Far North Prescribed Wells Area Groundwater Model
Volume 2 – Hydrogeological framework

Department for Environment and Water
September, 2023

DEW Technical report 2023-70

Government of South Australia

Department for Environment and Water

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81-95 Waymouth St, ADELAIDE SA 5000
Telephone +61 (8) 8463 6946
Facsimile +61 (8) 8463 6999
ABN 36702093234

www.environment.sa.gov.au

Contributors to this volume: Mark Keppel (Department for Environment and Water), Martin Novak (AusGeos Pty Ltd), Daniel Wohling (IGS)

Reviewers of this Volume: Lloyd Sampson and Juliette Woods (Department for Environment and Water) and Paul Howe (CDM Smith Pty Ltd), Keith Phillipson (Australasian Groundwater and Environmental Consultants Pty Ltd) and Hugh Middlemis (HydroGeoLogic Pty Ltd)

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Foreword

The Department for Environment and Water (DEW) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provide the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Landscape Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

John Schutz
CHIEF EXECUTIVE
DEPARTMENT FOR ENVIRONMENT AND WATER

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Internal review of the report was provided by:

- project technical lead Mark Keppel, Principal Hydrogeologist, Department for Environment and Water (DEW)
- Principal Hydrogeologist (former) Lloyd Sampson, DEW
- project groundwater modelling technical lead Juliette Woods, Principal Groundwater Modeller, DEW
- project technical geology lead Tony Hill, Deputy Director, Geoscience and Exploration Branch and Principal Geologist, Department for Energy and Mining (DEM)

The following people provided external review of the report:

- project independent expert technical advisor, Hugh Middlemis, Principal Groundwater Engineer, HydroGeoLogic.
- Paul Howe, Principal Hydrogeologist, CDM Smith Pty Ltd
- Keith Phillipson, Principal Modeller, Australasian Groundwater and Environmental Consultants Pty Ltd.

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Executive summary

The documentation for the Far North Prescribed Wells Area Groundwater Model is presented over several volumes. The purpose of these reports is to provide an overview of the study area, provide scientific evidence for the conceptual hydrogeological model used as the basis for the decisions and assumptions made during model construction and history matching. This volume (Volume 2) provides the following:

- a summary of the hydrogeological basin configuration, as well as stratigraphic and hydrostratigraphic underpinnings of the numerical groundwater model construction
- an overview of the potential impacts that inter-aquifer connectivity, tectonics and fault-related deformation of strata may have on hydrodynamics across the study area.

The main study area focus is the Far North Prescribed Wells Area in South Australia (SA), but also extends to encompass all the Eromanga Basin in SA and the Northern Territory (NT), with a 'buffer zone' extension into south-western Queensland (QLD) and north-western New South Wales (NSW) (Figure 1). This area also covers the Pedirka Basin in SA and the NT, the Arckaringa Basin in SA, and the Cooper Basin in SA, along with part of the Cooper Basin in south-western QLD, as these basins all have potential hydraulic interactions with the Eromanga Basin.

The most important groundwater resources found within the study area are those contained with Eromanga Basin strata. The Eromanga Basin can be described as having a bowl shape that is partly defined and modified by tectonic warping and faulting. Within the basin in SA, a zone of structural weakness and faulting associated with the underlying Adelaide Geosyncline and related Torren Hinge Zone, divides the basin. This is also connected with spring development. East of this zone, the aquifer system is largely confined and mostly artesian, while west of this zone, the aquifer system is largely unconfined. A series of mountain ranges composed of basement rocks frame the western and southern margins of the Eromanga Basin.

In the SA part of the Eromanga Basin, the most important strata sequence forming an aquifer consists of the Cadna-owie Formation, the Algebuckina Sandstone, and their lateral equivalents (primarily the Namur Sandstone and Adori Sandstone). The collective hydrostratigraphic terminology commonly used in SA for aquifers within these lithologically connected and extensive units is the 'J-K aquifer.' The name J-K aquifer is based on the general time period over which aquifer strata were deposited and the stratigraphic coding for these time periods being the Jurassic (J) to Cretaceous (K) period.

The other important aquifer is associated with the sub-basinal Hutton Sandstone and the Poolowanna Formation, found in the deeper parts of the Eromanga Basin near where it is underlain by the Cooper Basin. While these two geological units are lateral equivalents of the Algebuckina Sandstone and hence strictly part of the J-K aquifer, they are considered separately for this study as they are not pervasive across the study area and are separated from the other formations by a thick, more extensive, confining unit, the Birkhead Formation.

Several important confining units occur in various areas across the study area. The most important is the finer-grained sediments of the Rolling Downs Group (for example, Bulldog Shale) which overlies the Cadna-owie Formation. In addition, the Main Eromanga Aquifer Sequence itself includes intervening fine-grained confining units, such as the Birkhead Formation, Westbourne Formation and Murta Member in the deeper parts of the basin.

The conceptualisation is primarily focused upon describing groundwater flow within the sequence of strata defined by the top of the Cadna-owie Formation to the top of the pre-Jurassic units (Figure 2). Collectively, this package of aquifers and confining units is called the 'Main Eromanga Aquifer Sequence.' It is essentially the combination of the extensive J-K aquifer and the sub-basinal Hutton–Poolowanna Aquifer, including intervening confining units (Figure 2), noting that sub-regional lithological variation as well as structural deformation may contribute to modification of hydraulic properties and basin configuration, potentially leading to the development of semi-discrete sub-basinal regions.

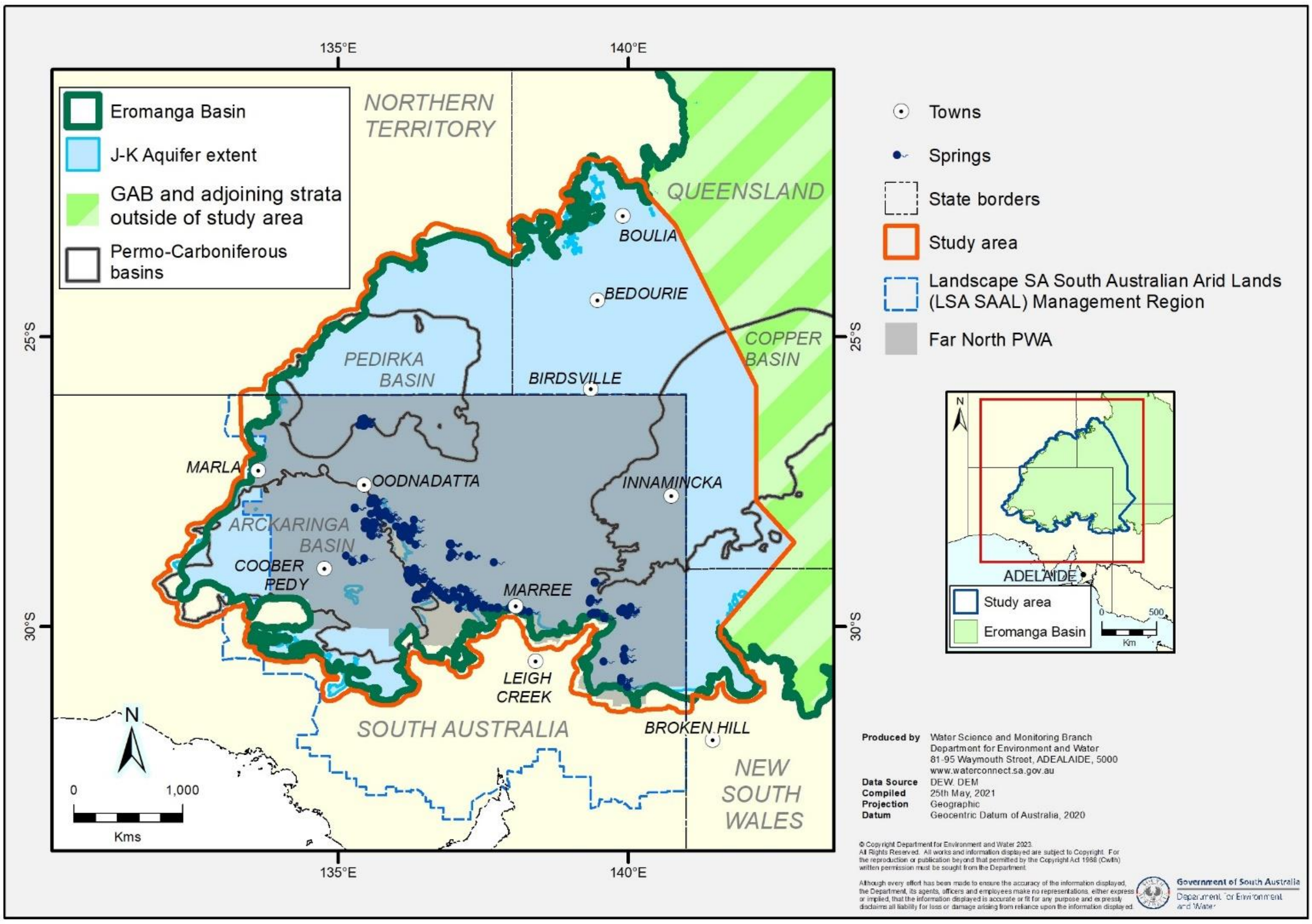

Figure 1: Location map of the study area

Based on this conceptualisation, a major component of data collation work was the development of structure surfaces used to describe the extent, configuration and thickness of aquifers and confining units within the study area. Data sources included water well logs, mineral exploration and petroleum drilling records, seismic data, and the updating and integration of existing structure surfaces. Structure surfaces, and consequent isopachs for the following formations within the study area were generated.

