. The Adavale Basin system, as defined by Draper et al. (2004), collectively refers to the Adavale Basin and other remnants of Devonian sedimentary and volcanic rocks in the region.

Two periods of granite emplacement have been inferred prior to onset of deposition of the Cooper Basin; one in the Silurian and the other in the Carboniferous (Draper et al., 2004) (Figure 15). In South Australia, granites have been intersected in basement beneath the Cooper Basin, mainly beneath the Nappamerri Trough (Figure 16). These are referred to as the Big Lake Suite and consist of granodiorite and are mainly S-type granites (Gatehouse et al., 1995). In the Nappamerri Trough granodiorites of the Big Lake Suite are associated with a present day elevated thermal anomaly and have a significant local thermal effect on the overlying sediments (e.g. Middleton, 1979; Beardsmore, 2004; McLaren and Dunlap, 2006; Meixner et al., 2012; Meixner and Holgate, 2009).

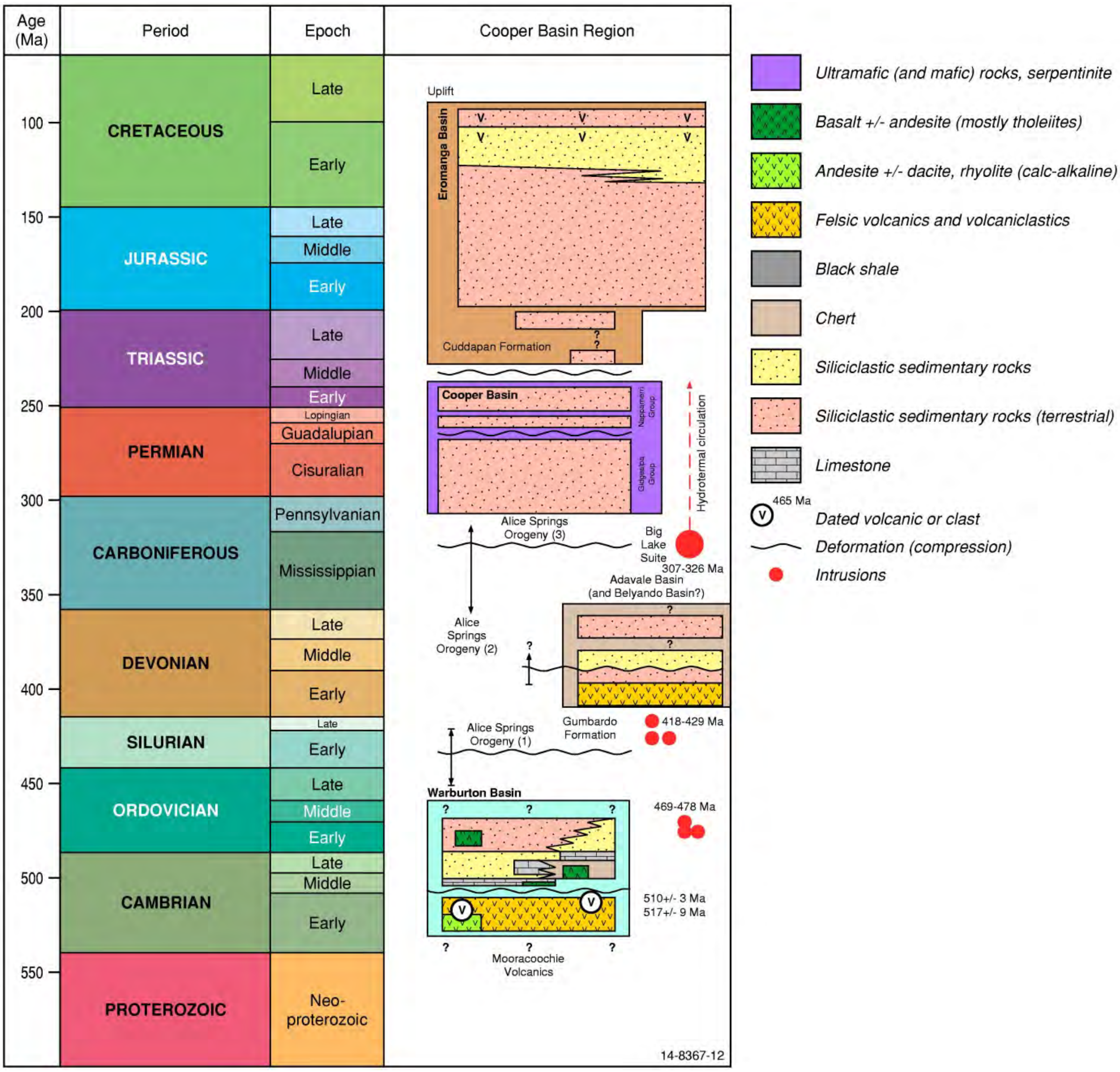

Figure 15 Late Neoproterozoic to Cretaceous time–space plot for the Cooper Basin region

Source: From Hall et al. (2015), modified from Champion et al. (2009)
Element: 14-8367-12

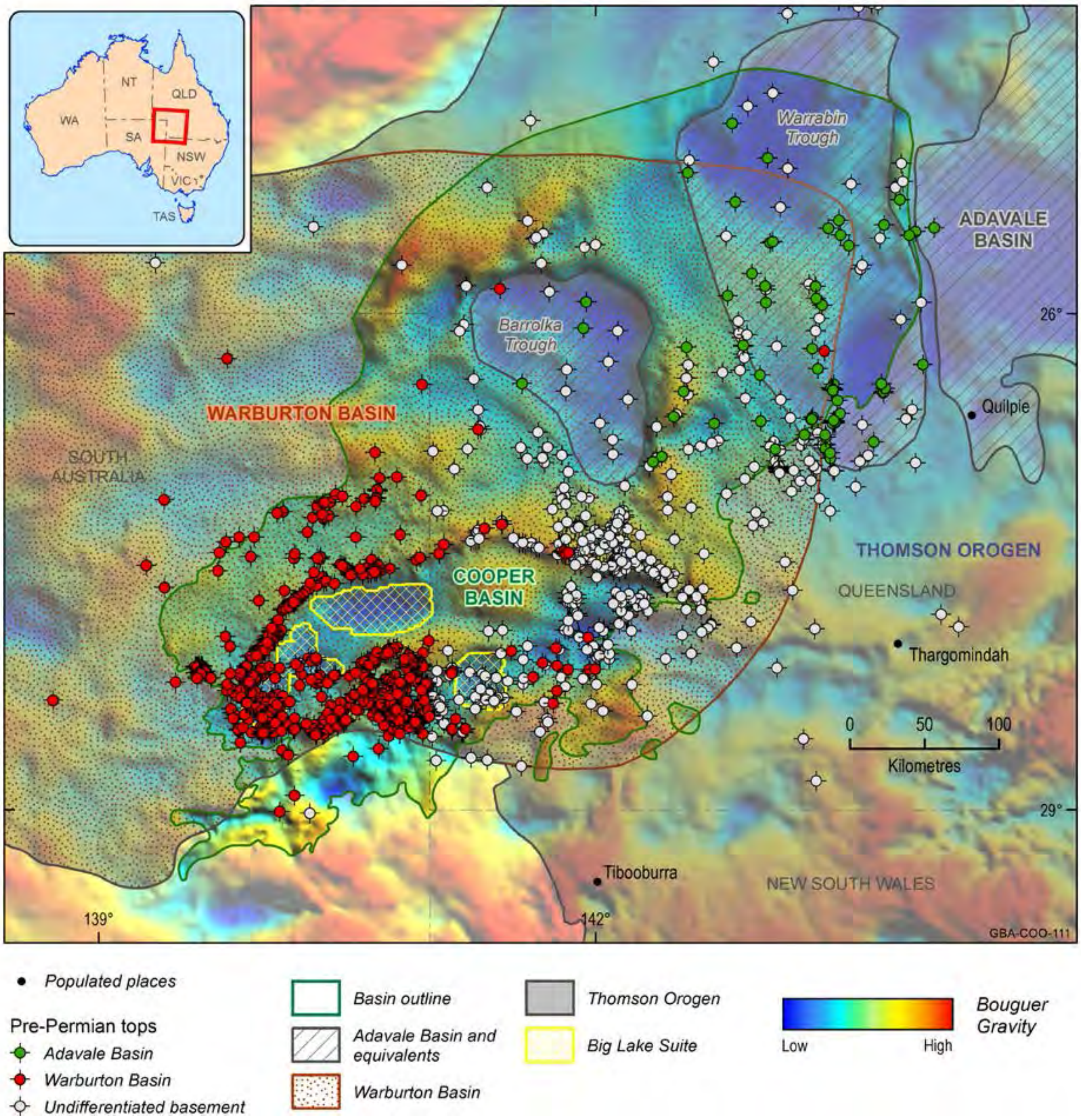

Figure 16 Pre-Permian geological provinces superimposed on regional gravity

Source: redrawn from Hall et al. (2015)
Data: Location of the Barrolka and Warrabin troughs are from Draper et al. (2004). Big Lake Suite granodiorite locations are from Meixner et al. (2012). Major crustal boundaries are from Korsch and Doublier (2016). Formation tops are from Queensland Government (2018) and Department of State Development (SA) (2018); Geological provinces are from Raymond et al. (2018); Bouguer gravity data is from Bacchin et al. (2008)
Element: GBA-COO-111

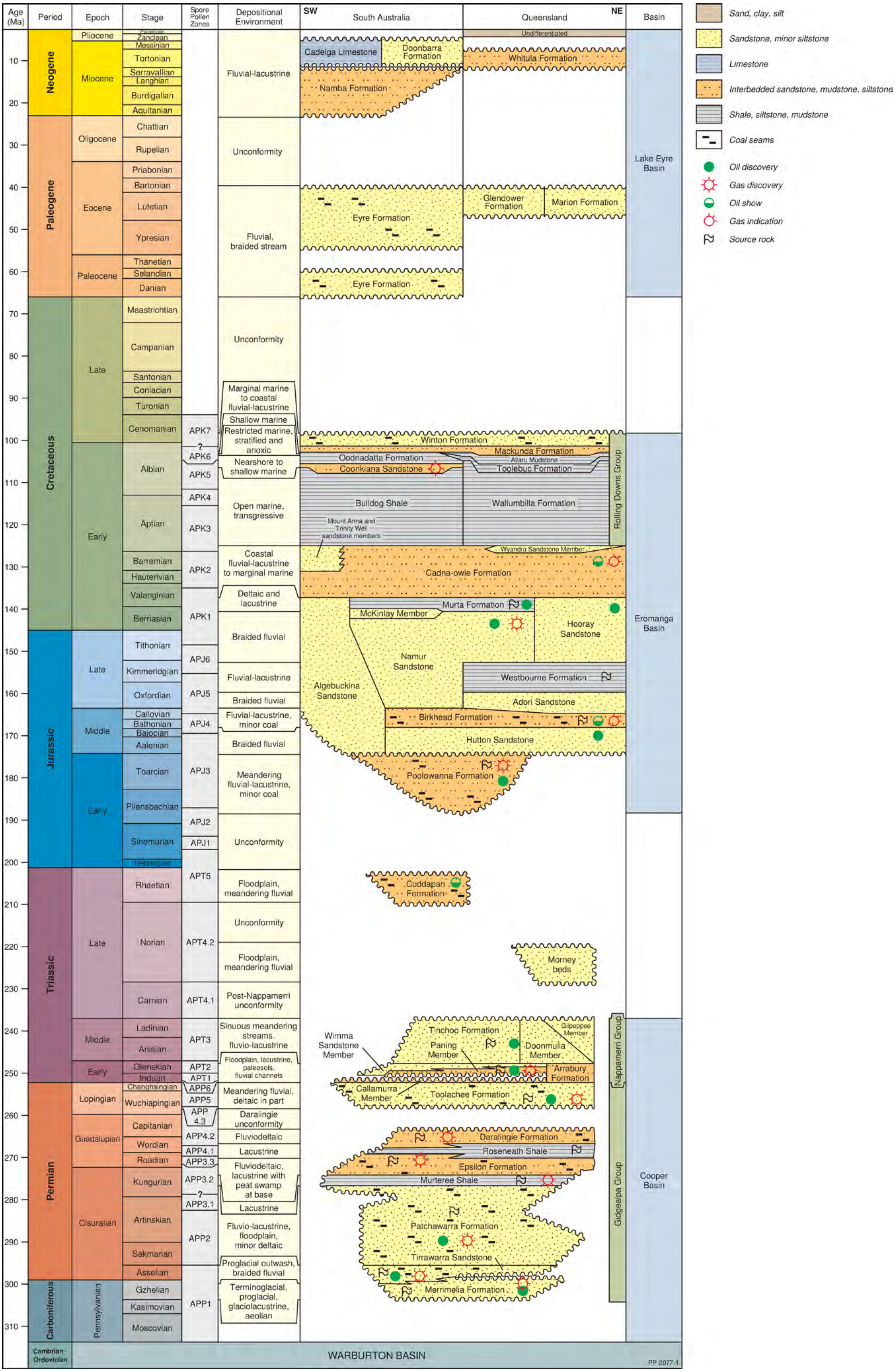

Figure 17 Stratigraphy of the Cooper, Eromanga and Lake Eyre basins showing depositional facies, conventional petroleum occurrences and identified source rocks

Source: After Hall et al. (2015); Smith et al. (2016)

Element: PP-2077-1

This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

3.2.2 Carboniferous–Triassic Cooper Basin

The Cooper Basin formed in an intraplate setting, well inboard of the convergent plate margin affecting eastern Australia. Despite being relatively well studied, the tectonic history of the Cooper Basin is complex and poorly understood, with continuing debate regarding the basin's origin and geological history (McKellar, 2013; Draper and McKellar, 2002; AWT International, 2013)

Numerous authors have suggested that the Cooper Basin initiated as an intracratonic sag basin due to thermal subsidence, possibly as a result of deep mantle processes or related to high heat flow from the high heat-producing granites of the Big Lake Suite and punctuated by episodic uplift (Kapel, 1966; Battersby, 1976; Zhou, 1993; Hill and Gravestock, 1995). However, the basin does not have the large circular geometry expected for this type of subsidence. Others have proposed a variety of tectonic models for basin development, including extension (e.g. Stanmore, 1989; Evans et al., 1990), contractional tectonism (Kuang, 1985; Wopfner, 1985; Apak et al., 1997; Sun, 1997) and dextral strike-slip tectonics (Kantsler et al., 1983; Middleton and Hunt, 1989).

Deposition in the Cooper Basin occurred over a time span of nearly 100 Myr which implies that it is likely to be a polyphase basin, having been influenced by both contractional and extensional events during its evolution. Thermal subsidence may have played a large role, but a number of other mechanisms are superimposed, such as the reactivation of pre-existing structures during contractional and extensional events. The orientations of these pre-existing structures are important as basement fault geometry is closely linked to timing of fault-reactivation and exhumation (Kulikowski and Amrouch, 2018; Kulikowski et al., 2017).

During the mid-Carboniferous, the Australian Plate within Gondwana drifted to high latitudes, and the Cooper Basin was located around 70^{o}S when Gondwana and Laurasia collided to form Pangaea (Figure 18) (Alexander et al., 1998; Veevers, 1984). During the Early Triassic, the Cooper Basin was located close to south magnetic pole (Figure 18), but there is no record of ice formation at this time (Alexander et al., 1998).