- top of the Cadna-owie Formation ('C' Horizon)
- top of the Murta Formation ('Dm' Horizon)
- top of the McKinlay Member (McKinlay Horizon)
- top of the Namur Sandstone ('Dn' Horizon)
- top of the Hutton Sandstone ('H' Horizon)
- base of the Poolowanna Formation ('J' Horizon).

For the purposes of this model, the base of the Poolowanna Formation was classified as 'basement'.

These structure surfaces were used to discretise the Main Eromanga Aquifer Sequence into 5 hydrostratigraphic units based on regional scale hydrostratigraphy. These included the Cadna-owie Formation aquifer, the Murta Formation confining unit, the Namur–Algebuckina Sandstone aquifer, the Birkhead Formation confining unit and the Hutton–Poolowanna aquifer. A sixth basement unit of nominal thickness representative of strata below the Main Eromanga Aquifer Sequence was also incorporated. Prior to the completion of these structure surfaces, rigorous data quality assessments on multiple draft surfaces were undertaken.

Neotectonics and faulting shaped the basin configuration and structure as well as altering the hydraulic properties of the strata. One of the most significant expressions of this is the development of springs, associated with either uplift and erosion stripping away confining unit rocks or by faulting and fracturing causing spring conduit formation. Faulting and fracturing may also impart a heterogeneous hydraulic condition on an aquifer, causing barriers to groundwater flow in some directions, while enhancing flow in others, with such features possible within the same fault zone.

Overlying aquifers in the Neocretaceous, Tertiary and Quaternary strata may have connectivity with the Main Eromanga Aquifer Sequence where the main confining unit of the Rolling Downs Group is absent. This occurs primarily near the western and southwestern margins of the basin. Connectivity with aquifers in Neocretaceous strata is difficult to ascertain with any certainty although there is potential for limited connectivity related to faulting deformation.

There are several groundwater systems underlying the Main Eromanga Aquifer Sequence that may have hydraulic connections at a regional scale. Aquifers within the underlying Permo-Carboniferous Cooper, Pedirka and Arckaringa basins may have zones of hydraulic communication with overlying Mesozoic Eromanga Basin aquifers. This connection may be lithological or related to structural deformation; however, the presence of confining units within these Permo-Carboniferous basins limits the extent and magnitude of such inter-aquifer connections.

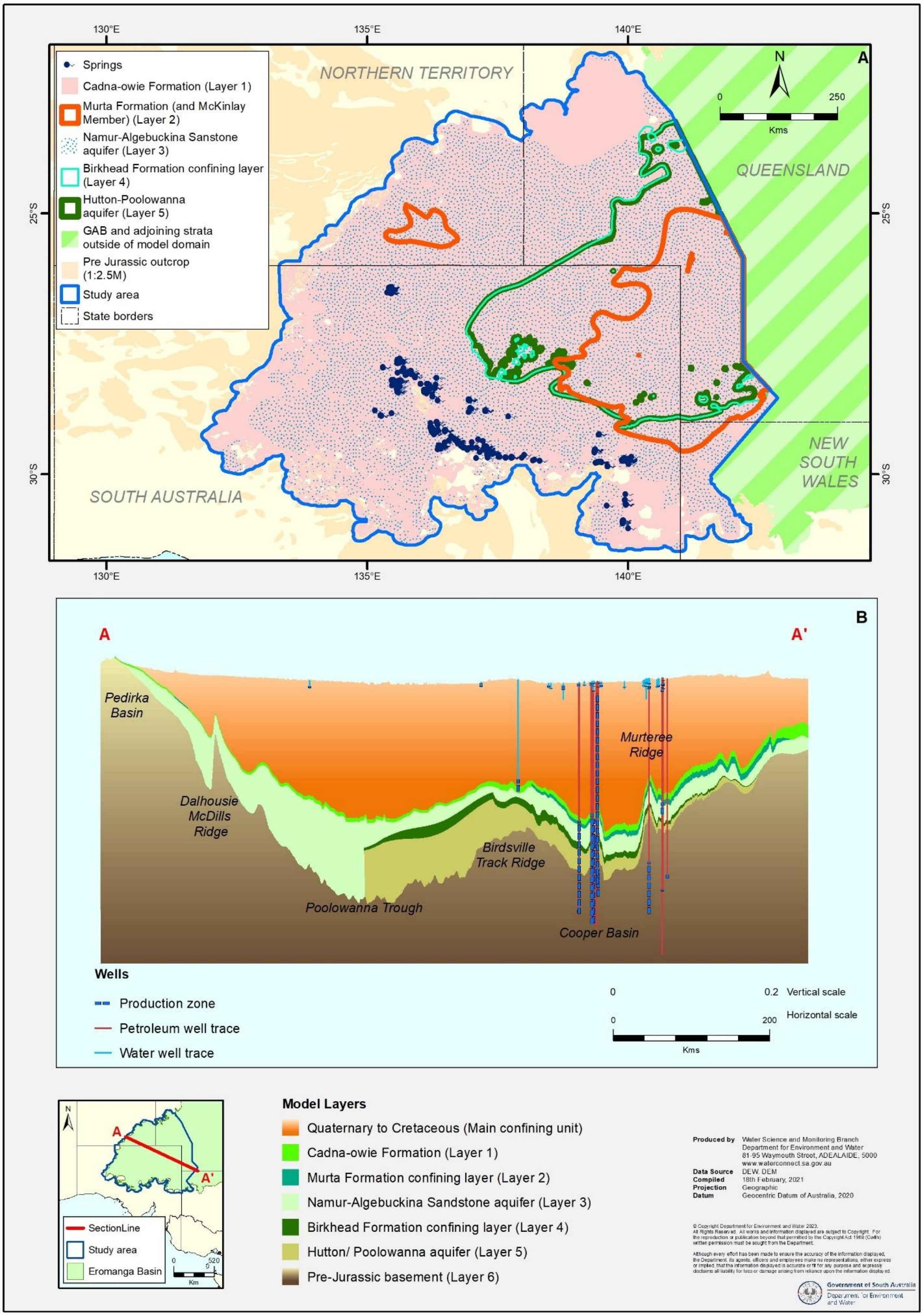

Figure 2: **A) Plan view of structure surface outlines used in numerical model. B) Cross-section through study area showing model layers and key structures**

From this data compilation, analysis and literature review, several limitations were made apparent. Of particular importance are that:

- The vertical discretisation is primarily based on stratigraphy. While this provides a simple and largely adequate means of grouping strata into logical hydrostratigraphic units, any lithological variation or variable impact of digenetic alteration within these hydrostratigraphic units may not be sufficiently captured within this conceptualisation.
- There is over-simplifying or misrepresentation in the model construction concerning the relationship between the Main Eromanga Aquifer Sequence and any overlying or underlying aquifers
- There is limited knowledge of the hydrogeological impact of faulting in the model. A determination as to whether there is sufficient evidence for a fault zone is required before an assessment can be made about whether a fault zone is having a material impact on groundwater flow at the scale of model construction.

1 Introduction

Groundwater in the Far North Prescribed Wells Area (FNPWA) is vital for the success of the mining, energy, pastoral and tourism industries, and the provision of community water supplies in the Landscape SA South Australian Arid Lands (LSA SAAL) Management Region (Figure 1.1). The continued success and expansion of these industries is dependent on balancing the needs of existing users and the environment. Of particular environmental importance are the spring wetland communities in the discharge areas of the Great Artesian Basin (GAB) hydrogeological super-basin, which are listed under the Commonwealth *Environmental Protection and Biodiversity Conservation (EPBC) Act 1999*. Protection of these environments is regulated and managed at a State level through the Far North Water Allocation Plan (FNWAP), through the description and implementation of spring buffer zones, water management zones and drawdown triggers at state borders. Further, the South Australian Government also has regulatory responsibilities over water management under the *Roxby Downs (Indenture Ratification) Act 1982*.

With demand for groundwater expected to grow in the mining and energy industries, a new numerical groundwater flow model is required to evaluate current knowledge and determine key knowledge gaps. This model will also be a tool to inform management of groundwater resources, both ongoing and for future major developments.

1.1 The Far North Prescribed Wells Area

Groundwater in the Far North Prescribed Wells Area (FNPWAP) is managed under the Far North Water Allocation Plan (FNWAP); a key principle within being to manage groundwater resources by pressure (head) and to allocate by volume. The FNPWA was prescribed on 27 March 2003, and the first FNWAP was adopted on 16 February 2009. The 2021 FNWAP was adopted on the 27 February 2021.

Currently, the total groundwater sourced is 176 ML/d (2018–19 data) (Figure 1.2), with the majority (approximately 76% or 134 ML/d) sourced from the GAB hydrogeological super-basin aquifers (Figure 1.3) This volume of water is made up of mining, industrial and human requirement supplies, co-produced water (water extracted with petroleum hydrocarbons), water for stock and domestic use, bore-fed wetlands and other amounts. Demand for the groundwater resources is expected to grow, particularly in response to growth in the mineral and energy industries.

1.2 Previous modelling

Although several groundwater models cover part of the western margin of the GAB hydrogeological super-basin, they are subject to one or more of the following limitations in terms of suitability for cumulative impact assessment to inform management of aquifers within SA:

- a small or constrained geographical extent
- an over-simplified or limited aquifer system representation
- proprietary ownership by private companies that prohibits use for regulatory water-resource assessments
- being based on outdated hydrogeological conceptualisations that do not reflect the current understanding of basin structure and groundwater processes, including recharge and discharge
- not considering other interconnected basins that form important water resources in the FNPWA
- not being designed to consider the cumulative impacts of multiple groundwater users.

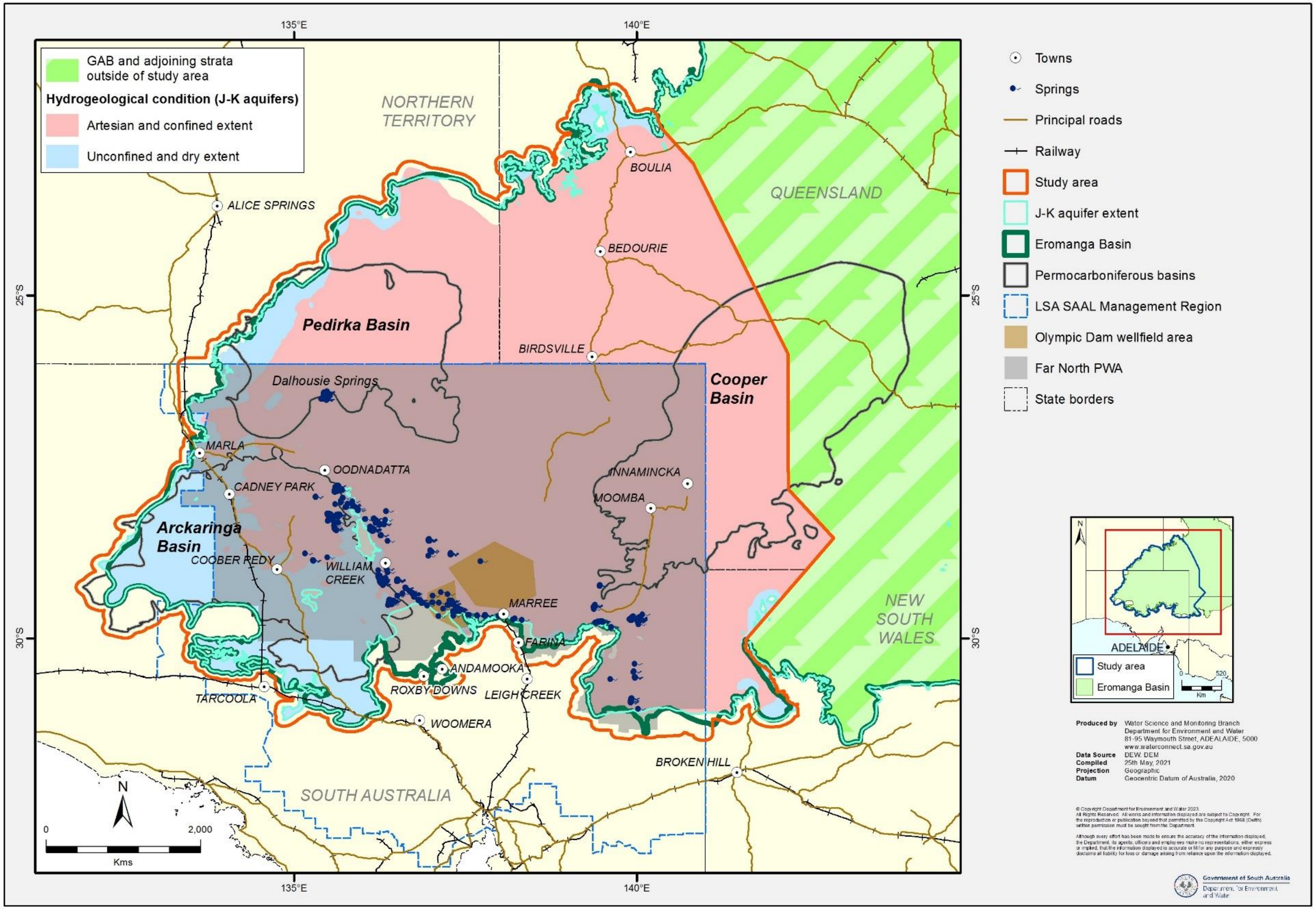

Figure 1.1: Location map of the Far North Prescribed Wells Area and study area.

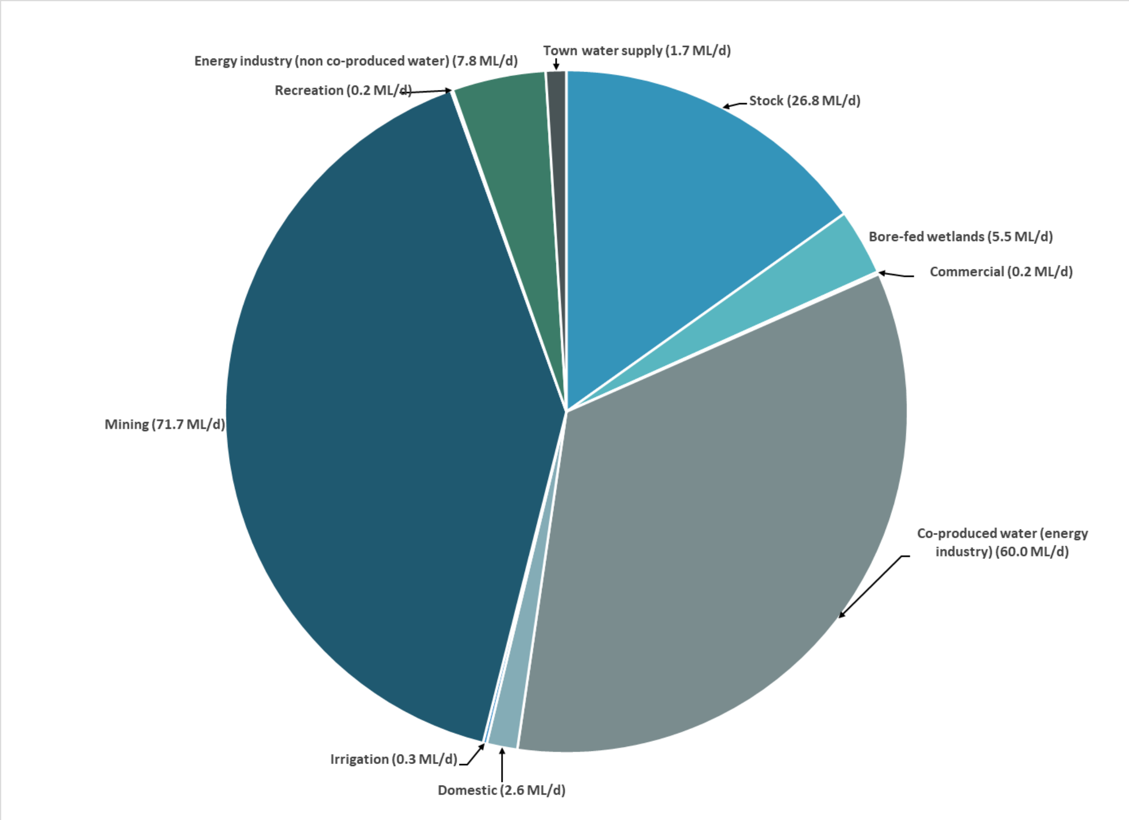

Figure 1.2: Total licensed volume (176 ML/d) presented by licence purpose description, FNPWA.