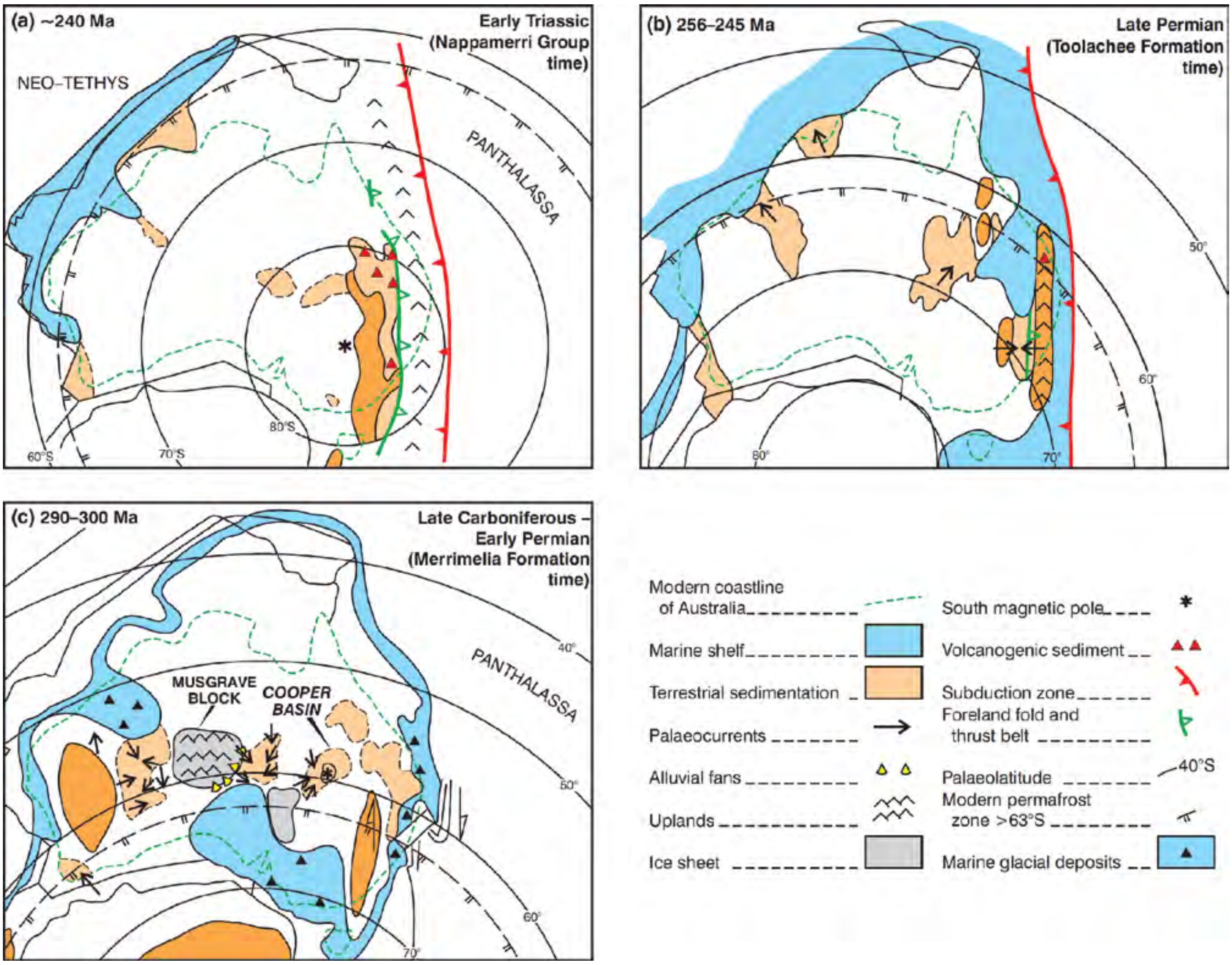

Figure 18 Palaeogeographic reconstructions of the Australian Plate for (a) the Early Triassic, (b) the Lopingian, and (c) the Pennsylvanian

Source: Reproduced from Alexander et al. (1998); and Veevers (1984); after Baillie et al. (1994)
Element: GBA-COO-2-328

Stratigraphically, the Cooper Basin is divided into two groups; the Pennsylvanian to Lopingian Gidgealpa Group, and the Lower to Middle Triassic Nappamerri Group (Figure 19). The Gidgealpa Group comprises initial glacial deposits transitioning to coal swamp, fluvial, lacustrine and deltaic deposits (Alexander et al., 1998; McKellar, 2013), which include the major source rock units for the basin (Boreham and Hill, 1998). In contrast to the underlying Gidgealpa Group, the Nappamerri Group is typically organically lean (Alexander et al., 1998; McKellar, 2013). Palaeoenvironments of the Nappamerri Group include braided to highly sinuous rivers, floodplains and ephemeral lakes (Alexander et al., 1998).

As part of a broader study, the stratigraphy of the Cooper Basin was updated by Hall et al. (2015), (Figure 19). This work used the revised formation ages, the timings of key tectonic events and erosion estimates together with a three-dimensional geological model to investigate the evolution and burial history of the Cooper-Eromanga-Lake Eyre succession.

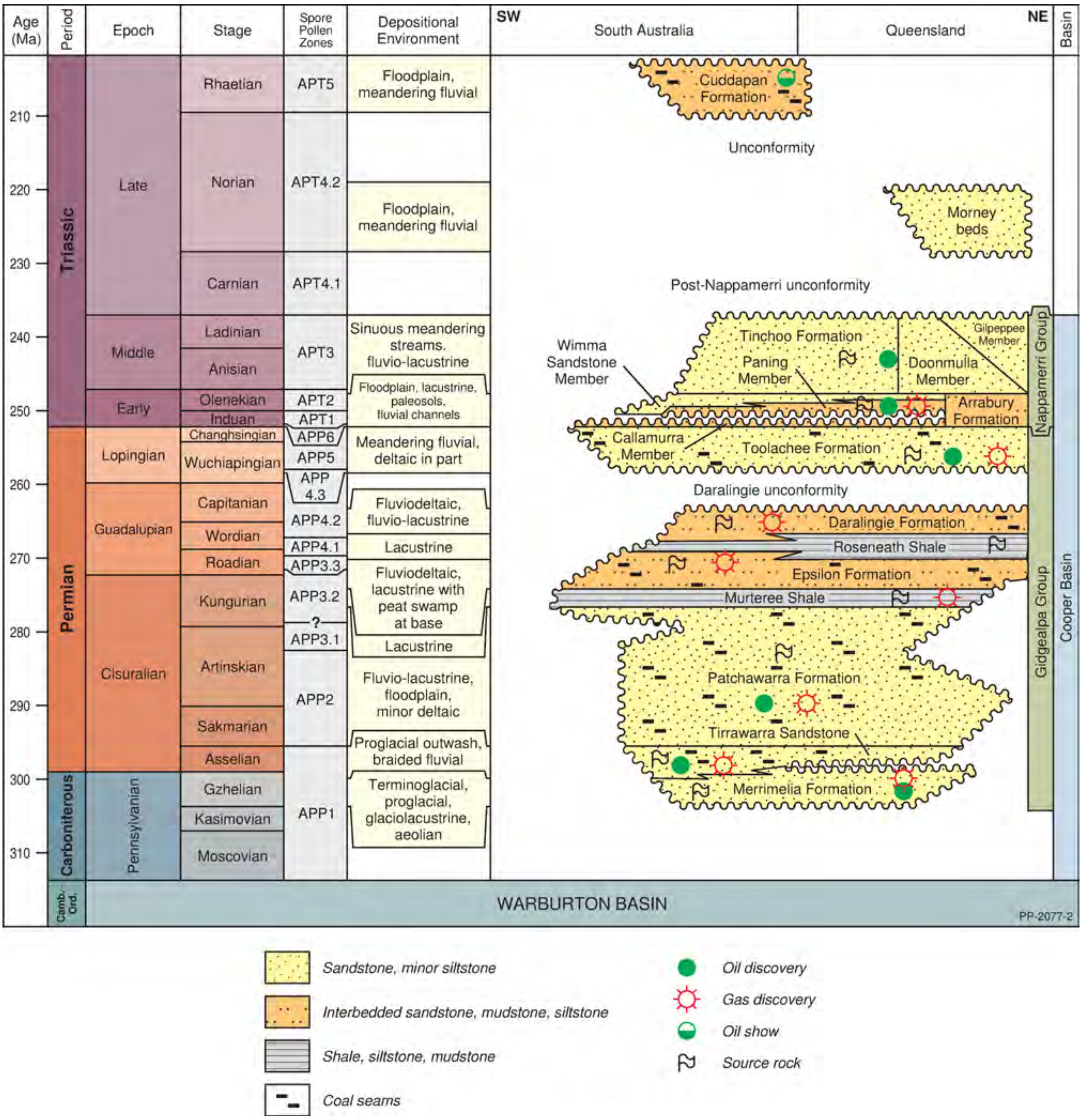

Figure 19 Stratigraphy of the Cooper Basin showing depositional facies, conventional petroleum occurrences and identified source rocks

Source: Redrawn from Hall et al. (2015)

Element: PP-2077-2

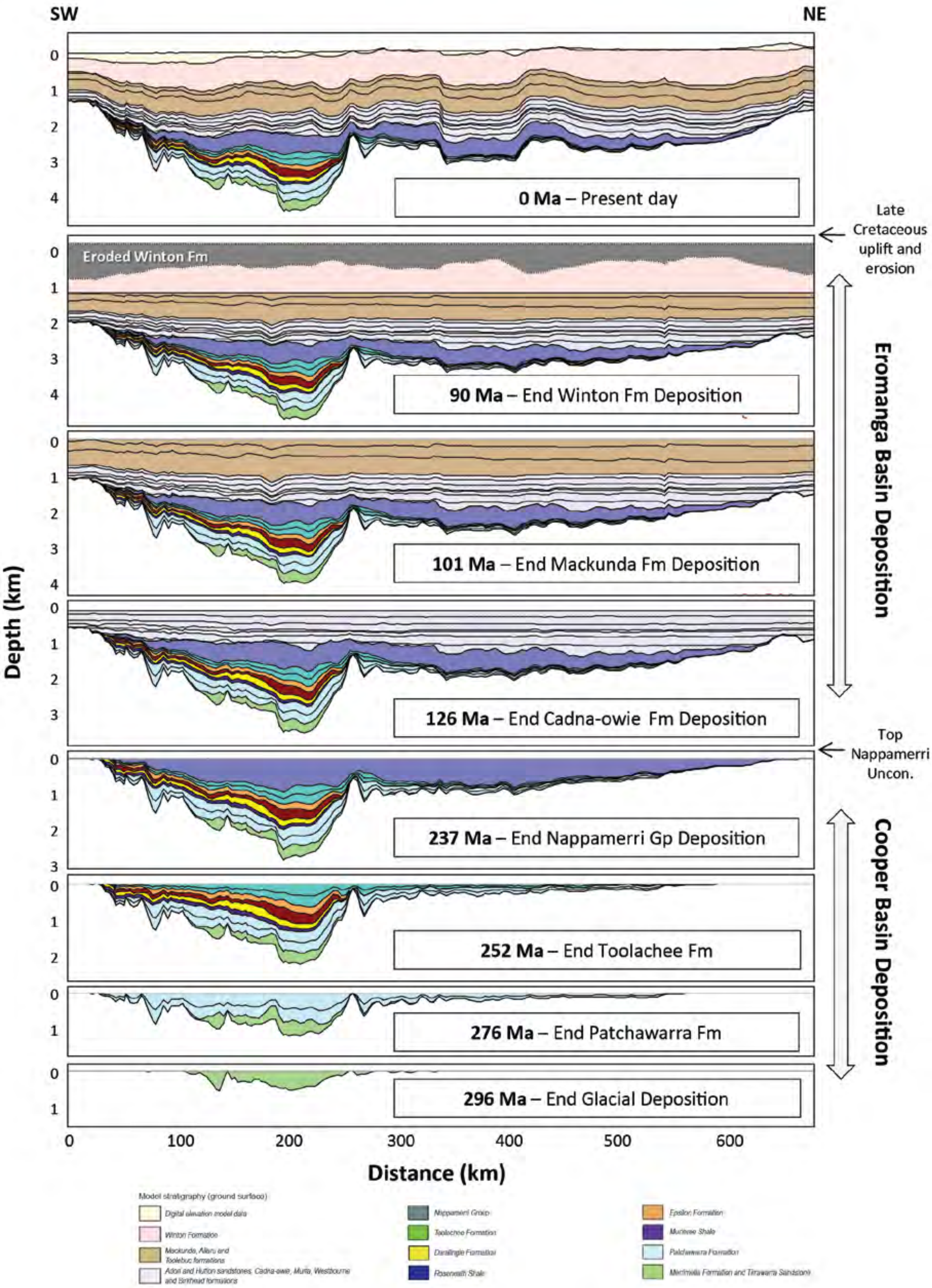

Figure 20 Modelled time-slice cross-sections through the Cooper–Eromanga–Lake Eyre basins succession, showing regional basin evolution and selected tectonic events. The cross-section used for this reconstruction is line A.26a shown in Figure 25 and Figure 26

Source: Hall et al. (2015)
Data: Hall et al. (2016); Hall and Palu (2016)
Element: GBA-COO-2-329

Stratigraphic information and depositional environments of the Cooper Basin sediments are described in Table 3. This succession is characterised in more detail, particularly in relation to their deep coal, shale and tight gas prospectivity, in the petroleum prospectivity technical appendix (Lech et al., 2020).

Table 3 Stratigraphy of the Cooper Basin

Group	Formation	Age	Lithological description	Thickness	Depositional environments	Stratigraphic relationships
Nappamerri Group	Tinchoo Formation	Middle Triassic	Siltstone, sandstone, minor coal	Maximum 263 m	Meandering fluvial	Conformably overlies the Arrabury Formation; is unconformably overlain by the Cuddapan Formation or units of the Eromanga Basin
Nappamerri Group	Arrabury Formation	Early Triassic	Mudstone, siltstone with fine sandstone interbeds	Maximum 390 m	Fluvial, flood plain and ephemeral lakes	Conformably overlies the Toolachee Formation; conformably overlain by the Tinchoo Formation in or unconformably overlain by Eromanga Basin sediments
Gidgealpa Group	Toolachee Formation	Lopingian	Sandstone, shale and minor coal	Average 61 m;maximum ~400 m	Meandering fluvial, floodplain, deltaic in part	Conformably, but slightly diachronously, overlain by the Arrabury Formation, or unconformably by sediments of the Eromanga Basin
Gidgealpa Group	Daralingie Formation	Guadalupian	Sandstone, shale and minor coal	Average 50 m; maximum 150 m	Deltaic, fluvio-lacustrine	Unit is transitional from and conformably overlies the Roseneath Shale and is disconformably overlain by the Toolachee Formation
Gidgealpa Group	Roseneath Shale	Guadalupian	Siltstone, shale and minor sandstone	Average 57 m; maximum 240 m	Lacustrine, fluviodeltaic	Conformably overlies and intertongues with the Epsilon Formation, and is conformably overlain by and intertongues with the Daralingie Formation
Gidgealpa Group	Epsilon Formation	late Cisuralian – early Guadalupian	Sandstone, siltstone, shale and coal	Average 50 m; maximum 225 m	Fluvio-deltaic, lacustrine with basal peat swamp	Conformably overlain by the Roseneath Shale, and conformably overlies the Murteree Shale

Group	Formation	Age	Lithological description	Thickness	Depositional environments	Stratigraphic relationships
Gidgealpa Group	Murteree Shale	late Cisuralian	Siltstone and sandstone	Average. 33 m;maximum 190 m	Lacustrine	Conformably overlies and interfingers with the Patchawarra Formation; conformably overlain by the Epsilon Formation
Gidgealpa Group	Patchawarra Formation	Cisuralian	Sandstone, siltstone, shale and coal	Average 130 m; maximum ~680 m	Fluvio-lacustrine, floodplain, minor deltaic	Overlies and interfingers with the glacial sediments of the Tirrawarra Sandstone, or unconformably overlies pre-Permian basement rocks
Gidgealpa Group	Tirrawarra Sandstone	Cisuralian	Sandstone, conglomerates, minor shale interbeds and rare coal	Maximum 75 m	Fluvio-glacial, braided fluvial, proglacial outwash	Interfingers with the underlying Merrimelia and overlying Patchawarra formations
Gidgealpa Group	Merrimelia Formation	Cisuralian	Conglomerate, diamictite, sandstone, conglomeratic mudstone, siltstone and shale	Maximum 80 m	Glacio-lacustrine, aeolian, terminoglacial, proglacial	Unconformably overlies Warburton Basin strata and interfingers with the overlying Tirrawarra Sandstone

Source: Gatehouse (1972); Kapel (1972); Morton and Gatehouse (1985); Powis (1989); Price (1997); Alexander et al. (1998); Draper (2002); Gray and McKellar (2002); Hall et al. (2015)

Pennsylvanian to Cisuralian subsidence

Subsidence of the Cooper Basin began in the Pennsylvanian, possibly related to cooling following the Pennsylvanian granite emplacement (Draper, 2002; Gallagher and Lambeck, 1989; Gravestock and Jensen-Schmidt, 1998). A major phase of extension commenced in the late Pennsylvanian well to the east of the Cooper Basin, and led to the initiation of the Bowen, Gunnedah and Sydney basins (e.g. Korsch et al., 2009a). This phase of mechanical extension was followed later in the Cisuralian by a phase of subsidence driven by thermal relaxation, prior to the onset of foreland loading in the mid Permian (see below). It is likely that these events had a far field effect on subsidence in the Cooper Basin. The sedimentary record suggests widespread tectonic quiescence through much of the early Permian. In the mid-Permian, a southeast-northwest oriented compressional event resulted in the development low-angle northeast-southwest striking conjugate fractures and developed, and/or reactivated, northeast-southwest striking faults (Kulikowski and Amrouch, 2017).

Decay of the ice sheet in the Cisuralian released enormous volumes of sediment to produce a typical Cooper Basin succession of basal diamictites (Tirrawarra Sandstone, Merrimelia Formation) overlain by non-marine peat swamps and floodplain facies of the Patchawarra, Epsilon and

Daralingie formations, interspersed with lacustrine deposits of the Roseneath and Murteree shales (Alexander et al., 1998).

Cisuralian to Guadalupian compression

Structural growth of the basement ridges commenced in the early to mid-Permian, leading to the formation of the Daralingie unconformity (Figure 19) (Apak et al., 1997; Heath, 1989; Kulikowski and Amrouch, 2017). This event was a strike-slip stress regime oriented NE-SW that reactivated north-west to south-east striking high-angle faults, including the JNP trend (Kulikowski and Amrouch, 2017). This event can be correlated with the Aldebaran deformational event in the eastern Australian marginal basins (Korsch and Totterdell, 2009a, 2009b; Korsch et al., 2009b), although it may have occurred slightly later in the Cooper Basin than in the Bowen and Gunnedah basins. This tectonic event had negligible effects in the troughs, but created significant erosion on some ridges (Alexander et al., 1998; Draper, 2002; Hill and Gravestock, 1995; Moussavi-Harami, 1996a).