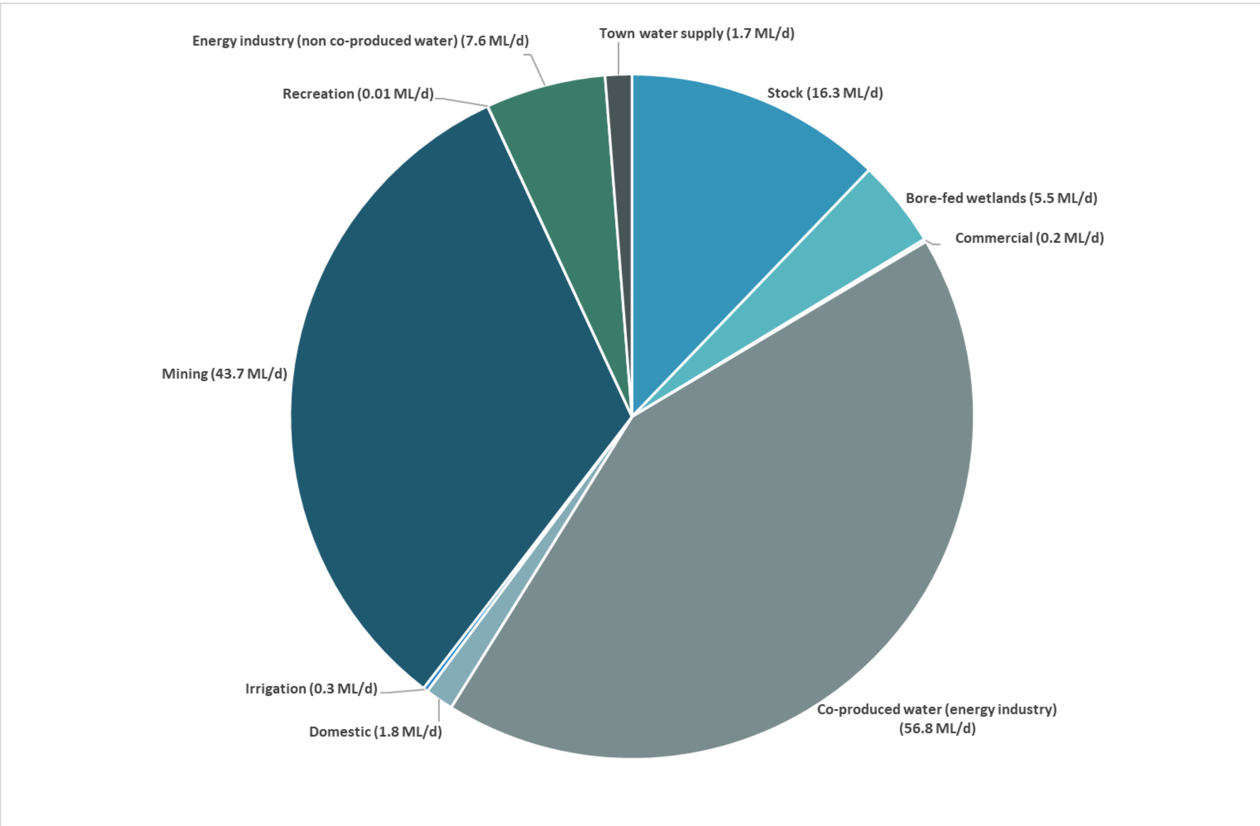

Figure 1.3: Licensed volume sourced from the GAB hydrogeological super-basin (134 ML/d) presented by licence purpose description, FNPWA.

DEW has developed a numerical groundwater flow model to address the gaps identified in the existing models and to provide a tool to inform management of groundwater resources in the FNPWA. This model is consistent with the latest science and knowledge and can be updated in the future, providing a quantitative and predictive tool for development assessments and to inform management decisions. Further discussion of previous modelling is provided in Volume 8 of this report.

1.3 The study area

To cover an area of sufficient extent to achieve the model objectives, the study area (Figure 1.1) encompasses portions of the Eromanga Basin in QLD and NSW, part of the Cooper Basin in QLD, and the entirety of the following administrative areas and features of hydrogeological significance:

- Eromanga Basin in SA and the NT
- Cooper Basin in SA
- Pedirka Basin
- Arckaringa Basin
- the Far North Prescribed Wells Area (PWA).

The initial model design is to simulate groundwater flow within the main Eromanga aquifer sequence, with a focus on the Far North PWA in SA.

The study area (Figure 1.1) covers a total area of about 721,370 km^2. A 10 km-wide external buffer encompassing the features described in the above dot points extends beyond the southern, western and northern perimeters of the study area. The eastern boundary extends between 245 km and 420 km from the NT border into QLD; between 125 km and 190 km from the SA border into QLD; and between 60 km and 140 km into NSW from SA border. The eastern boundary is designed to allow for lateral inflow of groundwater to the study area in some areas and no flow in others, consistent with the groundwater flow system contours interpreted during this project. The spatial extent of the eastern boundary was selected to provide a sufficient distance away from the areas of interest in SA, so that the hydraulic conditions along the boundary do not materially influence simulation results.

1.4 Reporting structure

Given the size and multi-faceted nature of the investigation that supported the model development, reporting occurs over several volumes:

1. Simplified technical summary
2. Hydrogeological framework
3. Hydraulic parametrisation
4. Groundwater flow system dynamics
5. Time series data
6. Recharge and discharge processes
7. Water use and balance estimations
8. Model construction and history matching

1.5 Volume objective

This volume (Volume 2) provides a summary of the basin configuration, stratigraphic and hydrostratigraphic underpinnings of model layer interpretation and construction, as well as an overview of the potential impact inter-aquifer connectivity, tectonics and fault-related deformation of strata may have on hydrodynamics. Additionally, a brief overview of pertinent features of the past and present climate, landscape and surface drainage is provided.

2 Landscape data, topography, and surface drainage

Topographical data within the model conceptualisation is primarily used to determine the extent of artesian and non-artesian conditions, as well as providing a means to determine the Reduced Standing Water Level (RSWL) against a standard Australian height datum (m AHD). Further, topography and hydrology descriptions potentially indicate key drivers of groundwater flow. For example, the gradient between highlands and potential discharge points like springs at lower elevations provides one basic line of evidence for a gravity driven groundwater flow system. Finally, the condition or permanence of such features may provide information concerning the magnitude or frequency of potential groundwater affecting phenomena, such as recharge events linked to streamflow.

2.1 Landscape data

Topographical data can be derived from several sources which have varying levels of resolution and accuracy.

2.1.1 Survey data

Modern survey data are used where possible for water level determination, with digital elevation model (DEM) data used where survey data is not available. Survey data may be sourced from either a differential global positioning system (GPS) methodology or a triangulation method. Further discussion is provided in Appendix A.

Wherever possible, surveyed reference and ground elevation data were used in preference to elevation data derived from the 1-second Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Wilson et al. 2011) or other elevation data sources (Appendix A). Several wells located near the Wellfield A and B areas of Olympic Dam mining operations (Figure 1.1) had shuttle-derived digital elevation model elevations in the database. In this case, Olympic Dam mining operations provided surveyed reference elevations for all 108 water wells in the Wellfield A and Wellfield B region to reduce topographical data uncertainties.

2.1.2 Digital Elevation Model

A DEM is used in conjunction with potentiometric surface data to map artesian conditions, as well as providing a means of calculating the elevation of structure surfaces of the various hydrostratigraphic units. The SRTM 1-second 'hydrologically-enforced' National Digital Elevation Model (1-second DEM-H) (Wilson et al. 2011) was used in conjunction with mapped surface drainage and land use data from the DEW Geographic Information System (GIS) server to determine topography. This DEM data has been hydrologically conditioned and drainage enforced to ensure drainage flow paths based on elevations and mapped streamlines are captured and that catchments and related hydrological attributes are accurately delineated. This informs model design in terms of stratigraphic surfaces, hydrology and depth-to-water calculations (Figure 2.1). Where high or medium quality survey data were not available, an elevation derived from the 1-second DEM-H was used in preference to other low-quality data (Appendix A).

2.1.3 Landscape data accuracy

Part of this application included replacing the DEM-derived ground elevation of more than 400 wells with the 1-second DEM-H in SA Geodata. Prior to this update, DEM-derived ground elevations for these wells were obtained from the bare earth National Digital Elevation Model (1-second DEM), which was considered less accurate. DEM-derived ground elevations are used where there are no survey elevations available for the calculation of the RSWLs. Although the average and median difference between 1-second SRTM DEM and 1-second SRTM DEM-H elevations at water wells in the 2019 dataset was small (− 0.053 m and −0.046 m, respectively), the minimum (− 7.98 m) and maximum (4.18 m) differences highlighted the need to update ground elevations for all water well records sourced from SA Geodata. This is an important correction because spring flows can be dependent on quite small artesian aquifer pressures.

The location of major rivers and creeks was described using the 'GEODATA TOPO 250K Series 2' geodatabase that is maintained by Geoscience Australia and copies of which are maintained by DEW (Geoscience Australia 2006) (Figure 2.1).

2.2 Topography

The topography encompassed by the study area is typically very flat. Topographic variation is largely derived from the rivers and creek-lines that typically drain toward the center of the study area (Figure 2.1). The larger rivers are generally wide, gently sloping and have in some cases developed an anastomosing habit reflective of the lack of relief. Rivers typically terminate in one of a few playa lakes near the center of the study area, or into delta-shaped sink holes (Figure 2.1). Headward erosion on the margins of catchment areas form escarpments or breakaways. Buttes and mesas form where hardpan development creates a caprock that is resistant to erosion. Notably, such features are prominent around limestone depositing spring environments.