Lopingian to Middle Triassic subsidence

Another phase of subsidence began in the Lopingian with continuing thermal subsidence (Draper, 2002) resulting in extensive deposition, incorporating the Toolachee Formation and Nappamerri Group (Figure 19). At this time, foreland loading was influencing the basins on the east coast (Waschbusch et al., 2009), and it is possible that far field effects of dynamic platform tilting played a role in the subsidence of the Cooper Basin.

Middle Triassic tectonism

Tectonism recommenced during deposition of the Middle Triassic Tinchoo Formation, resulting in north-west tilting of the Cooper Basin. This is reflected in the Nappamerri Group thickening to the north, and erosion from the southern areas of the basin. This is likely to be related to widespread contraction across eastern Australia, associated with later phases of the Hunter–Bowen Orogeny.

Late Triassic uplift and erosion

Deposition in the Cooper Basin *sensu stricto* was terminated by a final major phase of tectonic reactivation, uplift and erosion in the Late Triassic, driven by apparent north-east to south-west contraction, which lasted for up to 30 My, and gave rise to the major post-Nappamerri unconformity (Figure 20) (Kuang, 1985; Apak et al., 1997; Gravestock and Jensen-Schmidt, 1998; McKellar, 2013). As with the Daralingie unconformity, this event had negligible effect in the troughs, but resulted in erosion on the structural highs (Hill and Gravestock, 1995; Mavromatidis, 2006; Moussavi-Harami, 1996a). This Late Triassic unconformity is a common feature in coeval basins to the east, including the Galilee, Bowen, Gunnedah and Sydney basins, and marks the end of the Hunter–Bowen Orogeny (Korsch and Totterdell, 2009b; Wiltshire, 1982; Gravestock et al., 1998). The upper Triassic Hunter-Bowen event resulted in a compressional east-west oriented stress regime that developed and/or reactivated low-angle north-south striking faults (Kulikowski and Amrouch, 2017).

Coincident with fault reactivation and unconformity development, the region also experienced significant Late Triassic (202 ± 9 Ma) diagenesis associated with basin-wide hydrothermal fluid circulation (Zwingmann et al., 2001; Middleton et al., 2014; Middleton et al., 2015).

Deposition of Late Triassic sediments was not subject to the earlier Permo-Triassic controls on deposition, and was possibly a forerunner to events which influenced the broader development of the Early Jurassic – Late Cretaceous Eromanga Basin (Draper, 2002; Gray et al., 2002; Cook et al., 2013). These units are now preserved as isolated remnants, and have been found only in the Windorah and eastern Patchawarra troughs (Powis, 1989; Gravestock and Jensen-Schmidt, 1998). The sediments have been divided into the Morney beds and the Cuddapan Formation and are transitional between the Cooper and Eromanga Basins (Figure 19).

3.2.3 Jurassic–Cretaceous Eromanga Basin

The Eromanga Basin is a series of Early Jurassic to Late Cretaceous sedimentary rocks that extends well beyond the limit of the Cooper Basin (Raymond et al., 2018; Gravestock et al., 1998; Cook et al., 2013). The Eromanga sedimentary sequence is thickest in the Central Eromanga Depocentre, where the Eromanga Basin overlies the Cooper Basin, with the sequence overlying the Windorah Trough exceeding 2500 m thick (Figure 21). The Poolowanna Trough, an additional Eromanga Basin depocentre, lies to the west of the Cooper Basin and is separated from the Central Eromanga Depocentre by the Birdsville Track Ridge (Radke, 2009).

Early Jurassic to Late Cretaceous deposition within the Eromanga Basin was relatively continuous and widespread. Deposition was controlled by subsidence rates and plate tectonic events along the eastern margins of the Australian Plate. Volcanic activity on the evolving continental boundary also influenced sediment provenance and depositional environment. To the south, separation of Australia and Antarctica during the Late Cretaceous also influenced deposition within the Eromanga Basin (Alexander et al., 2006).

Early models of Eromanga Basin formation proposed that initial subsidence resulted predominantly from deep crustal metamorphism (Middleton, 1980; Zhou, 1993). There is also considerable evidence that subduction-related dynamic platform tilting contributed significantly to subsidence in the Eromanga Basin (Gallagher, 1990; de Caritat and Braun, 1992; Russell and Gurnis, 1994; Gurnis et al., 1998; Waschbusch et al., 2009; Matthews et al., 2011) and that this process occurred against a background of broader-scale vertical motions and tilting of the Australian continent (Russell and Gurnis, 1994).

In the Central Eromanga Depocentre, subsidence associated with the formation of the Eromanga Basin is inconsistent with platform tilting. An additional mechanism related to thermal decay was proposed by Gallagher (1990), along with a rapid increase in subsidence in the Early Cretaceous resulting from excess sediment loading. Several mechanisms have been proposed to explain the initiation of this subsidence. These include:

- Mantle downwelling, or avalanche events (Pysklywec and Mitrovica, 1997, 1998).
- The passive response to the continent passing over sinking detached lithospheric slabs in the mantle (Russell and Gurnis, 1994; Schellart and Spakman, 2015).
- Removal of a mantle plume (Waschbusch et al., 2009).

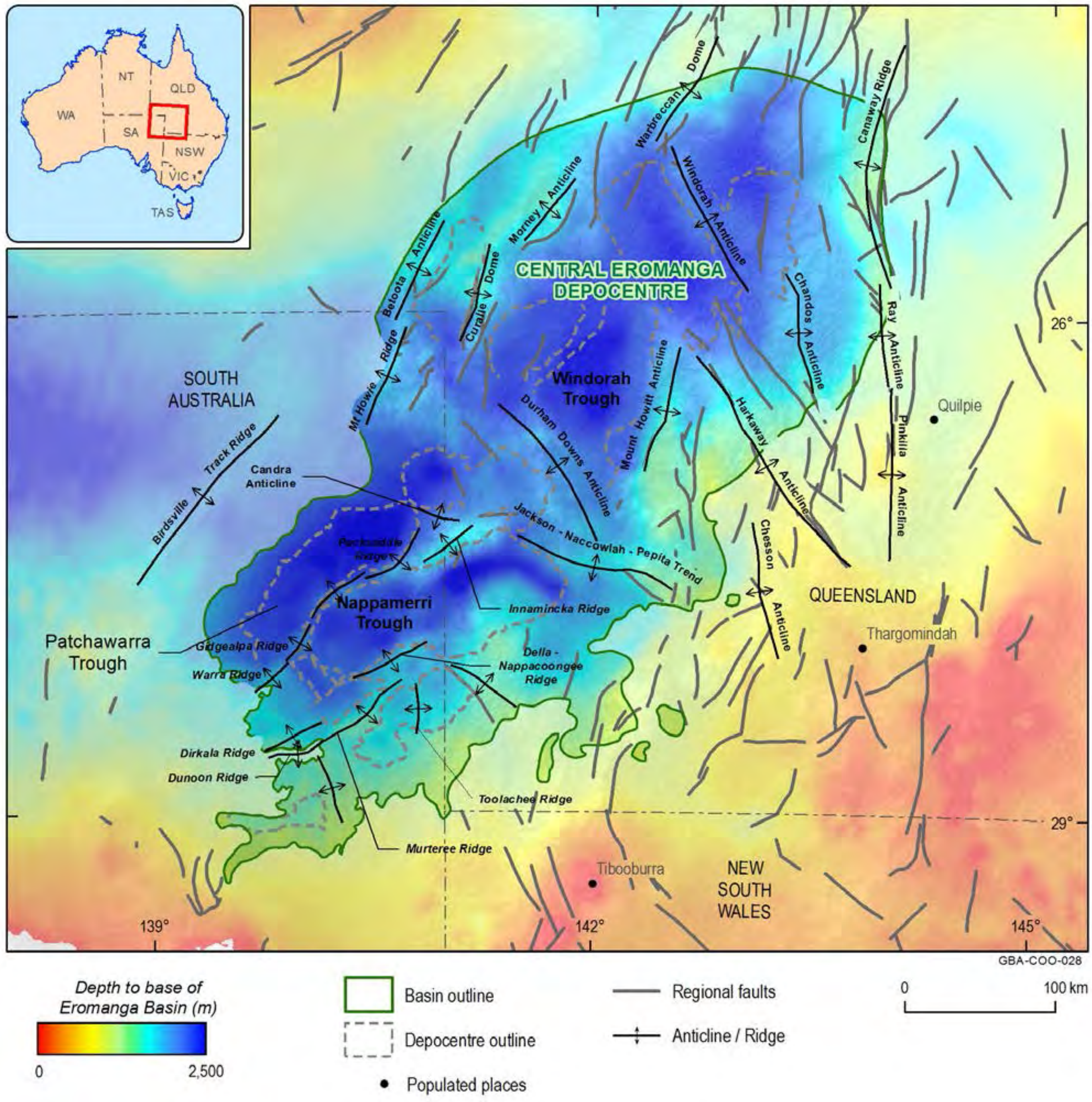

Figure 21 Structural elements map of the Eromanga Basin in the Cooper GBA region overlain on the depth to base Cadna-owie Formation

Anticlines depicted are regional trends and therefore to be used as a guide only.
Data: Depth to base Eromanga Basin and regional faults from Ransley and Smerdon (2012). Anticlines and depocentre outlines from Hall et al. (2015). Cooper Basin outline from Raymond et al. (2018)
Element: GBA-COO-028

The sedimentary succession of the Eromanga Basin (Figure 22) can be divided into three main depositional stages (Krieg et al., 1995; Moussavi-Harami, 1996a; Gray et al., 2002; Radke, 2009; Ransley and Smerdon, 2012; Cook et al., 2013):

- Stage I: Early Jurassic to Early Cretaceous extensive fluviatile and lacustrine deposition.
- Stage II: Early Cretaceous marine incursion.
- Stage III: late Early Cretaceous to Cenomanian paralic fluvial and lacustrine deposition.

The Eromanga Basin is comprised of a succession of terrestrial and marine origin that are summarised in **Table 4** and Figure 22. It includes a basal succession of terrestrial sedimentary rocks, followed by a middle marine succession, then finally an upper terrestrial succession. In the Early Jurassic to Early Cretaceous lower non-marine succession, large sand-dominated, braided fluvial systems drained into lowland lakes and swamps. The Early Cretaceous marine succession is dominated by thick transgressive shales, with thin sandstone units reflecting regressive cycles. In the Late Cretaceous non-marine succession, meandering fluvial systems were dominated by coal swamps and lakes (Alexander et al., 2006).

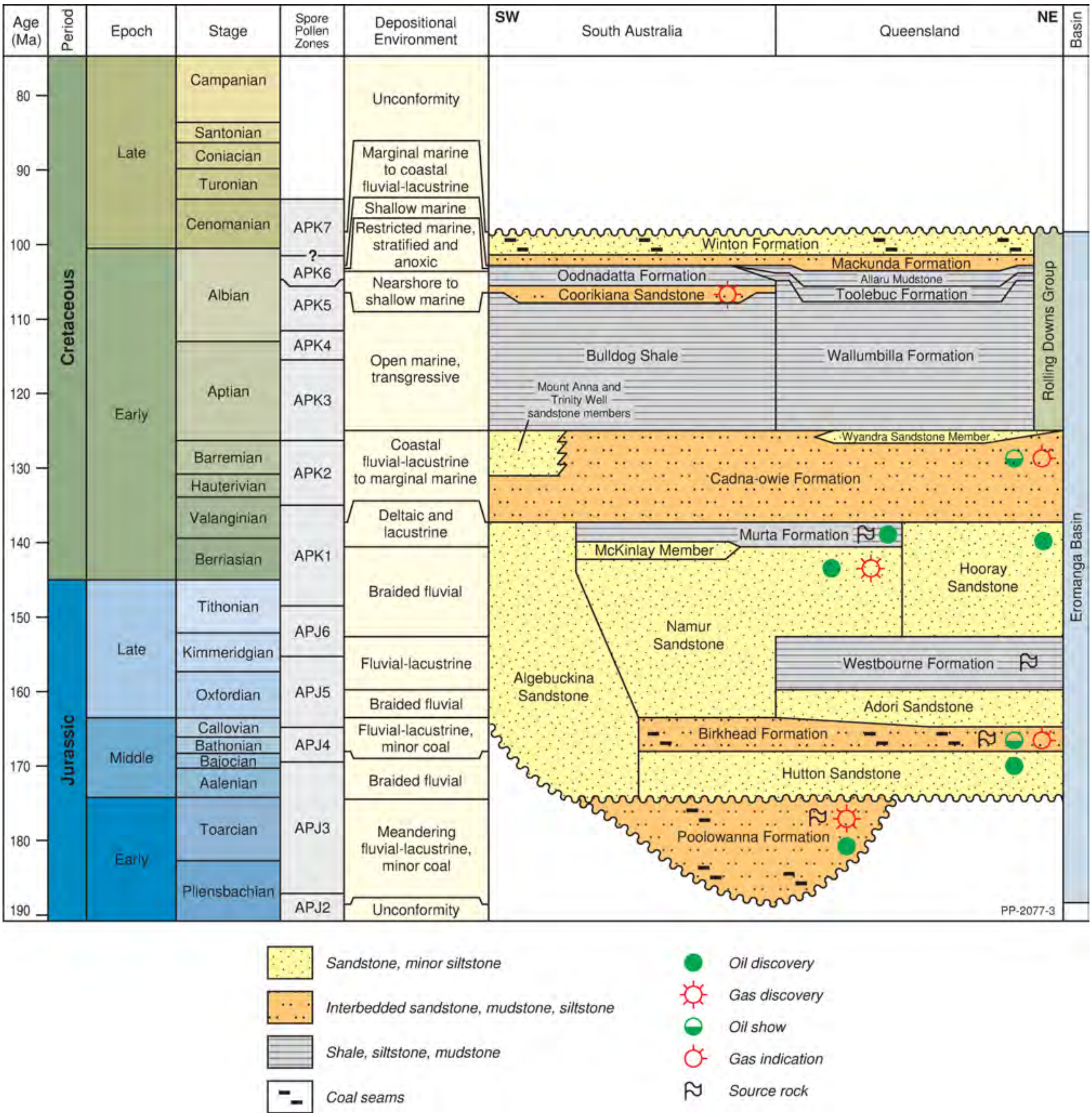

Figure 22 Stratigraphy of the Eromanga Basin showing depositional facies, conventional petroleum occurrences and identified source rocks

Source: Smith et al. (2016)

Element: GBA-COO-2-171

Table 4 Stratigraphy of the Eromanga Basin in the Cooper GBA region

Formation	Age	Lithological description	Thickness	Depositional environments	Stratigraphic relationships
Winton Formation (Rolling Downs Group)	Early to Late Cretaceous	Interbedded fine- to coarse-grained sandstone, carbonaceous shale, siltstone and coal seams with intraclast conglomerates	Greater than 400 m thick, maximum 1100 m	Fluvial and lacustrine in a coastal plain setting	Conformably overlies the Mackunda Formation. Unconformably overlain by Lake Eyre Basin rocks. Some structurally controlled outcrops found in the Cooper GBA area
Mackunda Formation (Rolling Downs Group)	Early Cretaceous	Interbedded, calcareous, very fine-grained sandstone, siltstone and shale	60 to 120 m	Alternating deep-marine and shoreface	Conformably overlies the Allaru Mudstone, conformably overlies and interfingers with the Oodnadatta Formation. Conformably underlies the Winton Formation
Allaru Mudstone (Rolling Downs Group)	Early Cretaceous	Mudstone, siltstone, calcareous mudstone with minor limestone and very fine-grained sandstone interbeds towards the top	100 to 240 m, maximum greater than 600 m	Quiet shallow marine	Conformably overlies the Toolebuc Formation and conformably underlies the Mackunda Formation
Toolebuc Formation (Rolling Downs Group)	Early Cretaceous	Oil shale, kerigenous shale, coquinitic limestone, nodular limestone with minor sandstone	20 to 45 m	Restricted marine at maximum high stand	Conformably overlies the Wallumbilla Formation and conformably underlies the Allaru Mudstone
Oodnadatta Formation (Rolling Downs Group)	Early Cretaceous	Laminate claystone and siltstone with fine-grained sandstone interbeds. Lower part contains calcareous siltstone and fossil-rich limestone	Up to 300 m	Low-energy, shallow marine	Conformably overlies the Coorikiana Sandstone. Interfingers with and conformably underlies the Mackunda Formation. Transitions laterally into the Wallumbilla and Toolebuc formations and Allaru Mudstone
Coorikiana Sandstone (Rolling Downs Group)	Early Cretaceous	Fine-grained, silty sandstone with minor conglomerate. Siltstone and mudstone interbeds at the base	20 m	Near-shore	Conformably overlies the Bulldog Shale, conformably underlies Oodnadatta Formation