Large playa lakes occur in much of the central and south-eastern portions of the study area, with the largest being Kati Thanda–Lake Eyre at approximated 9,500 km^2. Kati Thanda–Lake Eyre is also the lowest point topographically, below sea level at approximately −15 m AHD (Figure 2.1).

The study area is largely bordered by highlands and plateaus. The more prominent highlands include the Northern Flinders, Wiloran and Gawler ranges on the southern margin, the Musgrave and MacDonnell Ranges to the north-west, the Goyder and Hamilton Ranges to the north-east and the Barrier Ranges to the south-east (Figure 2.1). The Denison and Davenport Ranges, which coincide with the Precambrian Peake and Denison Inliers, form the most prominent highland within the study area and are located to the west of Kati Thanda–Lake Eyre. Further to the west, the low escarpments of the Stuart Range mark the western margin of the Lake Eyre hydrological basin (Figure 2.1). Simon-Coincon et al. (1996) interpreted the Denison and Davenport Ranges to be the remnant of a former drainage divide during the Tertiary Period, and that headward erosion by eastward flowing rivers and creeks formed the flat escarpment that now separates the Stuart Range from the Denison and Davenport Ranges (Figure 2.1).

A large percentage of the surface within the study area is composed of desert. Many named deserts occur in or near the margins of the study area, including the Great Sandy, Simpson, Strzelecki, Tiari, Pedirka, Great Victoria and Sturt Stony deserts (Figure 2.1). Mabbutt (1977) interpreted wind-driven (aeolian) deflation as the dominant physical process shaping the surficial environment. Longitudinal and lunette sand dune environments form prominent landscapes in the plains and playa lake region. Denudation may also be an important landscape altering process. Karlstrom et al. (2013) calculated denudation rates of between 15 to125 m/million years (Ma) using uranium-series dating on Mesozoic outcrops beneath spring-related limestone found on buttes and mesa within the study area, whereas Simon-Coincon et al. (1996) suggested denudation rates within a similar range (20 to100 m/Ma). Denudation is likely to be driven by neotectonic-related upwarping within the Australian continent, with Quigley et al. (2007), Sandiford et al. (2009) and Sandiford et al. (2020) all presenting evidence for intracontinental neotectonic deformation in the northern Flinders Ranges, on the southern margin of the study area, as well as from within the study area.

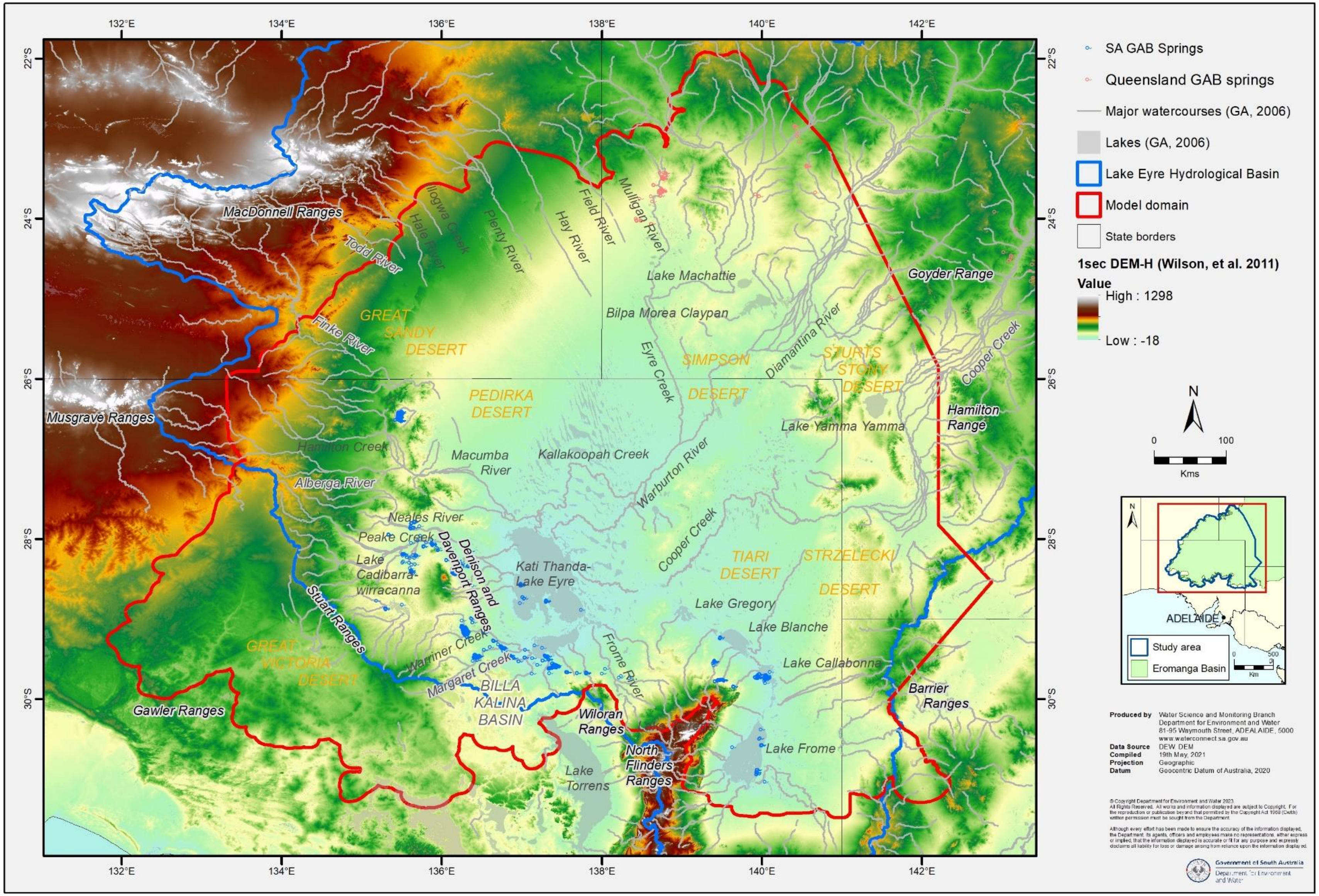

Figure 2.1: Topography of the study area, with key topographic features highlighted

2.3 Surface drainage

Surface drainage within the study area can be described as concentric, with headwaters located in highlands and escarpments near or outside of the study area and terminuses either within or within a distance of one of the playa lakes or ephemeral deltas near the center. The most prominent drainage terminus within the study area is the large playa of Kati Thanda–Lake Eyre, toward which most rivers and creeks in the region drain (Figure 2.1). Smaller playas that function as drainage terminuses within the south-eastern portion of the study area include Lake Blanche, Lake Gregory, Lake Callabonna and Lake Frome (Figure 2.1). Other lake terminuses with localised catchments include Lake Cadibarrawirracanna, located between the Stuart and Denison and Davenport Ranges, and Lake Yamma, Lake Mahattie, and the Bilpa Morea Claypan in QLD (Figure 2.1). Craddock et al. (2010) suggested that the number of rivers in the north-west of the study area terminating in ephemeral deltas and playas in the Simpson Desert were once likely to terminate in Kati Thanda–Lake Eyre during wetter climatic periods of the Oligocene–Miocene period.

Rivers, creeks, and lakes in the region are ephemeral, with flow events highly episodic and tending to be short lived. Kotwicki and Allan (1998) noted that such flow events are driven by either heavy monsoonal rains or heavy winter rains associated with La Niña events in the Pacific Ocean. Further, Habermehl (1980) noted that most flow events terminate only part way down the reach of many rivers due to the impact of low gradients and high evaporation and infiltration rates. Permanent surface water is typically associated with waterholes and spring-fed wetlands, or rock holes supplied from rainfall (Silcock 2010).

2.4 Great Artesian Basin Springs and other groundwater dependent ecosystems

There are two recognized types of groundwater dependent ecosystem (GDE) found within the study area. By far the most recognized are those associated with discharging groundwater from the GAB hydrogeological super-basin. The GAB springs are iconic features of the Central Australian landscape and are of great ecological, Cultural, and economic importance. Over 5,000 spring vents have been mapped in SA, stretched across a length of approximately 800 km from just south of the SA–NT state border to Lake Frome (Figure 2.1).

As mentioned in Chapter 1, the GAB springs are listed under the Commonwealth *EPBC Act 1999* as threatened ecological communities and consequently, much of the water resource-related regulation and legislation relating to this region focusses on GAB springs. The isolation of GAB springs within an otherwise arid environment makes them ecological ‘hotspots’ where endemic flora and fauna have evolved over very long periods of time. For example, Miller (1987) suggested the origins of the Desert Goby *Chlamydogobius eremius* that mostly occurs in artesian spring environments in Central Australia, dates spring activity from the end of the Tertiary Period. Similarly, Murphy et al. (2009) used mitochondrial DNA and allozyme analysis of the freshwater amphipods of the family *Chiltoniidae* found in the GAB Springs of SA to suggest most evolutionary lineages originated in the late Miocene.