Formation	Age	Lithological description	Thickness	Depositional environments	Stratigraphic relationships
Wallumbilla Formation (Rolling Downs Group)	Early Cretaceous	Fossiliferous, interbedded mudstone, siltstone, sandy mudstone, sandstone and minor limestone. Coarsening up to sandstone-dominated top	200 to 375 m, maximum 596 m	High latitude marine shelf	Conformably overlies the Cadna-owie Formation, lateral equivalent of Bulldog Shale. Conformably underlies the Toolebuc Formation
Bulldog Shale (Rolling Downs Group)	Early Cretaceous	Fossiliferous mudstone, with minor siltstone and very fine-grained sandstone interbeds. Basal portion is carbonaceous	Generally 200 m, maximum greater than 340 m	High latitude marine shelf	Conformably overlies the Cadna-owie Formation, lateral equivalent of the Wallumbilla Formation. Conformably underlies the Coorikiana Sandstone
Cadna-owie Formation	Early Cretaceous	Silty mudstone, siltstone and very fine- to fine-grained sandstone. Sand increases upwards. Rare coal and carbonaceous fragments, and shale clasts	60 to 115 m	Fluvial, lagoonal, shoreface, beach, offshore marine and lacustrine. Transition between terrestrial and marine environments	Gradational, conformably overlies Murta Formation, or conformably overlies the Algebuckina Sandstone. Unconformably underlies the Bulldog Shale or Wallumbilla Formation
Murta Formation (includes McKinlay Member)	Late Jurassic	Thin interbeds of shale, very fine- to fine-grained sandstone with minor medium- and coarse-grained sandstone. Base marked by siltstone	30 to 60 m, maximum 90 m	Lacustrine, possible marine transgression at the top	Lateral equivalent to upper part of the Hooray Sandstone. Interfingers with and conformably overlies the Namur Sandstone, gradation with Cadna-owie Formation
Namur Sandstone	Late Jurassic	Fine- to coarse-grained sandstone with minor siltstone and mudstone interbeds and rare conglomerate interbeds with carbonaceous mudclasts	40 to 240 m thick	Fluvial	Conformably overlies Birkhead Formation or interfingers with Westbourne Formation

Formation	Age	Lithological description	Thickness	Depositional environments	Stratigraphic relationships
Westbourne Formation	Late Jurassic	Shale and siltstone interbedded with minor fine- to very fine-, and some medium- to coarse-grained sandstone	30 to 140 m, maximum 166 m	Transition from fluvial to lacustrine and lake-shore	Conformably overlies Adori Sandstone. Conformably underlies and interfingers with Hooray, Namur and Algebuckina sandstones
Adori Sandstone	Late Jurassic	Upward-fining, very fine- to coarse-grained sandstone with minor siltstone and conglomerate	20 to 130 m	Braided fluvial	Conformable on Birkhead formation and unconformably underlies Westbourne Formation in SA. Unconformable on Birkhead and Conformably underlies Westbourne in Queensland
Birkhead Formation	Middle Jurassic	Interbedded siltstone, mudstone and fin-to medium-grained sandstone with thin coal seams	40 to 100 m, maximum 150 m	Lacustrine and coal swamp with some meandering channels and deltas	Conformable on and interfingers with Hutton Sandstone, unconformably overlain by Namur and Adori sandstones
Hutton Sandstone	Middle Jurassic	Fine- to coarse-grained quartzose sandstone with minor siltstone interbeds. Upper part is generally sandier than the lower part	40 to 360 m	Braided fluvial	Unconformable on Cooper and Warburton basins and Warrabin Trough. Interfingers with Birkhead Formation. Laterally equivalent to Algebuckina Sandstone
Algebuckina Sandstone	Middle Jurassic to Early Cretaceous	Fine- to coarse-grained sandstone with coarser layers and shale intraclasts. Minor shale and siltstone lenses	Up to 800 m	Braided fluvial	Lateral equivalent to Hutton Sandstone, Birkhead Formation, Adori Sandstone, Westbourne Formation, Namur Sandstone and Murta Formation

Formation	Age	Lithological description	Thickness	Depositional environments	Stratigraphic relationships
Poolowanna Formation	Early Jurassic	Interbedded carbonaceous siltstone, fine- to medium-grained pebbly sandstone and rare coal with carbonate and clay mineral cements. In Queensland, the lower part is coarser-grained sandstone	Up to 205 m	Alternating fluvial floodplain with minor coal swamps and lacustrine	Unconformable on Cooper and Warburton basins and Cuddapan Formation. Interfingers with Algebuckina Sandstone in the south and west and Hutton Sandstone in the north and east

Source: Smith et al. (2015a)

Early Jurassic to Early Cretaceous

Early Jurassic to Early Cretaceous deposition within the Eromanga Basin was relatively continuous and widespread. Deposition was controlled by plate tectonic events on the margins of the Australian plate to the east and south. Volcanic activity on the evolving continental boundary to the east influenced sediment provenance and depositional environments. On the southern margin, separation of Australia and Antarctica during the Late Cretaceous also influenced deposition within the Eromanga Basin (Alexander et al., 2006).

In the Early Jurassic to Early Cretaceous, the lower non-marine succession accumulated through extensive, sand-dominated, braided fluvial systems that drained centrally towards lowland lakes and swamps (Figure 22) (Wiltshire, 1989; Draper, 2002). In the Cooper GBA region, this lower non-marine succession consists of intertonguing braided fluvial sandstone (Hutton and Namur sandstones), lacustrine shoreface sandstone (McKinlay Member) and meandering fluvial, overbank and lacustrine sandstone, siltstone, shale and minor coal (Poolowanna, Birkhead and Murta formations) (Radke, 2009; Radke et al., 2012; Cook et al., 2013) (Figure 22). Little tectonic activity occurred in the Cooper GBA region during this time (Ransley and Smerdon, 2012).

In the Early Cretaceous, a continuation of the convergent plate setting is inferred along the eastern margin of Gondwana (Raza et al., 2009), with extension initiated in a back-arc setting at about 125 Ma as a precursor to the opening of the Tasman Sea (Crawford et al., 2003; Cook et al., 2013). Volcanic activity associated with the Whitsunday Volcanic Province also began around this time, ending by about 90 Ma. The youngest formation in the Eromanga Basin, the Cenomanian Winton Formation, contains volcanoclastic detritus, which suggests that it was deposited from about 99 Ma to at least 93 Ma (Bryan et al., 2012; Tucker et al., 2013).

Late Early Cretaceous

A widespread marine incursion occurred across the continent in the late Early Cretaceous (Frakes et al., 1987). There is a conformable transition from non-marine to marginal marine sediments (Cadna-owie Formation) to marginal to open marine shales and sandstones (Bulldog Shale, Coorikiana Sandstone, Oodnadatta, Wallumbilla, Toolebuc, Allaru and Mackunda formations; Figure 22; (Draper, 2002; Radke et al., 2012; Cook et al., 2013).

In the Late Cretaceous, a major plate realignment resulted in regional uplift, denudation and cooling along much of the eastern margin of Gondwana (Raza et al., 2009; Bryan et al., 2012). This period of activity ended with the inception of seafloor spreading in the southern Tasman Sea at about 84 Ma (Veevers et al., 1991; Gaina et al., 1998; Cook and Jell, 2013).

During the early stages of this event, uplift and erosion of the eastern highlands resulted in increased sediment supply to the Central Eromanga Basin and accumulation of the non-marine, Cenomanian Winton Formation (Gray et al., 2002; Alexander et al., 2006; Bryan et al., 2012; Radke, 2009; Radke et al., 2012; Ransley et al., 2012; Cook et al., 2013) (Figure 20, Figure 22). The Winton Formation was deposited by meandering fluvial systems that crossed a floodplain dominated by coal swamps and lakes. The thickness of the Winton Formation reaches up to around 1200 m over the Cooper Basin region, with maximum thicknesses occurring over the Patchawarra Trough. This deposition occurred very rapidly, equivalent to sedimentation rates of approximately 200 m/Ma.

Late Early Cretaceous to Cenomanian

The uplift of eastern Australia resulted in the termination of deposition in the Eromanga Basin in the Cenomanian, followed by erosion of much of the Winton Formation (Draper, 2002; Mavromatidis and Hillis, 2005; Jensen-Schmidt et al., 2006). Similar mid-Cretaceous uplift and erosion is observed in the Surat Basin to the east, highlighting the continental nature of this event (Korsch et al., 2009b; Raza et al., 2009).

The regional distribution and magnitude of erosion of the Winton Formation is not well constrained. Moussavi-Harami (1996a) used a restored isopach map to estimate that there was between 150 m and 440 m of missing section at the top of the Eromanga Basin. More recently, Mavromatidis and Hillis (2005) used compaction analysis to estimate exhumation of between 600 m and 1000 m of Eromanga Basin sediments over the Cooper GBA region during the entire Late Cretaceous–Quaternary period, the majority of which is likely to have occurred in the Late Cretaceous.

East-west compression resulted in the reactivation of north-south structures (Kulikowski and Amrouch, 2017). Structural inversion of the region produced significant fault reactivation within the Central Eromanga Basin, with fault displacements of up to 780 m on the Curalle Dome, 400 m on the Canaway Fault, and 300 m on the Harkaway Fault (Figure 23) (Hoffmann, 1989; Ransley et al., 2015; Ransley and Smerdon, 2012). Apatite fission track data suggest that the Cooper Basin was subjected to a high heatflow event in the mid-Cretaceous, where palaeotemperature profiles peaked at about 100–90 Ma, and cooled to 70 Ma (Duddy and Moore, 1999; Deighton et al., 2003; Deighton and Hill, 1998). Middleton et al. (2014; 2015) also identified a Cretaceous thermal event between about 128 Ma and 86 Ma, restricted to the Nappamerri Trough. This was interpreted to be an episodic fluid flow event associated with regional tectonism.

Polygonal faulting is pervasive within the entire Rolling Downs Group, as evident in seismic interpretation of the Lake Hope area (Watterson et al., 2000), and exposed in the floor of Lake Gregory (Ransley et al., 2015). More recent work has identified significant areas of the Eromanga Basin where intraformational faulting appears to be related to reactivation, or movement on, faults within the underlying Cooper Basin (Kulikowski et al., 2018).

3.2.4 Cenozoic Lake Eyre Basin

The Lake Eyre Basin is a Cenozoic sedimentary succession overlying the Eromanga Basin, covering parts of northern and eastern South Australia, south-eastern Northern Territory, western Queensland and north-western New South Wales (Raymond et al., 2018). The basin is less than 300 m thick over the Cooper Basin (Figure 23) (Ransley et al., 2012), and contains sediments deposited from the Paleocene (66 Ma) through to the Quaternary (Alley, 1998). The Lake Eyre Basin is further subdivided into sub-basins, with the northern part of the Callabonna Sub-basin overlying the Cooper Basin (Callen et al., 1995).

Cenozoic subsidence in north-eastern South Australia and south-western Queensland produced a large shallow depression, which continued to accommodate fluvial and lacustrine sediments. Initially, a fluvial system probably drained through to the Eucla Basin. With Early Oligocene deformation and renewed relief of the Birdsville Track Ridge (Wopfner, 1974; Moore and Pitt, 1984), sub-basins formed to create internally-draining basins. Uplift of the northern Flinders Ranges in the Miocene (Foster et al., 1994) further subdivided drainage in the Tirari Sub-basin which is located approximately 200 km to the west of the Cooper GBA region (Figure 23). Renewed uplift of the Eastern Highlands generated a regional south-westward tilt that greatly increased drainage (Figure 23) (Ransley et al., 2012).

Deposition within the Lake Eyre Basin is recognised to have occurred in three phases, punctuated by periods of tectonic activity and deep weathering (Callen, 1990; Krieg et al., 1995). The first phase of deposition from the late Paleocene to the middle Eocene is represented by the Eyre, Glendower and Marion formations; the second phase from the end of the Oligocene to the Miocene is represented by the Namba, Whitula and Doonbarra formations and the Cadelga Limestone; and the third phase occurred during the latest Pliocene to the Quaternary (Alley, 1998; Callen et al., 1995).

The stratigraphy and depositional environments of the Lake Eyre Basin are summarised in Figure 24 and Table 5.

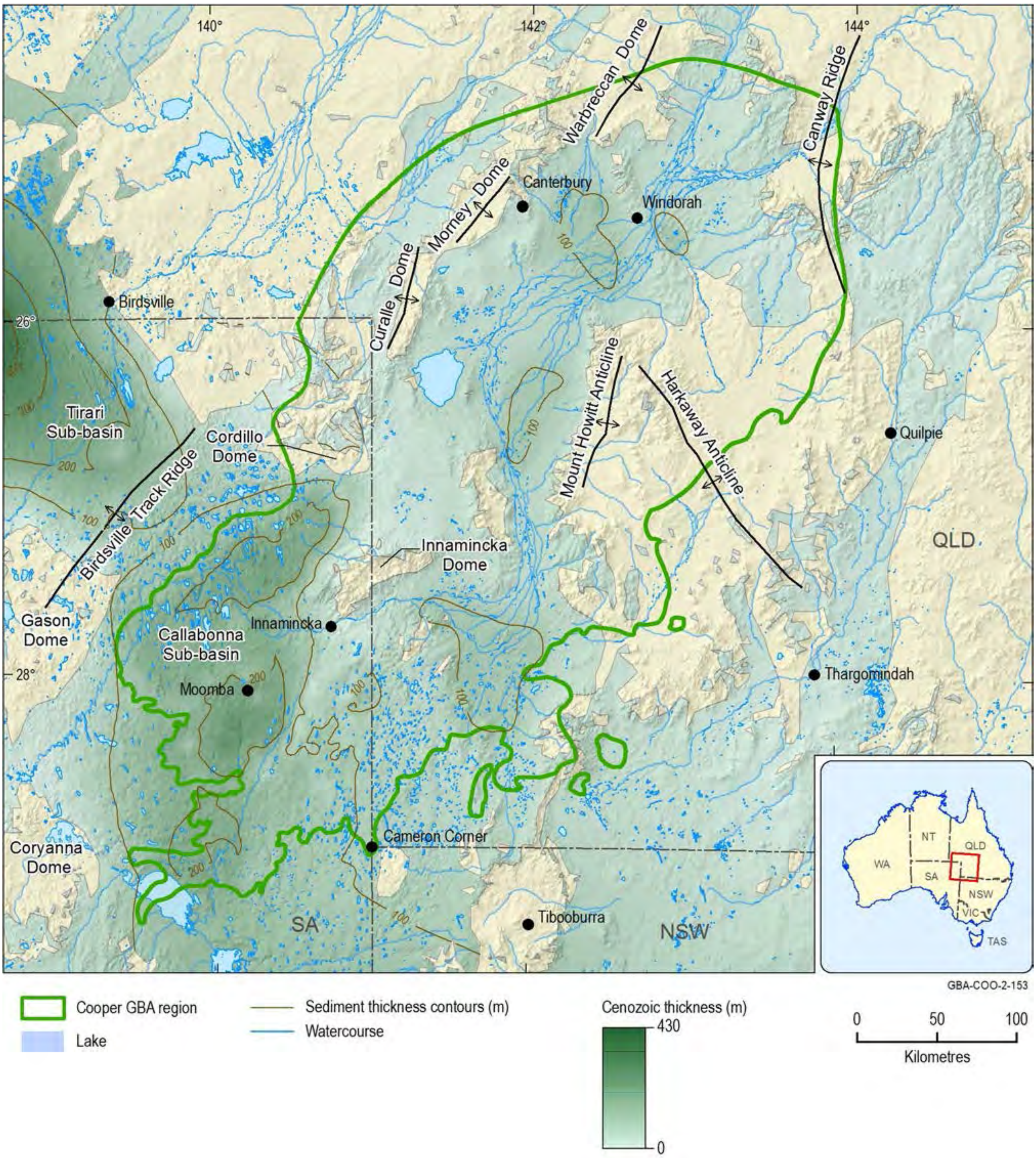

Figure 23 Thickness of the Cenozoic Lake Eyre Basin succession over the Eromanga Basin and regional structures

Cream areas represent outcrop of rocks that are older than the Cenozoic sediments. In the Cooper GBA region these areas represent outcrop of Winton Formation. Anticlines depicted are regional trends and therefore to be used as a guide only.
Data: Cenozoic thickness from Ransley et al. (2012); Cooper Basin outline from Raymond et al. (2018); hill-shade derived from 9-second DEM (Hutchinson et al., 2008); major water courses, lakes and salt lakes from Bureau of Meteorology (2014)
Element: GBA-COO-2-153

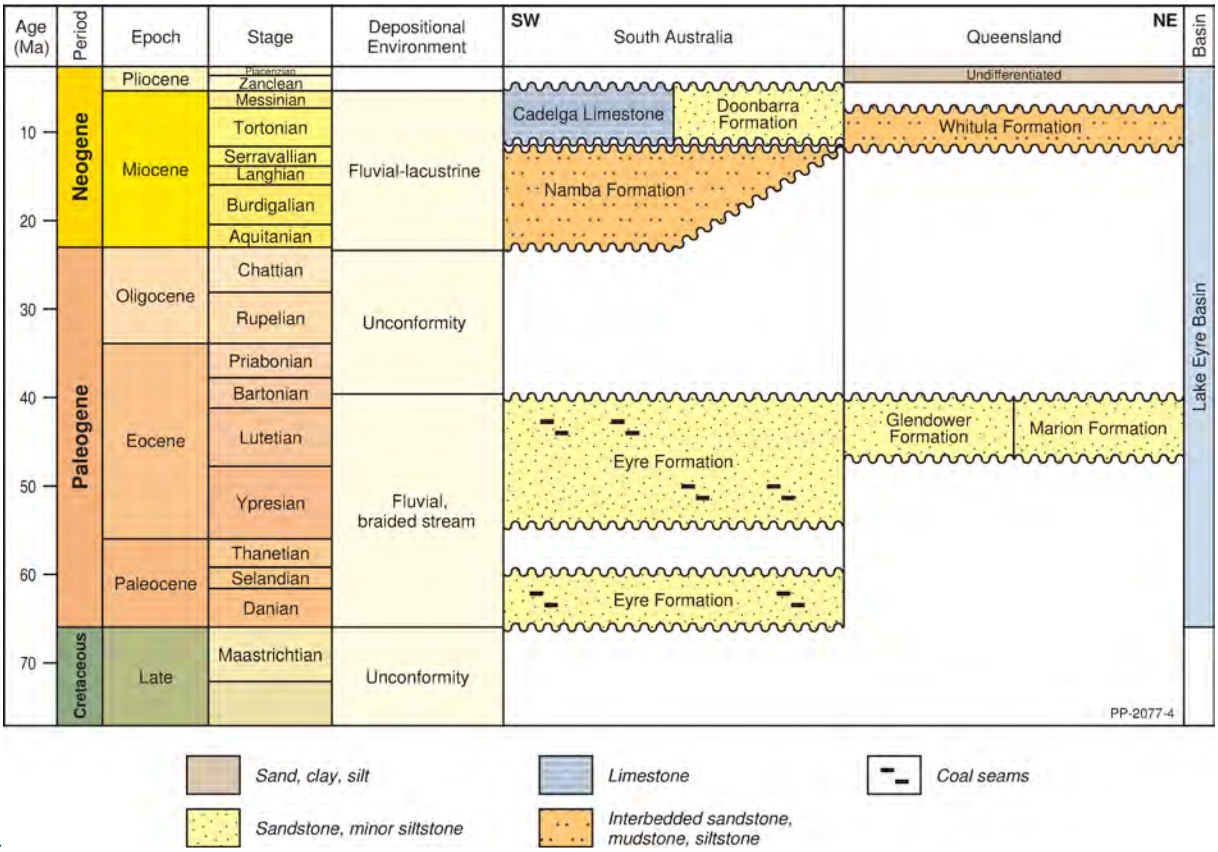

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Figure 24 Lake Eyre Basin stratigraphy and depositional environment

Source: Redrawn and modified from Smith et al. (2016)

Element: PP-2077-4

Table 5 Stratigraphy of the Lake Eyre Basin in the Cooper GBA region

Formation	Age	Simplified lithological description	Thickness	Depositional environments
Undifferentiated	Latest Pliocene to Quaternary	Sandstone, siltstone, claystone, evaporates and paleosols	Up to 60 m	Aeolian dunes, fluvial systems, lacustrine and gibber plains
Doonbarra Formation	Miocene	Sandstone and conglomerate	Generally 7–10 m, maximum 40 m	Fluvial-lacustrine
Cadelga Limestone	Miocene	Cherty dolomitic limestone	5 m	Lacustrine
Whitula Formation	Miocene	Sandstone, siltstone, mudstone and claystone with minor conglomerate, lignite and gypsum	Up to 160 m	Fluvial-lacustrine
Namba Formation	Miocene	Claystone, sandstone, carbonate, with minor conglomerate and dolomite	Up to 210 m	Fluvial-lacustrine
Marion Formation	Eocene	Sandstone and conglomerate	Up to 8 m	Fluvial, braided stream
Glendower Formation	Eocene	Sandstone, conglomerate and minor siltstone	Generally 70 m	Fluvial, braided stream
Eyre Formation	Paleocene to Eocene	Sandstone, siltstones and gravel with minor lignite and clay beds	0–100 m	Fluvial, braided stream

Source: Smith et al. (2015a)

Late Paleocene to the middle Eocene

The first phase of deposition lasted from the late Paleocene to the middle Eocene and is represented by the Eyre Formation and equivalents (Wopfner, 1974; Callen et al., 1995). The Eyre Formation consists of carbonaceous sand, silt and gravel, with some lignite and clay beds, interpreted to represent deposition in a braided stream fluvial setting (Alexander et al., 2006; Alley, 1998). It is of variable thickness over the Cooper GBA region, generally under 100 m, but known to exceed this above the Tenappera Trough (reaching 112.5 m in Mulga 2).

Late Eocene to late Oligocene

There is little evidence of deposition between the late Eocene and late Oligocene, and this hiatus is marked by silcrete formation on the top of the Eyre Formation (Roach, 2012). Widespread gentle folding and uplift, including on the Birdsville Track Ridge, initiated the division of the Lake Eyre Basin into sub-basins during this time. Moussavi-Harami (1996a) estimated the total amount of erosion above the Cooper Basin associated with this event is less than 30 m.

Late Oligocene

The second phase of deposition commenced in the late Oligocene (ca 28 Ma) and extended through to the Pliocene (Roach et al., 2014; Callen et al., 1995). Sediments include clay, fine-grained sand, carbonate, and minor conglomerate of the Namba and Whitula formations and correlatives (Callen et al., 1995). The Namba Formation is restricted to the Callabonna Sub-basin in South Australia, where it reaches a maximum thickness of 210 m (Alexander et al., 2006). The Whitula Formation overlies the Windorah Trough, Yamma Yamma Depression, Farrars Syncline and Thomson Depression, and has a maximum recorded thickness of 160 m.

Miocene

A new phase of contraction began during the Miocene, which resulted in a relative increase in paleoseismic activity, fault reactivation and deformation across many Australian basins in Miocene to Holocene times (Hillis et al., 2008). This was driven by plate boundary forces at the margins of the Indian–Australian Plate, including its ongoing continental collision with the Eurasian Plate and subduction along the Tonga–Kermedec Trench (Hillis et al., 2008; Sandiford et al., 2004). Fault reactivation and associated localised uplift and erosion coinciding with the Cooper Basin occurred along the Morney and Betoota anticlines and the Warbreccan and Curalle domes (Ambrose et al., 2007). Moussavi-Harami (1996a) interpreted only 15–54 m of missing section from selected wells directly overlying the Cooper Basin. Further Miocene uplift of the Southern Highlands initiated artesian conditions and westward through flow of groundwater within the Great Artesian Basin (Ransley et al., 2012).

Pliocene to Quaternary

The third phase of deposition in the Lake Eyre Basin began in the Pliocene and was characterised by deposition of red and yellow–brown sand and sandy clay (aeolian Tirari Formation and equivalents), and development of gypsum and carbonate paleosols (Roach et al., 2014).

This was followed by the deposition of Quaternary sediments in fluvial and lacustrine environments, as well as the development of extensive desert dunefields.

4 Region-scale structural and stratigraphic framework

This section reviews the main structural elements of the Cooper Basin and how these relate to the stratigraphy. The basin is over 4400 m deep and the unconformity at its upper surface varies in depth below present land surface from 970 m to 2800 m (Figure 13 and Figure 14).

4.1 Troughs

The troughs, synclines and depressions in the Cooper Basin are host to the key shale, tight and deep coal gas-bearing formations. These are outlined in more detail below, and are shown in a series of cross-sections, refer to Figure 25 to Figure 32.

4.1.1 Nappamerri Trough

The Nappamerri Trough contains the thickest sedimentary succession in the Cooper Basin. The trough is deepest in its eastern half, where it reaches depths over 4400 m and contains a Pennsylvanian to Triassic succession up to approximately 2400 m thick (Figure 13, Figure 14, Figure 19, Figure 26, Figure 27, Figure 29; Gravestock and Jensen-Schmidt, 1998). Although the Halifax 1 well does not reach basement, it intersects the deepest Permian sediments drilled in the basin to date at a total depth of 4209 m (Beach Energy, 2013a). The trough trends north-east–south-west, and is bound by major structures both to the north-west and south-east. The south-western end of the Nappamerri Trough appears to be compartmentalised by north–north-west to north-west-trending structures (Gravestock and Jensen-Schmidt, 1998). These may mark the location of strike-slip faults in the underlying Warburton Basin succession (Apak et al., 1997; Kuang, 1985).

4.1.2 Wooloo and Allunga troughs

The Wooloo Trough lies to the south-west of the Nappamerri Trough and is separated from it by north-west-striking strike-slip faults (Boucher, 1991). The Allunga Trough runs parallel to the Nappamerri Trough, intersecting the southern end of the Wooloo Trough (Figure 14). At its eastern end of the Allunga Trough is the Dunoon Ridge. The Wooloo and Allunga troughs contain a maximum thickness of Permian–Triassic rocks of 1000 to 1200 m, and reach maximum depths of up to 3100 m (Figure 13, Figure 14, Figure 27).

4.1.3 Tenappera Trough

The Tenappera Trough is an indistinct north-east–south-west trending structural depression separated from the Nappamerri Trough to the north by the Murteree Ridge (Gravestock and Jensen-Schmidt, 1998). Although much shallower than the Nappamerri Trough (with a maximum depth of around 3000 m), this depocentre contains a considerable thickness (>1000 m) of Carboniferous–Permian strata (Figure 14, Figure 27).

4.1.4 Patchawarra Trough

The Patchawarra Trough is located entirely within South Australia, and trends north-east to south-west along the north-western margin of the basin. It is subtly compartmentalised by north-west-trending structures that are interpreted to mark an underlying strike-slip fault assemblage through the Warburton Basin (Roberts et al., 1990; Gravestock and Jensen-Schmidt, 1998). The Patchawarra Trough reaches a maximum depth of over 3650 m (Figure 13, Figure 27, Figure 30). Although the thickness of the Cooper Basin succession in this trough reaches a maximum of 1000 m, it is still less than half of that in the Nappamerri Trough (Figure 14) with significant sections of the Permian rocks missing as a result of non-deposition or erosion at the Guadalupian Daralingie unconformity (Gravestock and Jensen-Schmidt, 1998).

4.1.5 Weena Trough and Milpera Depression

The Weena Trough lies in the south-west corner of the basin. It is aligned east–west and has a flat-bottomed, steep-sided geometry (Gravestock and Jensen-Schmidt, 1998; Simon, 2000). This trough has been interpreted as a Pennsylvanian glacial valley by Gravestock and Jensen-Schmidt (1998). Maximum depths reach only around 2240 m, although the total thickness of the Cooper succession reaches over 1000 m (Figure 13, Figure 14). Although the full Cooper Basin section is not penetrated, a minimum of approximately 490 m of Permo-Triassic sediments were intersected in Davenport 1 (Beach Energy, 2012).

4.1.6 Arrabury Trough

The Arrabury Trough is a poorly defined feature which lies immediately to the north of the JNP Trend (McKellar, 2013). The north-western part of this trough is a deep embayed extension to the Patchawarra Trough, but becomes shallower and more irregular to the east.

Depocentre geometries are less well constrained than other troughs to the south, but limited well intersections show a maximum depth of around 3050 m and a maximum Cooper Basin succession thickness of 770 m (Figure 13, Figure 14, Figure 31).

4.1.7 Windorah Trough

The Windorah Trough forms the central part of the northern Cooper Basin (Figure 13, Figure 14,; McKellar, 2013). Structural depressions within the Windorah Trough are separated by a subtle north-east-trending high, and collectively overlie the Devonian Barrolka Trough (Figure 16; Draper et al., 2004). The Windorah Trough coincides with the curved axis of the Cooper Syncline of Hoffmann (1989), and shows thickening of Permo-Triassic strata into its component depressions. Well intersections indicate that Permian sediments reach depths of over 3000 m, and show a total thickness for the Cooper Basin succession of over 625 m (Figure 13, Figure 14, Figure 28, Figure 32).

4.1.8 Yamma Yamma Depression and Farrars Syncline

To the west of the Windorah Trough are the Yamma Yamma Depression and Farrars Syncline (Figure 13, Figure 14, Figure 28). These are separated by the north–north-east trending Curalle Dome. Although poorly constrained, the Cooper Basin succession in Farrars Syncline and the Yamma Yamma Depression are estimated to have maximum depths of around 2300 m and 3000 m, respectively, with a maximum thickness of only about 250 to 300 m of late Permian to Triassic sediments.

4.1.9 Ullenbury Depression

The northern Cooper Basin extends to the north-east into the Ullenbury Depression. The Ullenbury Depression is deeper than the other northern depocentres (maximum depth 2750 m). Although poorly constrained, the total thickness of the Cooper Basin succession is only estimated to reach 500 to 600 m (Figure 13, Figure 14, Figure 26). The Ullenbury Depression has a pronounced asymmetric tilt deepening to the north-west, where it ends abruptly against the uplifted zone between the Morney Anticline and Warbreccan Dome. This depression is elongate and constrained by the parallel Harkaway and Windorah anticlines (Figure 13).

4.1.10 Thomson Depression

North-east of the Ullenbury Depression and Windorah Trough, the regional depocentre terminates in the shallower Thomson Depression, which overlies the Devonian succession of the Warrabin Trough (Figure 13; Draper et al., 2004). Limited well intersections give a maximum depth of around 2545 m and a maximum thickness for the Cooper Basin succession of about 300 m (Figure 13, Figure 14, Figure 28).

4.2 Ridges

Structural highs partition the Cooper basin into discrete depocentres. More detail is provided below, and are shown in a series of cross-sections, refer to Figure 25 to Figure 32.

4.2.1 Gidgealpa, Merrimelia, Packsaddle and Innamincka ridges

The most prominent structural highs in the southern part of the basin are the Gidgealpa, Merrimelia, Packsaddle and Innamincka ridges (Figure 13, Figure 14, Figure 27, Figure 29, Figure 30; Gravestock and Jensen-Schmidt, 1998; McKellar, 2013). These are located partly in-line and partly *en-echelon*, to form an arcuate south-west to north-east trending ridge complex (GMI Trend), separating the Nappamerri and Patchawarra troughs. Each ridge is asymmetric with major faults bounding the northern margin, and minor faults on the southern margin (Gravestock and Jensen-Schmidt, 1998). Some are demonstrably cored by deep thrust faults in the underlying Warburton Basin (Roberts et al., 1990), which were reactivated during episodes of contraction from the Permian to the Cenozoic (Sun, 1997).

4.2.2 Dunoon, Murteree and Della–Nappacoongee ridges

Further south are the north-east-trending Dunoon, Murteree and Della–Nappacoongee ridges (commonly known as the MN Trend), which separate the Allunga and Nappamerri troughs from the Tenappera Trough (Gravestock and Jensen-Schmidt, 1998; McKellar, 2013). The Dunoon and Murteree ridges are flat-topped, symmetrical ridges, faulted on both sides, whereas the major bounding fault for the Della–Nappacoongee Ridge is on its northern side.

These ridges are considered to have developed as a result of reactivation of north-west-directed thrust faults in the underlying Warburton Basin during a deformational event pene-contemporaneous with the Devonian–Carboniferous Alice Springs Orogeny in central Australia and the Middle–Late Carboniferous Kanimblan Orogeny in eastern Australia. It has been suggested that this created a high-relief paleotopography that controlled facies deposition in the troughs (Gravestock and Jensen-Schmidt, 1998). Timing and mechanisms of tectonics, however, remain debated. Both well and seismic data show that the Permian is eroded and Triassic strata are thin along many of the more prominent ridges (Figure 14, Figure 27, Figure 29). For example, the Dunoon and Murteree ridges are devoid of Permian–Triassic sediments (Figure 14).

4.2.3 Tinga Tingana Ridge

The Tinga Tingana Ridge strikes north–south, stretching from the southern margin of the Cooper Basin to the Dunoon Ridge, separating the Weena Trough from the rest of the Cooper Basin (Figure 14; Gravestock and Jensen-Schmidt, 1998).

4.2.4 Jackson – Naccowlah – Pepita (JNP) Trend

The JNP Trend marks the boundary between the north-eastern and south-western Cooper Basin (Figure 13, Figure 14, Figure 26; Heath, 1989; Hill and Gravestock 1995; McKellar, 2013). It aligns west–north-west to east–south-east and extends to the south-east beyond the Cooper Basin. The JNP Trend is most prominent on the south-eastern side of the Cooper Basin, where it marks the northern boundary of the Nappamerri Trough.

4.2.5 North-west trending structures

Prominent north-west-trending ridges bound the major depocentres in the north-east part of the basin, and include the Durham Downs, Harkaway and Windorah anticlines (Figure 13, Figure 14, Figure 26). In the zone north-east of the Harkaway Anticline, the anticlines are faulted along their main axes, with modest down-throw on their north-eastern flanks. These disruptions change from thrust faults at the south-eastern margin of the basin to extensional faults north-westwards into the basin (Hoffmann, 1989).

4.2.6 North trending structures

North trending ridges lie to the south-eastern side of the north-eastern Cooper Basin, including the Mount Howitt Anticline, Chandos Anticline, and the Canaway Ridge (Figure 13, Figure 14, Figure 26). The thrust faulted Canaway Ridge marks the north-eastern- boundary of the Cooper Basin, separating the Cooper Basin from concurrent deposition farther east in the southern Galilee and Bowen basins (Hoffmann, 1989; McKellar, 2013).