The cultural and economic significance of the GAB springs encompasses both Indigenous and non-Indigenous communities. Evidence found at GAB springs through Central Australia suggests that they provided a water source for game and itinerant habitation for Indigenous populations for up to the last 10,000 years (Cox and Barron 1998). Hercus et al. (1985) and McLaren and Hercus (1986) noted that GAB springs are often spiritually and culturally significant locations with Indigenous peoples who have a close relationship with the land.

European settlement of the region commencing in the 1800s relied on the GAB springs as both a source of water and a means of navigation. Stuart (1865) made special note of the importance of the springs to the survival of his expedition. Later, the Overland Telegraph and the first Adelaide to Alice Springs rail line closely followed the line of springs through this region. Today, while their ecological significance takes precedence, the GAB springs still hold economic importance for the local tourism industry.

Other GDEs found within the study area are associated with riparian vegetation near rivers and creeks. Usually, these GDEs are thought to be dependent on shallow occurrences of groundwater. Such groundwater stores may be perched and separated from underlying aquifers by a confining unit (Miles and Costelloe 2015). Many of the region's waterholes would therefore fall within this category. While still important ecological and economic sources of water within the region, their generally low reliance on deeper groundwater sources means they are not a focus of this modelling study.

The hydrogeology of springs as they pertain to this study are discussed further in Volume 6.

3 Climate

Climate is a fundamental component of the hydrological cycle driving both recharge through rainfall and discharge through evaporation. Currently, most groundwater resources that are the focus of this study are derived from lateral through-flow. However, rainfall is of more importance in the west where Mesozoic-aged aquifer rocks outcrop and sub-crop (Chapter 4) and where important points of recharge, such as the ephemeral river recharge at the Finke and Plenty Rivers has been identified (Fulton et al. 2013). Likewise, evaporation as a driver of discharge occurs in regions where groundwater resources are found in the near surface, such as shallow aquifers near springs.

With respect to paleoclimate, Habermehl (2001) noted that groundwater within the GAB hydrogeological super-basin is of meteoric origin and may have an age of over 1 Ma near the centre of the basin, inferring that groundwater flow can be described using continental-scale flow lines. Over such time-periods, paleoclimatic variation and its impact on recharge rates may influence the GAB groundwater resource. Consequently, an appreciation of paleoclimatic variation may be helpful to understand long-term natural transience in groundwater pressures. Further, paleoclimatic variation and its relationship to recharge and groundwater flow may lead to a greater understanding of the potential implications of future climate change.

Looking forward, the potential impacts of anthropological climate change are pertinent for shallow aquifers or those parts of the study area that are potentially recharge zones, as it is these areas that respond most quickly to changes in rainfall and evapotranspiration (and hence recharge potential) in the timeframes considered.

3.1 Current climate

3.1.1 Temperature

The recent climate of the study area is arid (Allan 1990; McMahon et al. 2005). Average maximum daily temperatures range from 21 to 32 °C, whereas average minimum daily temperatures range from 8 to 17 °C (Figure 3.1, Bureau of Meteorology (BoM) 2019). The average mean daily temperature for the study area ranges between 15 and 25 °C. Monthly average temperatures typically vary between 17 °C and 40 °C at the Moomba Airport, Oodnadatta Airport and Marla Police Station weather stations (Figure 3.2, Figure 3.3). Generally, the northern and eastern portions of the study area are hotter than the southern and western portions.

3.1.2 Rainfall

For the purposes of estimating recharge, Radke et al. (2000) noted that given its size, the GAB hydrogeological super-basin may fall within more than one local climate zone. The study area occupies a large portion of the south-western, western and central portions of the GAB hydrogeological super-basin and thus largely falls within an arid zone where prevailing rainfall is largely sourced from weak winter cold fronts. Rainfall is typically higher along the north-western, north-eastern and eastern margins of the study area, which are likely receiving influence from northern monsoonal weather patterns. Rainfall is generally less than 250 mm per year, with mean annual average rainfall varying between 131 and 375 mm/y (Figure 3.4; BoM 2019). Rainfall occurrence within the study area is sporadic, and the intensity of rainfall can vary considerably. Notably, McMahon et al. (2005) stated that precipitation within the wider Lake Eyre Basin was more variable than 65% of equivalent arid regions internationally. Estimates of recharge from rainfall are discussed in Volume 6 of this report.

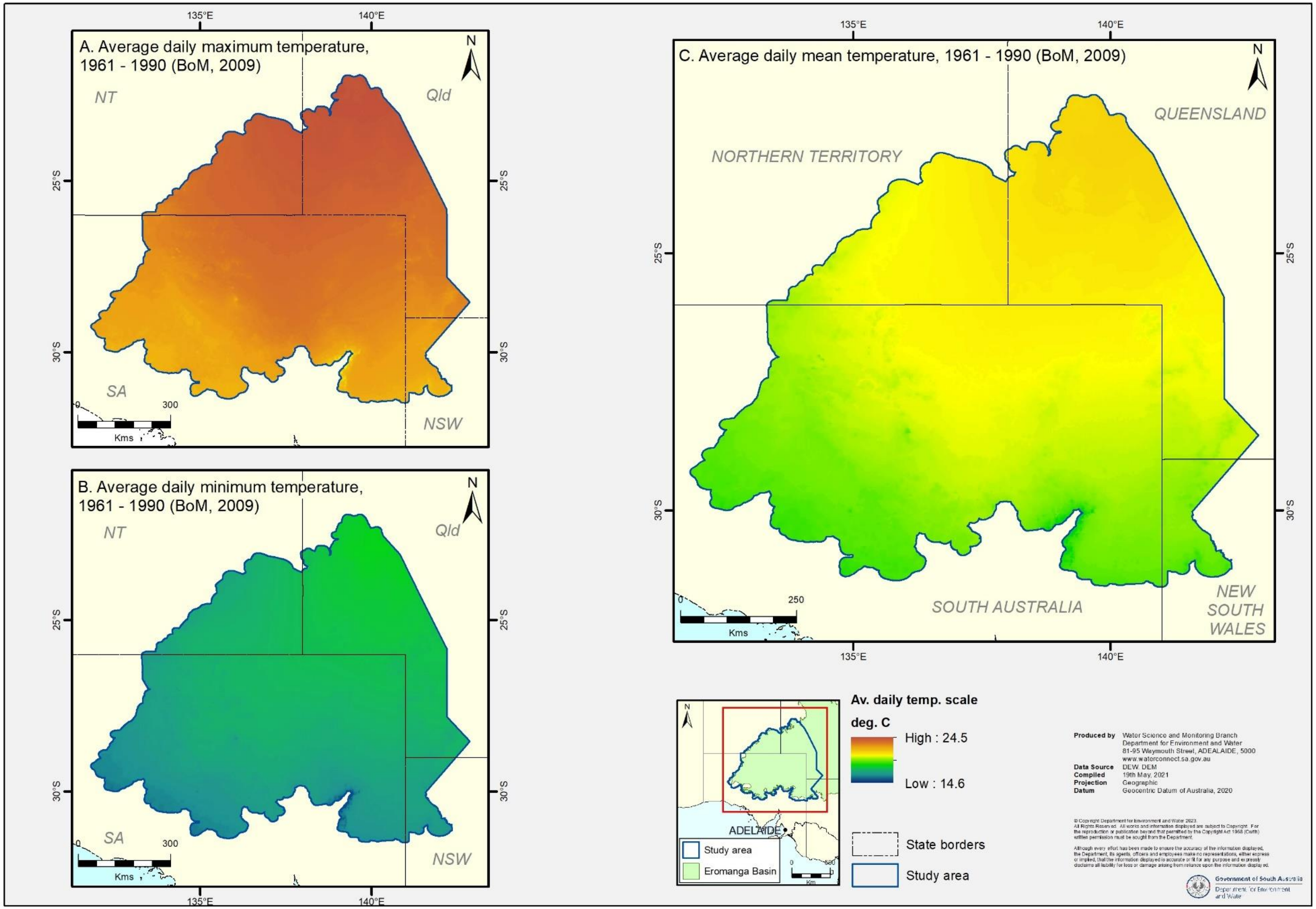

Figure 3.1: Average daily, maximum, minimum and mean temperatures, study area

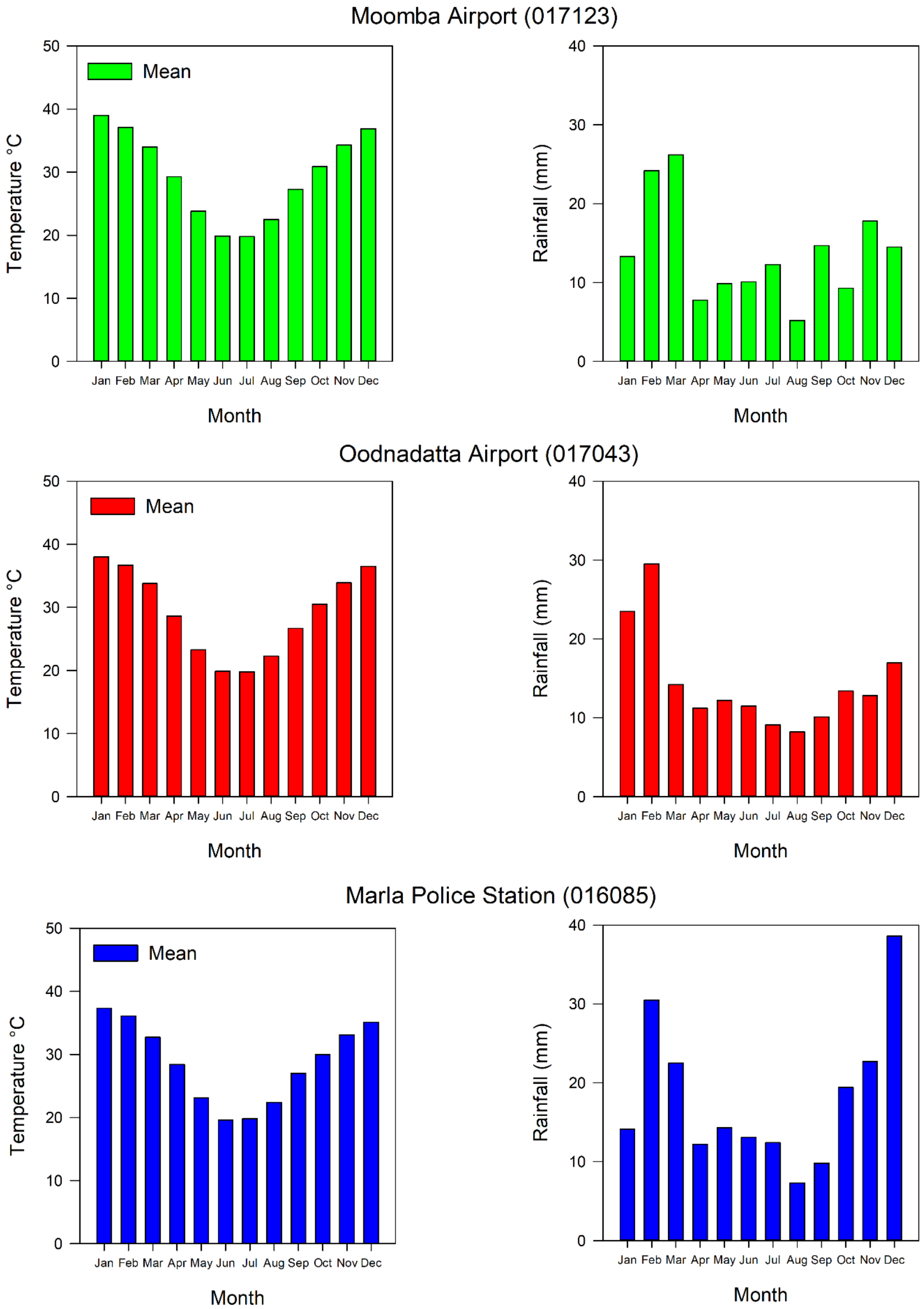

Figure 3.2: Average monthly temperature and rainfall, Moomba Airport, Oodnadatta Airport and Marla Police Station weather stations.