4.2.7 North-east to north–north-east trending structures

Along the shallower, north-western margin of the north-eastern Cooper Basin lie a series of north-east to north–north-east trending anticlines and ridges. This structural belt includes the, Morney and Betoota anticlines, the Warbreccan and Curalle domes and the Mount Howie Ridge (Figure 13). This belt transitions south-westwards into the Deramookoo Shelf and the Birdsville Track Ridge, which separates the Cooper from the Pedirka Basin to the north-west (Hibburt and Gravestock, 1995). This structural belt is part of a major north–north-east trending belt of *en-echelon* faults that extends from the Adelaide Rift System through to northern Queensland (Sprigg, 1986; Campbell and O'Driscoll, 1989). Contractional reactivation of these structures occurred in the mid Miocene (Ambrose et al., 2007), and produced uplifts in the order of 350 m to 500 m near the margin of the basin during the Cenozoic (Foster et al., 1994; Alexander and Jensen-Schmidt, 1995; Krieg, 1985).

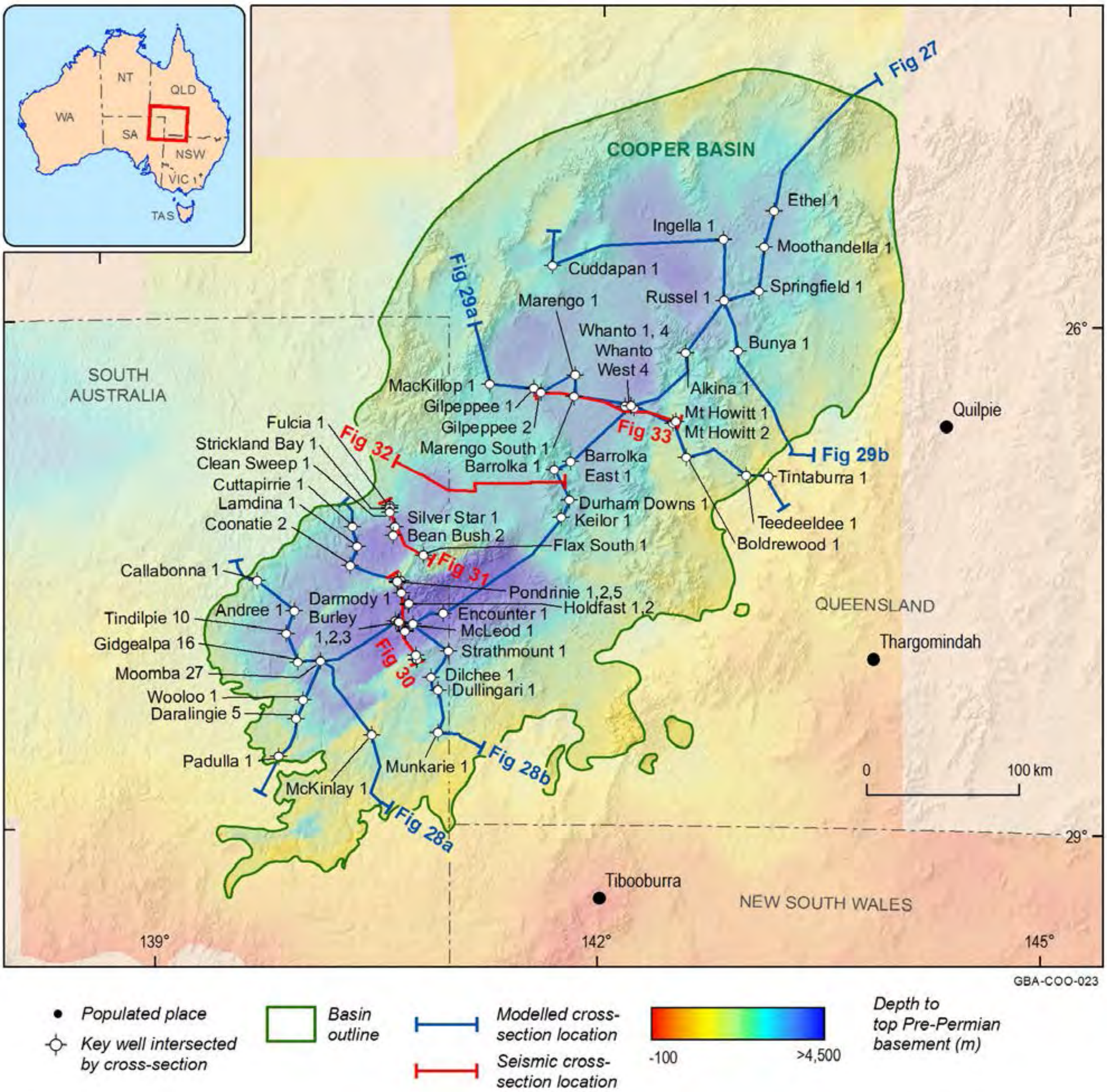

Figure 25 Location map for regional cross-sections through the Cooper Basin shown in Figure 26 to Figure 32

Source: Hall et al. (2015)

Data: Cooper Basin outline from Raymond et al. (2018); hill-shade derived from 9-second DEM (Hutchinson et al., 2008); depth to pre-Permian basement NGMA (National Geoscience Mapping Accord) (2001); wells (Department for Energy and Mining (SA) and Department of Natural Resources and Mines (Qld), 2019) (Queensland Government, 2018; Department of State Development (SA), 2018)

Element: GBA-COO-023

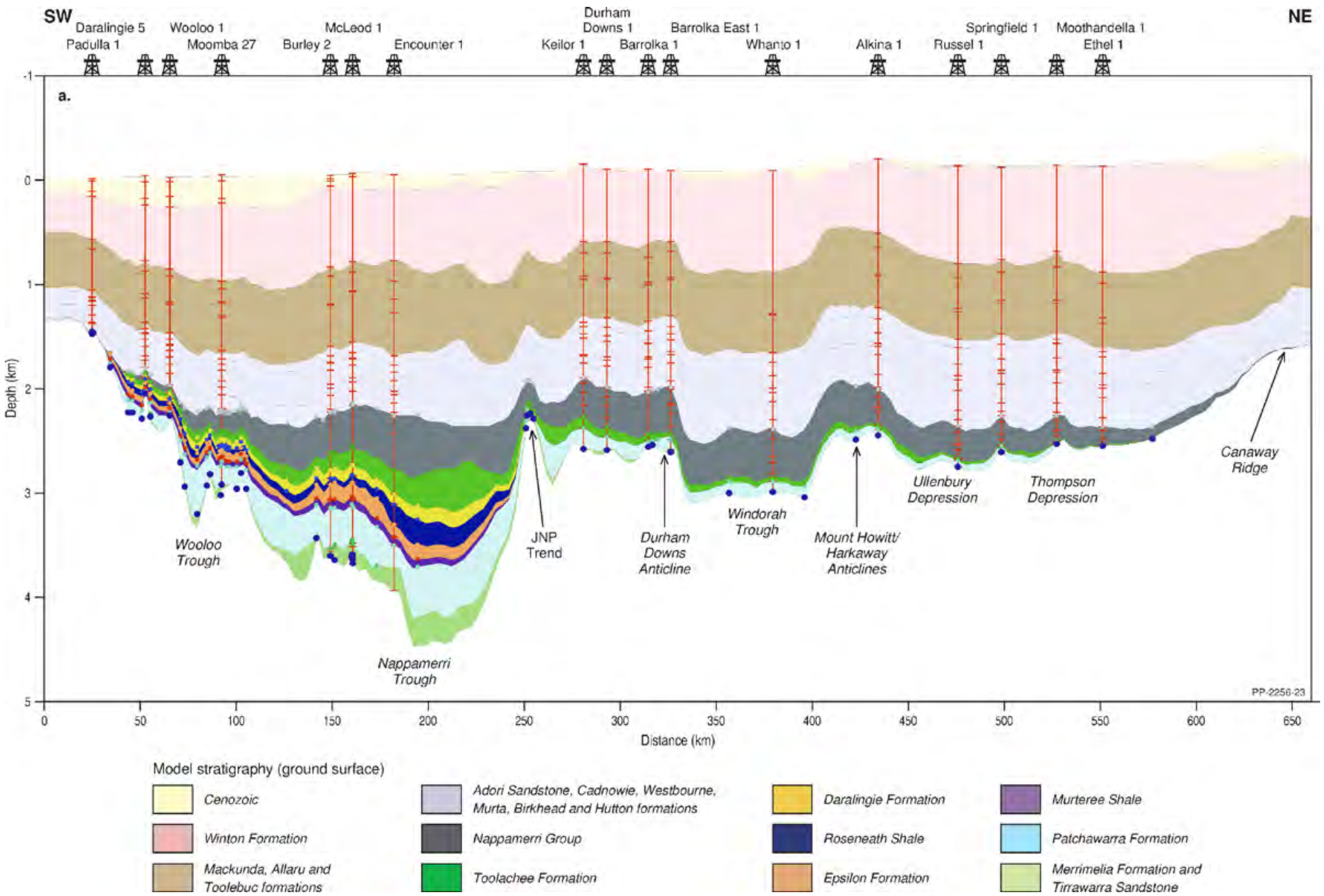

Figure 26 Regional cross-section through the Cooper Basin extracted from the three-dimensional model. Cross-section location map is shown in Figure 25. Control points for generating the surfaces are shown as blue dots. Faults were not interpreted in the three-dimensional model

Source: After Hall et al. (2015)
Data: Hall et al. (2016); Hall and Palu (2016)
Element: PP-2256-23

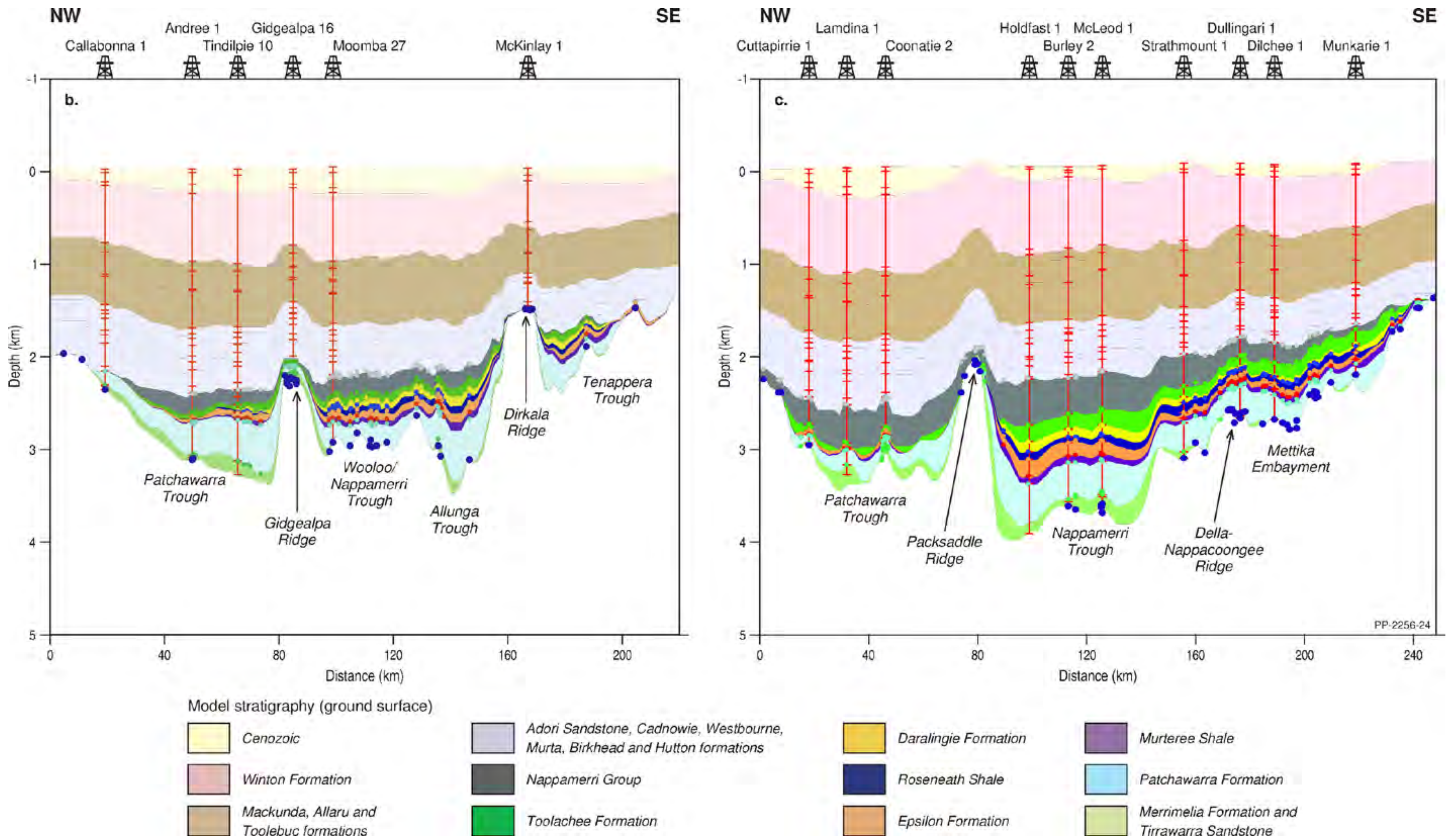

Figure 27 (a) and (b) Regional cross-sections through the Cooper Basin extracted from the three-dimensional model. Cross-section location map is shown in Figure 25. Control points for generating the surfaces are shown as blue dots. Faults were not interpreted in the three-dimensional model

Source: After Hall et al. (2015)

Data: Hall et al. (2016); Hall and Palu (2016)

Element: PP-2256-24

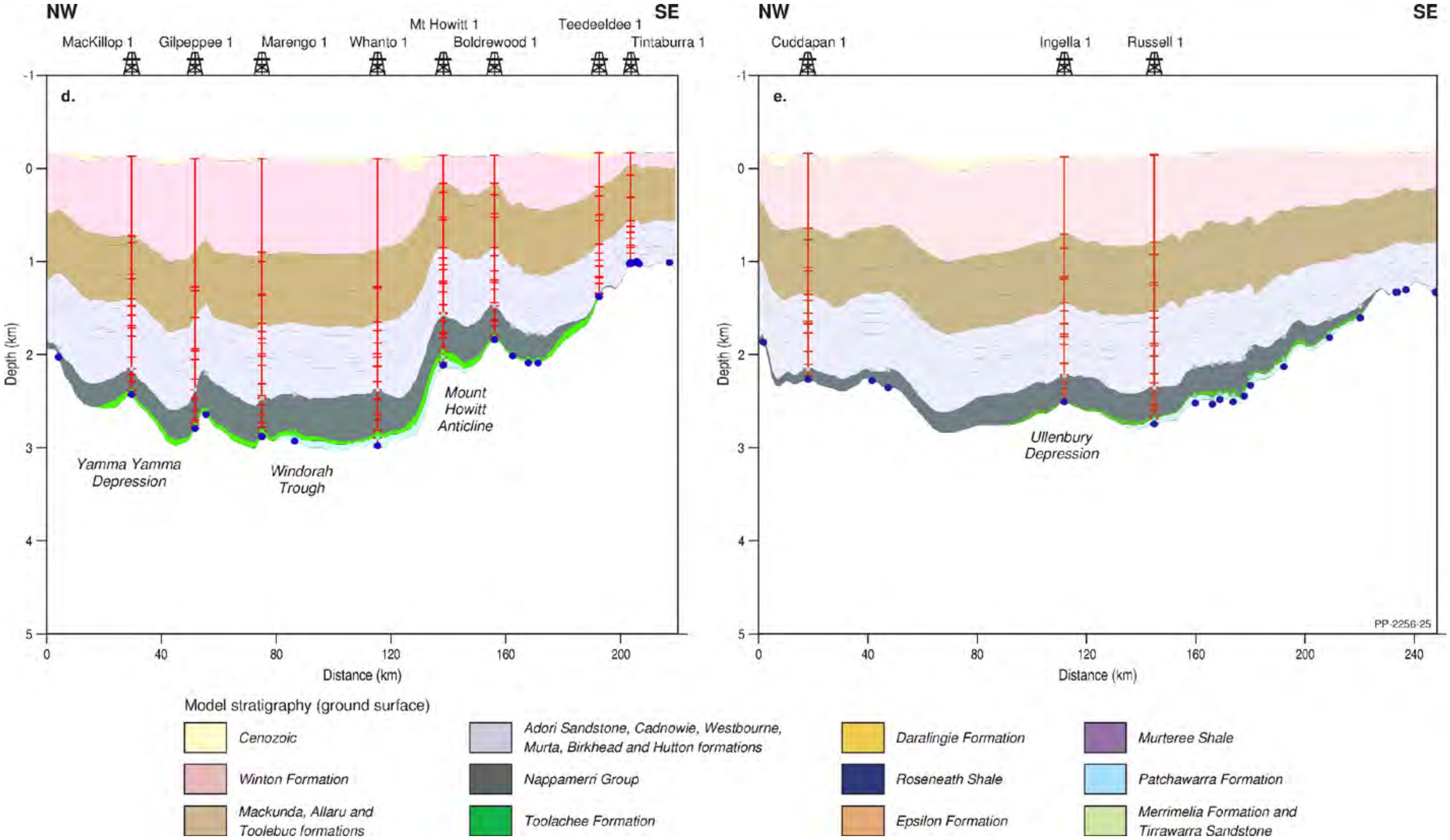

Figure 28 (a) and (b) Regional cross-sections through the Cooper Basin extracted from the three-dimensional model. Cross-section location map is shown in Figure 25. Control points for generating the surfaces are shown as blue dots. Faults were not interpreted in the three-dimensional model

Source: After Hall et al. (2015)
Data: Hall et al. (2016); Hall and Palu (2016)
Element: PP-2256-25

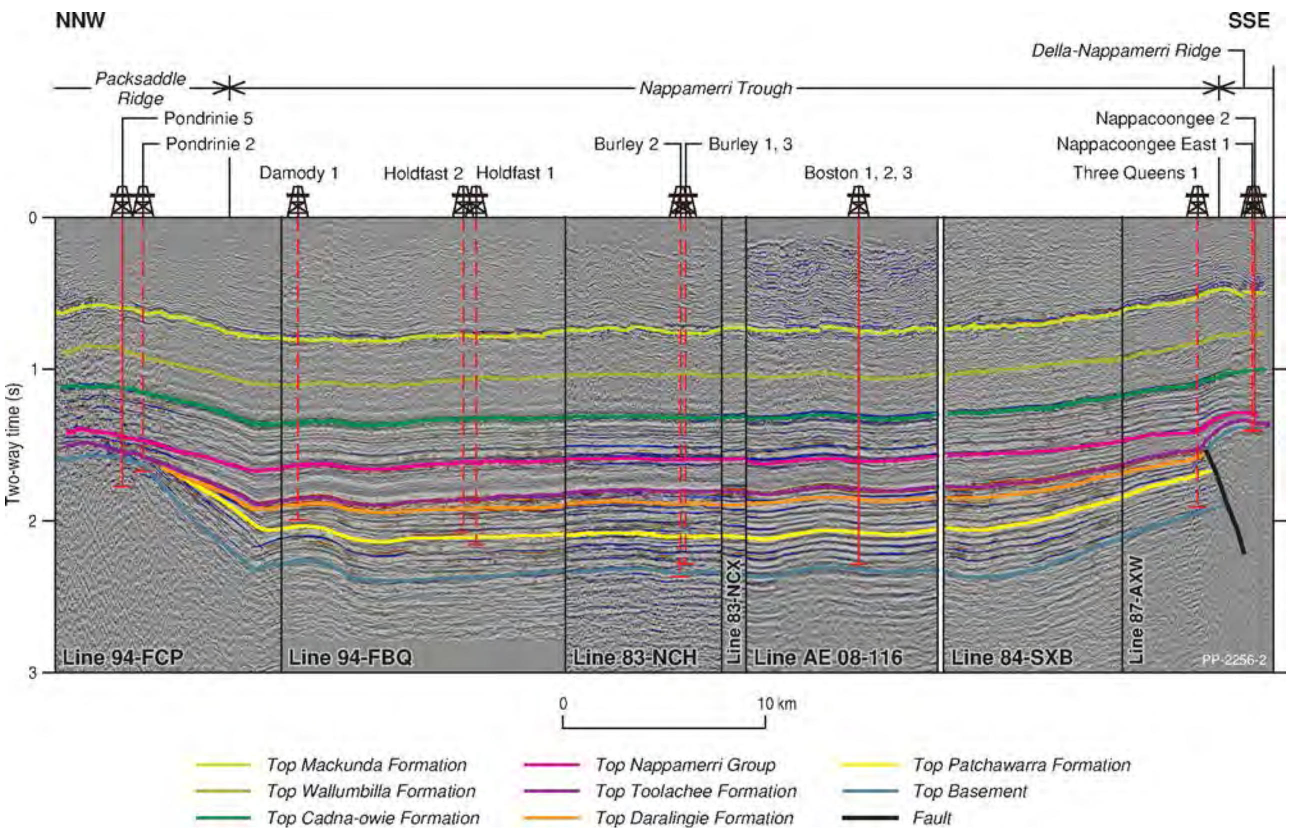

Figure 29 Regional seismic cross-section across the Nappamerri Trough. Cross-section location map is shown in Figure 25

Source: Seismic interpretation modified from NGMA (National Geoscience Mapping Accord) (2001), Department for Manufacturing Innovation Trade Resources and Energy (DMITRE) (SA) (2001), Department for Manufacturing (2009) and Hall et al. (2015)
Element: PP-2256-2

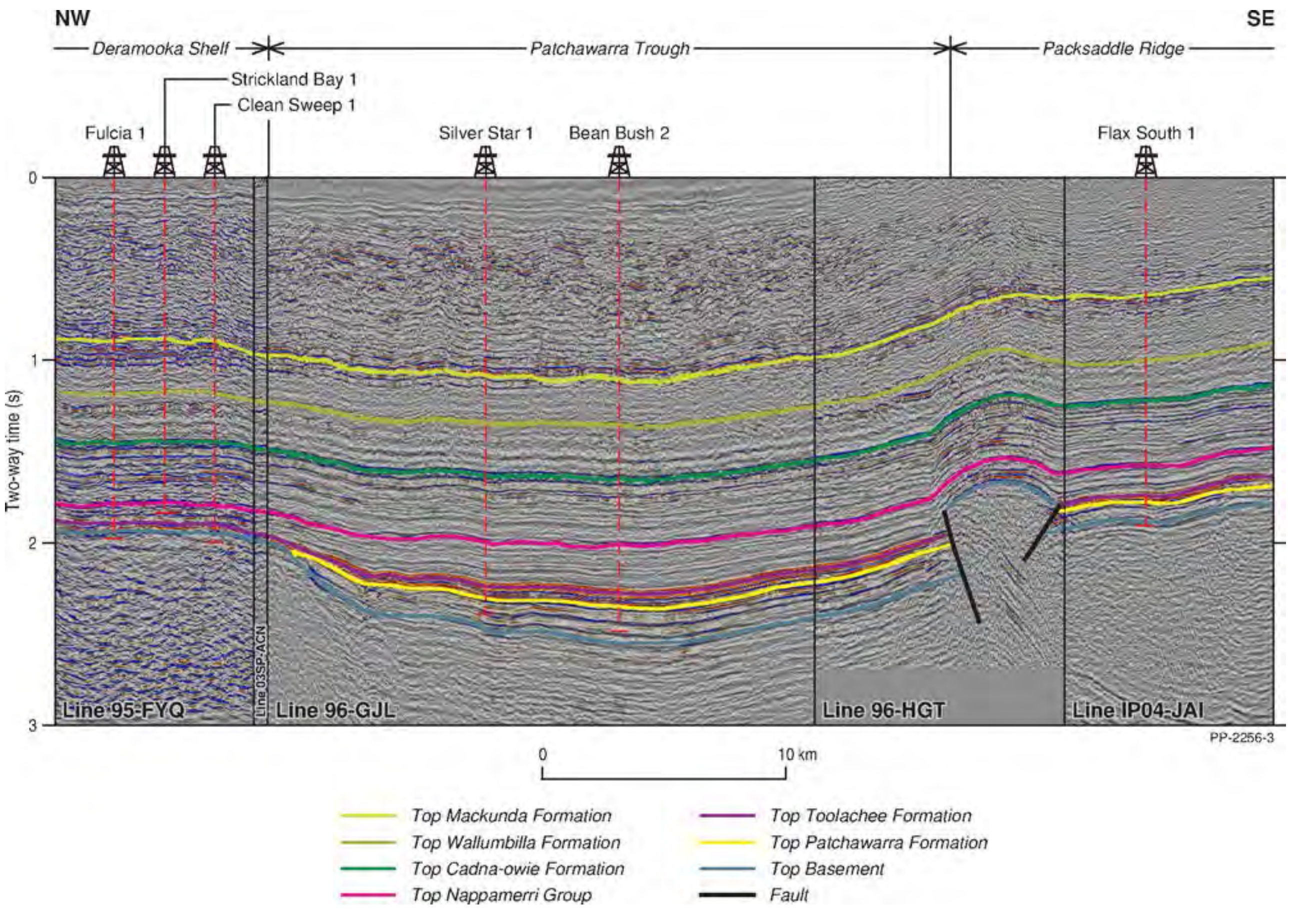

Figure 30 Regional seismic cross-section across the Patchawarra Trough. Cross-section location map is shown in Figure 25

Source: Seismic interpretation modified from NGMA (National Geoscience Mapping Accord) (2001), Department for Manufacturing Innovation Trade Resources and Energy (DMITRE) (SA) (2001), Department for Manufacturing (2009) and Hall et al. (2015)
Element: PP-2256-3

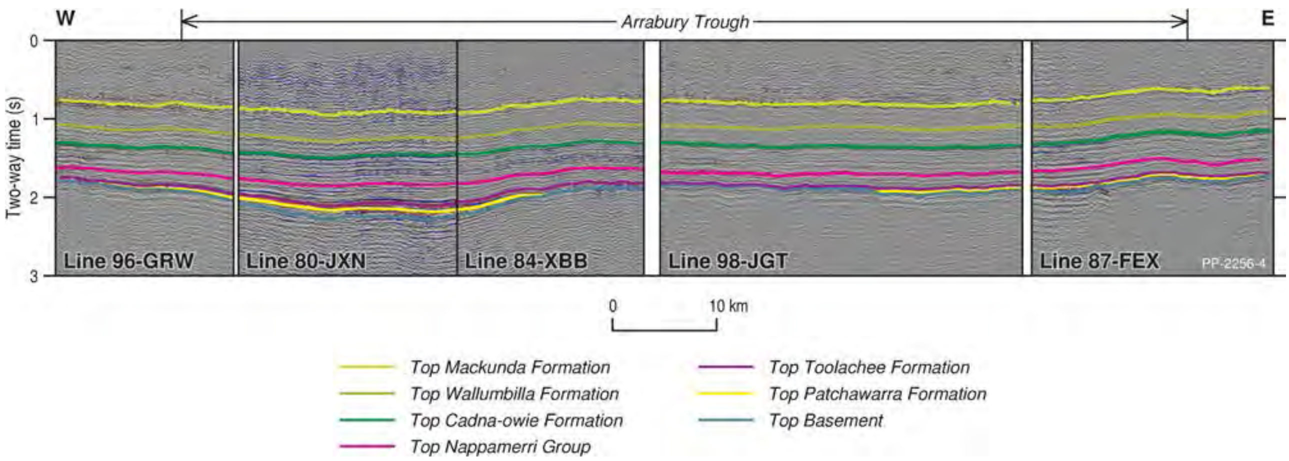

Figure 31 Regional seismic cross-section across the Arrabury Trough. Cross-section location map is shown in Figure 25

Source: Seismic interpretation modified from NGMA (National Geoscience Mapping Accord) (2001), Department for Manufacturing Innovation Trade Resources and Energy (DMITRE) (SA) (2001), Department for Manufacturing (2009) and Hall et al. (2015)
Element: PP-2256-4

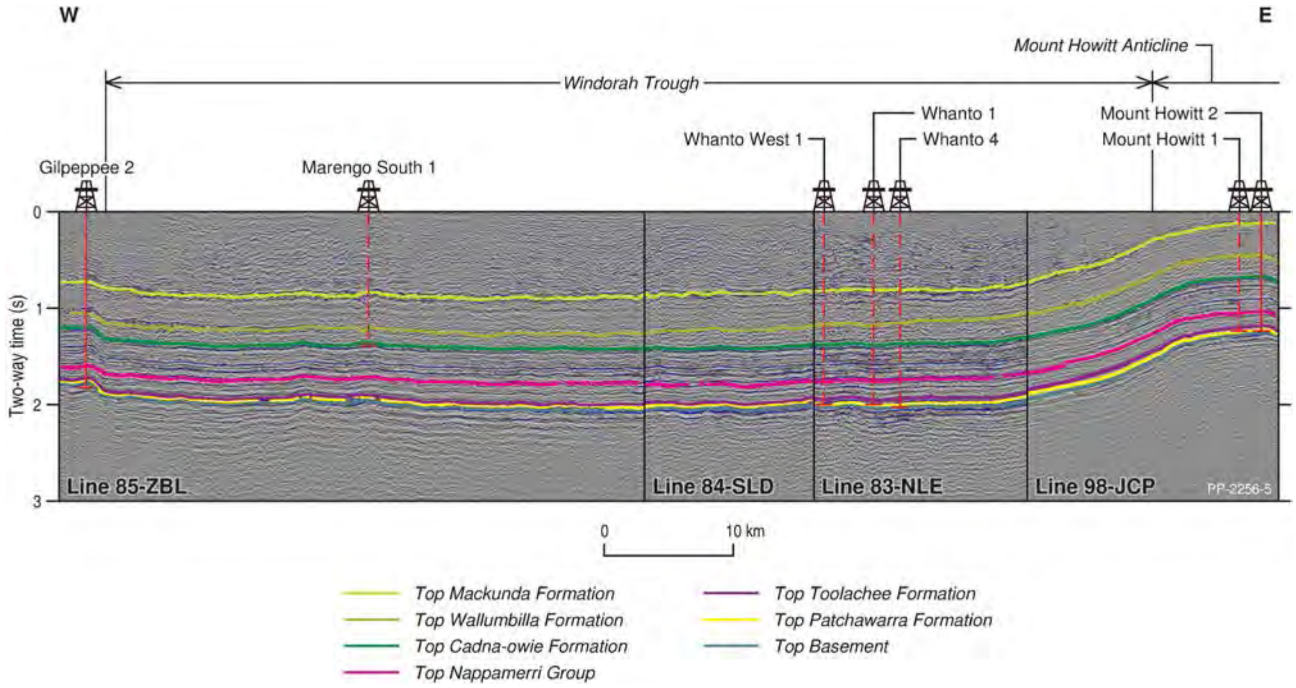

Figure 32 Regional seismic cross-section across the Windorah Trough. Cross-section location map is shown in Figure 25

Source: Seismic interpretation modified from NGMA (National Geoscience Mapping Accord) (2001), Department for Manufacturing Innovation Trade Resources and Energy (DMITRE) (SA) (2001), Department for Manufacturing (2009) and Hall et al. (2015)
Element: PP-2256-5

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Glossary

The register of terms and definitions used in the Geological and Bioregional Assessment Program is available online at https://w3id.org/gba/glossary (note that terms and definitions are respectively listed under the 'Name' and 'Description' columns in this register). This register is a list of terms, which are the preferred descriptors for concepts. Other properties are included for each term, including licence information, source of definition and date of approval. Semantic relationships (such as hierarchical relationships) are formalised for some terms, as well as linkages to other terms in related vocabularies. Many of the definitions for these terms have been sourced from external glossaries – several from international sources; spelling variations have been preserved to maintain authenticity of the source.

accumulation: in petroleum geosciences, an 'accumulation' is referred to as an individual body of moveable petroleum

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with unconventional gas resource development. For example, activities during the exploration life-cycle stage include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into ten major activities, which can occur at different life-cycle stages.

aeolian: relating to or arising from the action of wind

anticline: an arch-shaped fold in rock in which rock layers are upwardly convex. The oldest rock layers form the core of the fold, and outward from the core progressively younger rocks occur.

aquifer: rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit quantities of water to bores and springs

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards commonly form a confining layer over an artesian aquifer.

artesian aquifer: an aquifer that has enough natural pressure to allow water in a bore to rise to the ground surface

asset: an entity that has value to the community and, for the purposes of geological and bioregional assessments, is associated with a GBA region. An asset is a store of value and may be managed and/or used to maintain and/or produce further value. An asset may have many values associated with it that can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

barrel: a standard unit of measurement for all production and sales of oil. It has a volume of 42 US gallons [0.16 m^3].

basement: the oldest rocks in an area; commonly igneous or metamorphic rocks of Precambrian or Paleozoic age that underlie other sedimentary formations. Basement generally does not contain significant oil or gas, unless it is fractured and in a position to receive these materials from sedimentary strata.

bed: in geosciences, the term 'bed' refers to a layer of sediment or sedimentary rock, or stratum. A bed is the smallest stratigraphic unit, generally a centimetre or more in thickness. To be labeled a bed, the stratum must be distinguishable from adjacent beds.

biogenic gas: hydrocarbon gases (which are overwhelmingly (greater than or equal to 99%) methane) produced as a direct consequence of bacterial

bore: a narrow, artificially constructed hole or cavity used to intercept, collect or store water from an aquifer, or to passively observe or collect groundwater information. Also known as a borehole or piezometer.

burial history: the depth of a sedimentary layer versus time, usually corrected for compaction

charge: in petroleum geoscience, a 'charge' refers to the volume of expelled petroleum available for entrapment

clastic: sedimentary rock that consists of fragments or clasts of pre-existing rock, such as sandstone or shale

cleat: the vertical cleavage of coal seams. The main set of joints along which coal breaks when mined.

coal: a rock containing greater than 50 wt.% organic matter

coal seam gas: coal seam gas (CSG) is a form of natural gas (generally 95% to 97% pure methane, CH_4) extracted from coal seams, typically at depths of 300 to 1000 m. Also called coal seam methane (CSM) or coalbed methane (CBM).

compression: lateral force or stress (e.g. tectonic) that tends to decrease the volume of, or shorten, a substance

conceptual model: an abstraction or simplification of reality that describes the most important components and processes of natural and/or anthropogenic systems, and their response to interactions with extrinsic activities or stressors. They provide a transparent and general representation of how complex systems work, and identify gaps or differences in understanding. They are often used as the basis for further modelling, form an important backdrop for assessment and evaluation, and typically have a key role in communication. Conceptual models may take many forms, including descriptive, influence diagrams and pictorial representations.

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

conglomerate: a sedimentary rock dominated by rounded pebbles, cobbles, or boulders

consequence: synonym of impact

context: the circumstances that form the setting for an event, statement or idea conventional gas: conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock, with the gas trapped by buoyancy. The gas can often move to the surface through the gas wells without the need to pump.

Cooper Basin: the Cooper Basin geological province is an Upper Carboniferous – Middle Triassic geological sedimentary basin that is up to 2500 m thick and occurs at depths between 1000 and 4400 m. It is overlain completely by the Eromanga and Lake Eyre basins. Most of the Cooper Basin is in south-west Queensland and north-east SA, and includes a small area of NSW at Cameron Corner. It occupies a total area of approximately 130,000 km^2, including 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW.

craton: the old, geologically stable interior of a continent. Commonly composed of Precambrian rocks at the surface or covered only thinly by younger sedimentary rocks.

crude oil: the portion of petroleum that exists in the liquid phase in natural underground reservoirs and remains liquid at atmospheric conditions of pressure and temperature. Crude oil may include small amounts of non-hydrocarbons produced with the liquids.

crust: the outer part of the Earth, from the surface to the Mohorovicic discontinuity (Moho)

dataset: a collection of data in files, in databases or delivered by services that comprise a related set of information. Datasets may be spatial (e.g. a shape file or geodatabase or a Web Feature Service) or aspatial (e.g. an Access database, a list of people or a model configuration file).

deep coal gas: gas in coal beds at depths usually below 2000 m are often described as ‘deep coal gas’. Due to the loss of cleat connectivity and fracture permeability with depth, hydraulic fracturing is used to release the free gas held within the organic porosity and fracture system of the coal seam. As dewatering is not needed, this makes deep coal gas exploration and development similar to shale gas reservoirs.

deformation: folding, faulting, shearing, compression or extension of rocks due to the Earth’s forces

delta: a low, nearly flat area near the mouth of a river, commonly forming a fan-shaped plain that can extend beyond the coast into deep water. Deltas form in lakes and oceans when sediment supplied by a stream or river overwhelms that removed by tides, waves, and currents

depocentre: an area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin

deposition: sedimentation of any material, as in the mechanical settling of sediment from suspension in water, precipitation of mineral matter by evaporation from solution, and accumulation of organic material

depositional environment: the area in which, and physical conditions under which, sediments are deposited. This includes sediment source; depositional processes such as deposition by wind, water or ice; and location and climate, such as desert, swamp or river.

development: a phase in which newly discovered oil or gas fields are put into production by drilling and completing production wells discovered: the term applied to a petroleum accumulation/reservoir whose existence has been determined by its actual penetration by a well, which has also clearly demonstrated the existence of moveable petroleum by flow to the surface or at least some recovery of a sample of petroleum. Log and/or core data may suffice for proof of existence of moveable petroleum if an analogous reservoir is available for comparison.

dome: a type of anticline where rocks are folded into the shaped of an inverted bowl. Strata in a dome dip outward and downward in all directions from a central area.

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), a change to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat. An effect is a specific type of an impact (any change resulting from prior events).

Eromanga Basin: an extensive geologic sedimentary basin formed from the Early Jurassic to the Late Cretaceous that can be over 2500 m thick. It overlies several older geological provinces including the Cooper Basin, and is in part overlain by the younger Cenozoic province, the Lake Eyre Basin. The Eromanga Basin is found across much of Queensland, northern SA, southern NT, as well as north-western NSW. The Eromanga Basin encompasses a significant portion of the Great Artesian Basin.

erosion: the wearing away of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, wind, and underground water

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels. In the oil and gas industry, extraction refers to the removal of oil and gas from its reservoir rock.

facies: the characteristics of a rock unit that reflect the conditions of its depositional environment

fault: a fracture or zone of fractures in the Earth's crust along which rocks on one side were displaced relative to those on the other side

field: in petroleum geoscience, a 'field' refers to an accumulation, pool, or group of pools of hydrocarbons or other mineral resources in the subsurface. A hydrocarbon field consists of a reservoir with trapped hydrocarbons covered by an impermeable sealing rock, or trapped by hydrostatic pressure.

floodplain: a flat area of unconsolidated sediment near a stream channel that is submerged during or after high flows

fluvial: sediments or other geologic features formed by streams

fold: a curve or bend of a formerly planar structure, such as rock strata or bedding planes, that generally results from deformation

footwall: the underlying side of a fault, below the hanging wall

formation: rock layers that have common physical characteristics (lithology) deposited during a specific period of geological time fracking: see hydraulic fracturing

fracture: a crack or surface of breakage within rock not related to foliation or cleavage in metamorphic rock along which there has been no movement. A fracture along which there has been displacement is a fault. When walls of a fracture have moved only normal to each other, the fracture is called a joint. Fractures can enhance permeability of rocks greatly by connecting pores together, and for that reason, fractures are induced mechanically in some reservoirs in order to boost hydrocarbon flow. Fractures may also be referred to as natural fractures to distinguish them from fractures induced as part of a reservoir stimulation or drilling operation. In some shale reservoirs, natural fractures improve production by enhancing effective permeability. In other cases, natural fractures can complicate reservoir stimulation.

free gas: the gaseous phase present in a reservoir or other contained area. Gas may be found either dissolved in reservoir fluids or as free gas that tends to form a gas cap beneath the top seal on the reservoir trap. Both free gas and dissolved gas play important roles in the reservoir-drive mechanism.

gas cap: part of a petroleum reservoir that contains free gas

geological formation: stratigraphic unit with distinct rock types, which is able to mapped at surface or in the subsurface, and which formed at a specific period of geological time

granite: an intrusive igneous rock with high silica (SiO_2) content typical of continental regions

groundwater: water occurring naturally below ground level (whether stored in or flowing through aquifers or within low-permeability aquitards), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.

hanging wall: the overlying side of a fault, above the footwall

hydraulic fracturing: also known as ‘fracking’, ‘fraccing’ or ‘fracture simulation’. This is a process by which geological formations bearing hydrocarbons (oil and gas) are ‘stimulated’ to increase the flow of hydrocarbons and other fluids towards the well. In most cases, hydraulic fracturing is undertaken where the permeability of the formation is initially insufficient to support sustained flow of gas. The process involves the injection of fluids, proppant and additives under high pressure into a geological formation to create a conductive fracture. The fracture extends from the well into the production interval, creating a pathway through which oil or gas is transported to the well.

hydrocarbons: various organic compounds composed of hydrogen and carbon atoms that can exist as solids, liquids or gases. Sometimes this term is used loosely to refer to petroleum.

hydrogeology: the study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of interactions between water and rock

hydrostatic pressure: equal pressure in all direction, equivalent to the pressure which is exerted on a portion of a column of water as a result of the weight of the fluid above it impact: the difference between what could happen as a result of activities and processes associated with extractive industries, such as shale, tight and deep coal gas development, and what would happen without them. Impacts may be changes that occur to the natural environment, community or economy. Impacts can be a direct or indirect result of activities, or a cumulative result of multiple activities or processes.

impact mode: the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events.

Impact Modes and Effects Analysis: a systematic hazard identification and prioritisation technique based on Failure Modes and Effects Analysis

injection: the forcing or pumping of substances into a porous and permeable subsurface rock formation. Examples of injected substances can include either gases or liquids

isopach: a contour that connects points of equal thickness. Commonly, the isopachs, or contours that make up an isopach map, display the stratigraphic thickness of a rock unit as opposed to the true vertical thickness. Isopachs are true stratigraphic thicknesses (i.e. perpendicular to bedding surfaces).

kerogen: insoluble (in organic solvents) particulate organic matter preserved in sedimentary rocks that consists of various macerals originating from components of plants, animals, and bacteria. Kerogen can be isolated from ground rock by extracting bitumen with solvents and removing most of the rock matrix with hydrochloric and hydrofluoric acids.

Lake Eyre Basin: a geologic province containing Cenozoic terrestrial sedimentary rocks within the Lake Eyre surface water catchment. It covers parts of northern and eastern SA, south-eastern NT, western Queensland and north-western NSW. In the Cooper GBA region, the basin sedimentary package is less than 300 m thick.

life-cycle stage: one of five stages of operations in unconventional gas resource development considered as part of the Impact Modes and Effects Analysis (IMEA). These are exploration, appraisal, development, production, and rehabilitation. Each life-cycle stage is further divided into major activities, which are further divided into activities.

likelihood: probability that something might happen

lithology: the description of rocks, especially in hand specimen and in outcrop, on the basis of characteristics such as color, mineralogic composition and grain size

mantle: the region of the Earth composed mainly of solid silicate rock that extends from the base of the crust (Moho) to the core–mantle boundary at a depth of approximately 2900 km

material: pertinent or relevant

metamorphic rock : a rock formed from pre-existing rock due to high temperature and pressure in the Earth's crust, but without complete melting methane: a colourless, odourless gas, the simplest parafin hydrocarbon, formula CH4. It is the principal constituent of natural gas and is also found associated with crude oil. Methane is a greenhouse gas in the atmosphere because it absorbs long-wavelength radiation from the Earth's surface.

migration: the process whereby fluids and gases move through rocks. In petroleum geoscience, 'migration' refers to when petroleum moves from source rocks toward reservoirs or seep sites. Primary migration consists of movement of petroleum to exit the source rock. Secondary migration occurs when oil and gas move along a carrier bed from the source to the reservoir or seep. Tertiary migration is where oil and gas move from one trap to another or to a seep.

Moho: the Mohorivicic discontinuity (seismic reflector) at the base of the crust

natural gas : the portion of petroleum that exists either in the gaseous phase or is in solution in crude oil in natural underground reservoirs, and which is gaseous at atmospheric conditions of pressure and temperature. Natural gas may include amounts of non-hydrocarbons.

oil: a mixture of liquid hydrocarbons and other compounds of different molecular weights. Gas is often found in association with oil. Also see Petroleum.

oil-prone: organic matter that generates significant quantities of oil at optimal maturity.

operator: the company or individual responsible for managing an exploration, development or production operation

organic matter: biogenic, carbonaceous materials. Organic matter preserved in rocks includes kerogen, bitumen, oil and gas. Different types of organic matter can have different oil-generative potential.

orogeny: the process of mountain building; the process whereby structures within fold-belt mountainous areas formed

outcrop: a body of rock exposed at the surface of the Earth

palaeoenvironment: an ancient depositional environment

permeability: the measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the ground.

petroleum: a naturally occurring mixture consisting predominantly of hydrocarbons in the gaseous, liquid or solid phase

petroleum system: the genetic relationship between a pod of source rock that is actively producing hydrocarbon, and the resulting oil and gas accumulations. It includes all the essential elements and processes needed for oil and gas accumulations to exist. These include the source, reservoir, seal, and overburden rocks, the trap formation, and the hydrocarbon generation, migration and accumulation processes. All essential elements and processes must occur in the appropriate time and space in order for petroleum to accumulate.

play: a conceptual model for a style of hydrocarbon accumulation used during exploration to develop prospects in a basin, region or trend and used by development personnel to continue exploiting a given trend. A play (or group of interrelated plays) generally occurs in a single petroleum system.

porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass

producing: a well or rock formation from which oil, gas or water is produced

production: in petroleum resource assessments, 'production' refers to the cumulative quantity of oil and natural gas that has been recovered already (by a specified date). This is primarily output from operations that has already been produced.

production well: a well used to remove oil or gas from a reservoir

reservoir: a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids and gases. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

reservoir rock: any porous and permeable rock that contains liquids or gases (e.g. petroleum, water, CO_2), such as porous sandstone, vuggy carbonate and fractured shale

reverse fault: a fault in which the hanging wall appears to have moved upward relative to the footwall. Common in compressional regimes.

ridge: a narrow, linear geological feature that forms a continuous elevated crest for some distance (e.g. a chain of hills or mountains or a watershed)

risk: the effect of uncertainty on objectives (ASNZ ISO 3100). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest.

sandstone: a sedimentary rock composed of sand-sized particles (measuring 0.05–2.0 mm in diameter), typically quartz

seal: a relatively impermeable rock, commonly shale, anhydrite or salt, that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

sediment: various materials deposited by water, wind or glacial ice, or by precipitation from water by chemical or biological action (e.g. clay, sand, carbonate)

sedimentary rock: a rock formed by lithification of sediment transported or precipitated at the Earth’s surface and accumulated in layers. These rocks can contain fragments of older rock transported and deposited by water, air or ice, chemical rocks formed by precipitation from solution, and remains of plants and animals.

sedimentation: the process of deposition and accumulation of sediment (unconsolidated materials) in layers

seismic survey: a method for imaging the subsurface using controlled seismic energy sources and receivers at the surface. Measures the reflection and refraction of seismic energy as it travels through rock.

shale: a fine-grained sedimentary rock formed by lithification of mud that is fissile or fractures easily along bedding planes and is dominated by clay-sized particles

shale gas: generally extracted from a clay-rich sedimentary rock, which has naturally low permeability. The gas it contains is either adsorbed or in a free state in the pores of the rock.

shear: a frictional force that tends to cause contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact

siltstone: a sedimentary rock composed of silt-sized particles (0.004 to 0.063 mm in diameter)

source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Under the right conditions, source rocks may also be reservoir rocks, as in the case of shale gas reservoirs.

spring: a naturally occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool of water. Typically, it represents the point at which the watertable intersects ground level.

stratigraphy: the study of the history, composition, relative ages and distribution of stratified rock strata, and its interpretation to reveal Earth's history. However, it has gained broader usage to refer to the sequential order and description of rocks in a region.

stress: the force applied to a body that can result in deformation, or strain, usually described in terms of magnitude per unit of area, or intensity

stressor: chemical or biological agent, environmental condition or external stimulus that might contribute to an impact mode

strike-slip fault: a type of fault whose surface is typically vertical or nearly so. The motion along a strike-slip fault is parallel to the strike of the fault surface, and the fault blocks move sideways past each other. A strike-slip fault in which the block across the fault moves to the right is described as a dextral strike-slip fault. If it moves left, the relative motion is described as sinistral.

structure: a geological feature produced by deformation of the Earth's crust, such as a fold or a fault; a feature within a rock, such as a fracture or bedding surface; or, more generally, the spatial arrangement of rocks subsidence: the sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved.

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs

syncline: a concave-upward fold in rock that contains stratigraphically younger strata toward the center

tectonics: the structural behaviour of the Earth's crust

terrane: an area of crust with a distinct assemblage of rocks (as opposed to terrain, which implies topography, such as rolling hills or rugged mountains)

thrust fault: a low-angle reverse fault, with inclination of fault plane generally less than 45 °

tight gas: tight gas is trapped in reservoirs characterised by very low porosity and permeability. The rock pores that contain the gas are minuscule, and the interconnections between them are so limited that the gas can only migrate through it with great difficulty.

total organic carbon: the quantity of organic matter (kerogen and bitumen) is expressed in terms of the total organic carbon (TOC) content in mass per cent. The TOC value is the most basic measurement for determining the ability of sedimentary rocks to generate and expel hydrocarbons.

trap: a geologic feature that permits an accumulation of liquid or gas (e.g. natural gas, water, oil, injected CO_2) and prevents its escape. Traps may be structural (e.g. domes, anticlines), stratigraphic (pinchouts, permeability changes) or combinations of both.

unconfined aquifer: an aquifer whose upper water surface (watertable) is at atmospheric pressure and does not have a confining layer of low-permeability rock or sediment above it

unconformity: a surface of erosion between rock bodies that represents a significant hiatus or gap in the stratigraphic succession. Some kinds of unconformities are (a) angular unconformity – an unconformity in which the bedding planes above and below the unconformity are at an angle to each other; and (b) disconformity – an unconformity in which the bedding planes above and below the stratigraphic break are essentially parallel.

unconventional gas: unconventional gas is generally produced from complex geological systems that prevent or significantly limit the migration of gas and require innovative technological solutions for extraction. There are numerous types of unconventional gas such as coal seam gas, deep coal gas, shale gas and tight gas.

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to unconventional gas resource development

watertable: the upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.

weathering: the breakdown of rocks and other materials at the Earth's surface caused by mechanical action and reactions with air, water and organisms. Weathering of seep oils or improperly sealed oil samples by exposure to air results in evaporative loss of light hydrocarbons.

well: typically a narrow diameter hole drilled into the earth for the purposes of exploring, evaluating, injecting or recovering various natural resources, such as hydrocarbons (oil and gas), water or carbon dioxide. Wells are sometimes known as a 'wellbore'.

well integrity: maintaining full control of fluids (or gases) within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid (gas or liquid) movement between formations with different pressure regimes, or loss of containment to the environment

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