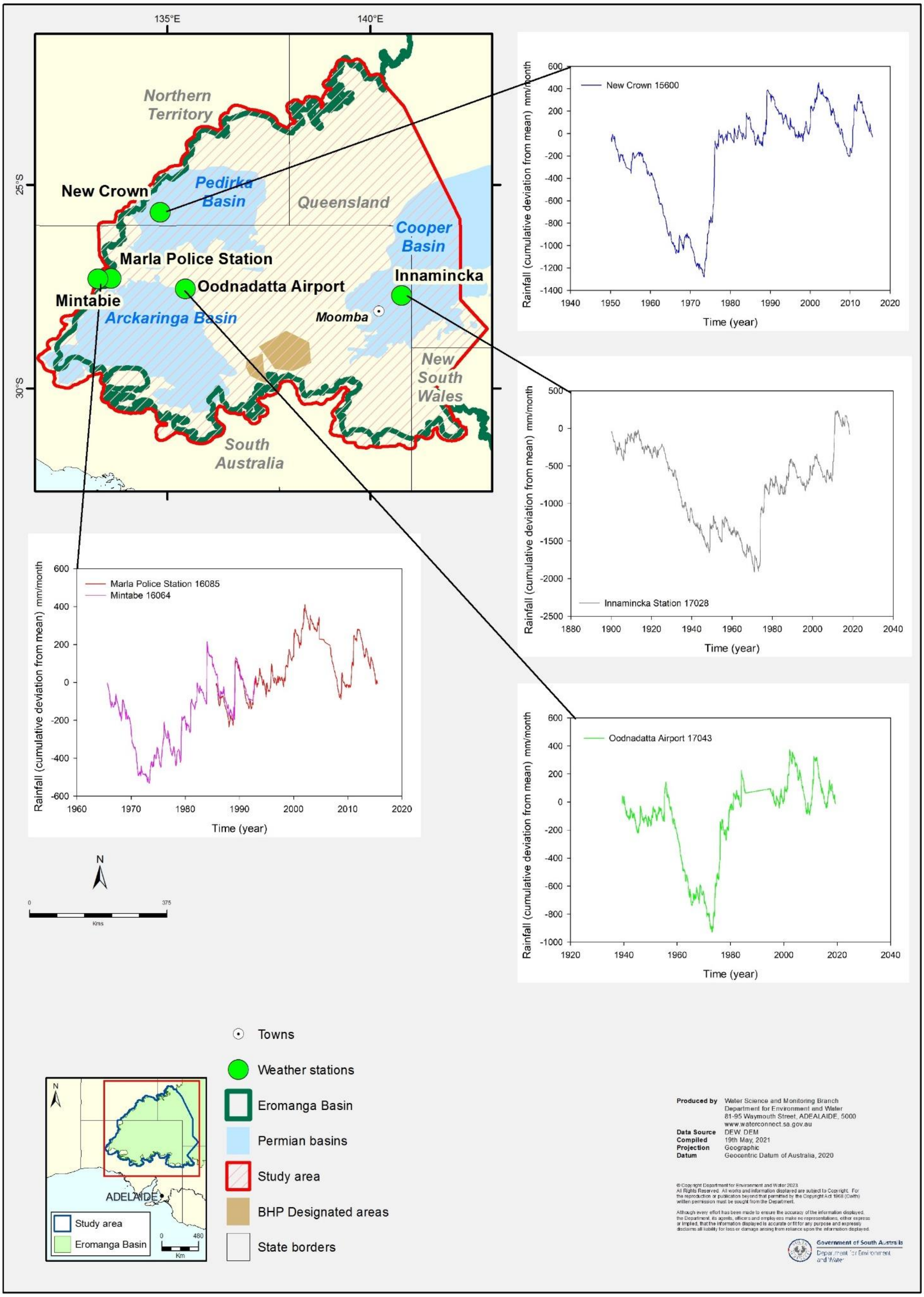

Figure 3.3: Weather stations and cumulative deviation from mean rainfall

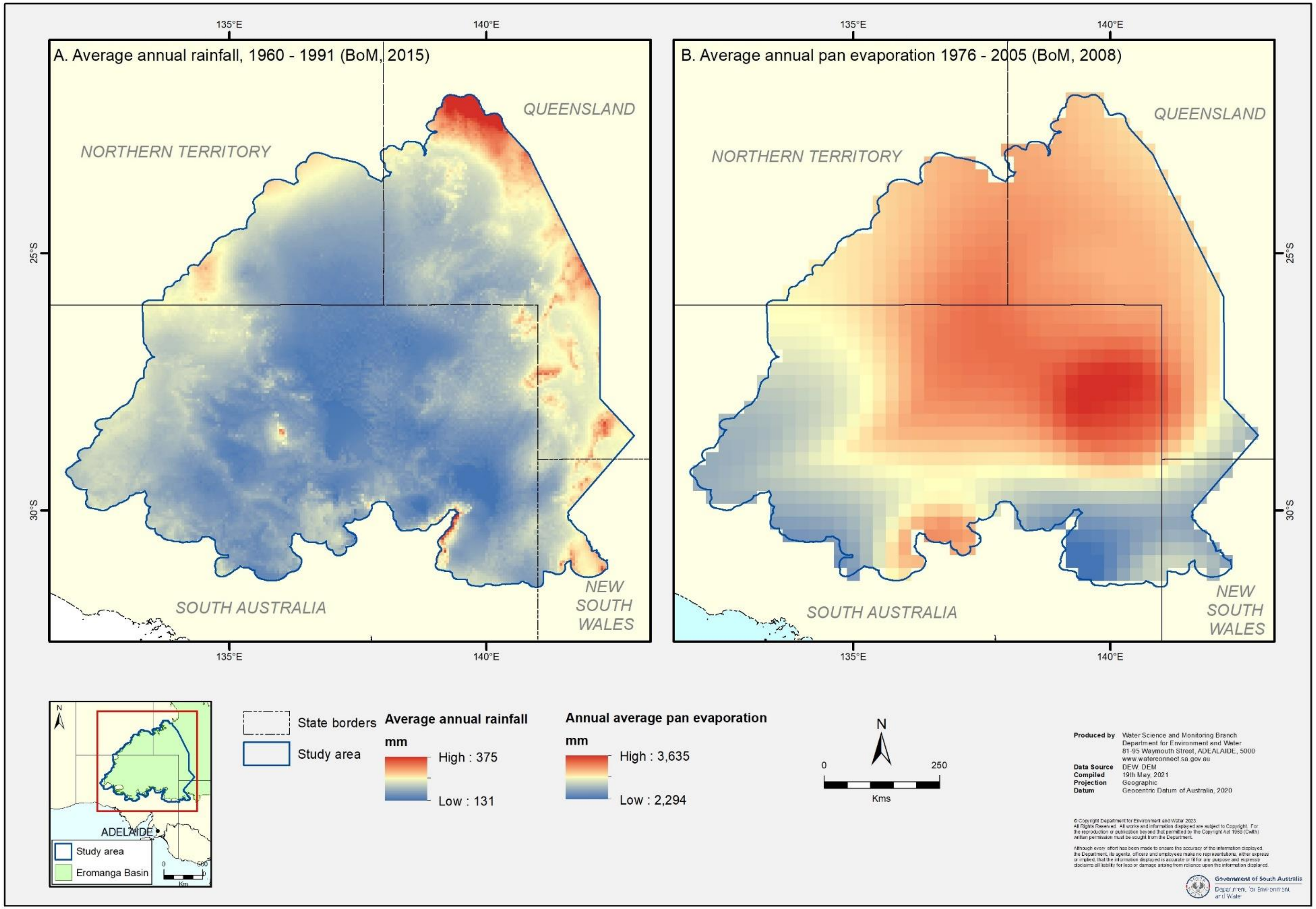

Figure 3.4: Average annual rainfall) and pan evapotranspiration

Rainfall totals from several weather stations across the study area viewed as a cumulative deviation from the mean show a similar pattern (Figure 3.3). While the different time-periods over which data was collected mean that the deviations exhibited within each station dataset are not directly comparable, patterns in relative deviation may still be used to describe climatic trends. Where sufficient records are available, a notable drying occurred between the later 1920s and the 1970s. The 1970s display a significant increase in rainfall, concomitant with flooding experienced in the region, which culminated in Kati Thanda–Lake Eyre filling between 1974 and 1977 (Allan 1985). Between 1980 and the present day there have been a few lesser high rainfall periods, coinciding with 1989, 1999 to 2001, 2009 to 2011 and 2015 to 2016. Drier periods typically followed these events.

3.1.3 Evaporation

Hamilton et al. (2005) measured average pan evaporation rates in the Cooper Creek region of Central Australia of 2,500 mm/y, while Tetzlaff and Bye (1978) reported an evaporation rate of approximately 3,000 mm/y in the Lake Eyre region. Based on interpolation, evaporation rates across the study area vary between 2,300 and 3,600 mm/y (Figure 3.4). Pan evaporation is modelled to be highest near the north-eastern border of SA and lowest in the south-eastern and south-western corners of the study area. Notably, the minimum rate of 2,300 m/y (6.3 mm/d) and the maximum of 3,600 mm/y (9.8 mm/d) are like the estimated evaporation rate at Dalhousie Springs (6.5 ±0.7 mm/d). Further, it is also like the maximum evaporation rate estimated using the energy budget (10 mm/d) for the region by Williams and Holmes (1978) and Holmes et al. (1981).

3.2 Paleoclimate

With respect to the hydrogeology of the study area, a review of paleoclimatic science indicate that there are three important factors to consider during hydrogeological conceptualisation:

- The current rate of recharge to the GAB hydrological super-basin is much less than discharge and consequently groundwater pressures in the basin are potentially in a state of natural, long-term decline.
- There is some ambiguity in determining changes in overall rainfall patterns between glacial and interglacial periods using Quaternary Period-fluvial and lacustrine records from Central Australia.
- There is some hydrochemical evidence for changes in groundwater flow direction that might be attributable to paleoclimate.

The past climate in the study area depends on global glacial and interglacial periods. Stable isotopes of elements like oxygen -are often used to investigate paleoclimate, because variations in the ratio of $^{18}O/^{16}O$ ($\delta^{18}O$) are linked to varying evaporation from the earth's oceans, which is directly linked to ocean temperature and by extension, climatic temperature. Using $\delta^{18}O$ isotope data from a combination of speleothem, polar ice and deep-sea cores, Waelbroeck et al. (2002) and Lisiecki and Raymo (2005) determined that there had been 12 interpretable glacial and interglacial periods in the last 500,000 years, with six occurring within the past 150,000 years. Glacial and interglacial periods have been linked by Lee et al. (2017) to Milankovich cycles, or cyclic changes in the precession (wobble around the earth's spin axis) that peaks every 20,000 years approximately, obliquity (tilt of the earth's axis) that peaks every 40,000 years and eccentricity (shape) of the earth's orbit that peaks every 100,000 years.

In the context of Australia, Frakes (1979), Duguid et al. (2005) and Nanson et al. (2008) all suggested that paleoclimatic proxy records indicate a general shift to more arid conditions throughout the late Cenozoic Era from between 10 and 17 Ma. Extending this concept, Rousseau-Gueutin et al. (2013) and Welsh et al. (2012) used groundwater modelling to argue that the current rate of recharge to the GAB hydrogeological super-basin is much less than discharge and consequently groundwater pressures in the basin are potentially in a state of natural, long-term decline.

How variations in global paleoclimate are reflected at more localised scales require additional data to establish. Such records may include pollen and vegetation records, local speleothem growths, as well as sedimentation records from lacustrine, fluvial and dunal environments. These kinds of records may provide relative data concerning the rainfall and temperature within a paleo-environment and therefore may serve as proxies in the absence of direct climate data. With respect to Central Australia and in particular areas within the study area, Priestley et al. (2017a) found evidence linking periods of increased travertine deposition at springs with wetter periods mapped using climatic proxies. However, they were unable to distinguish a pattern between shifts from monsoonal (northern) to temperate (southern) rainfall patterns, citing the size and complexity of groundwater flow paths contained within the GAB hydrogeological super-basin. Further Croke et al. (1996), Keppel et al. (2013) and Priestley et al. (2017a) noted some ambiguity in determining changes in overall rainfall patterns between glacial and interglacial periods using Quaternary Period-fluvial and lacustrine records from Central Australia.

Finally, the impact of paleoclimate on recharge and hydrodynamics has also been used to partly explain variations in hydrochemistry within the general area. Keppel et al. (2015b) noted that distributions in major ion and isotope hydrochemistry from bores completed in the Boorthanna Formation aquifer near Margaret Creek in the south-eastern portion of the study area suggested groundwater flowed from east to west, in contrast to modern groundwater flow that is west to east, based on head data. Keppel et al. (2015b) interpreted hydrochemistry as indicative of paleo-groundwater flow paths from recharge areas on the margins of the Billa Kalina Basin (Figure 2.1). From this, they surmised that the ephemeral wetlands in this area were potentially larger, wetter and acting as a source of recharge to the Boorthanna Formation aquifer at the time this flow path was active. Keppel et al. (2015b) suggested that, in the intervening time, a combination of a drying climate and to a lesser extent neotectonics had altered the groundwater flow path, but there had been insufficient time for this new pressure regime to flush the aquifer of this prior hydrochemical signature.

3.3 Climate change

3.3.1 Historical data analysis

To understand the potential impacts of climate change within the GAB region and to contextualise results from global climatic models, Fu et al. (2020) analysed observed climatic variability in the GAB region from 1960 to 2016. This was in addition to the future climatic projections for the GAB region from 40 global climatic models described in the Intergovernmental Panel on Climate Change Fifth Assessment Report.

From analysis of historical results, Fu et al. (2020) found that although rainfall and temperature generally increased across the GAB hydrogeological super-basin region (see Figure 3-3 for cumulative deviation from Mean (CDM) rainfall data), the statistical significance of these measures varied. While the increase in temperature year per year (y^2) was considered statistically significant, the general increase in rainfall across the super-basin was not, except in a few locations, one of which was near Marla on the south-west margin of the basin (calculated as approximately 3 mm/y^2).

With respect to evapotranspiration, Fu et al. (2020) examined pan evaporation observations and FAO56 Penman-Monteith estimations, which returned contrasting results. Pan evaporation observations displayed a significant decrease (≤ -5mm/y^2) for a large portion of the western GAB hydrogeological super-basin region, with most of the study area showing at least some decrease in evapotranspiration. In contrast, FAO56 Penman-Monteith estimations show most of the study area experiencing a statistically insignificant increase in evapotranspiration, except for an area near Marla and the Frome embayment, where a decrease was observed.

The increase in rainfall, concomitant decrease in evaporation and therefore potential increase in recharge near Marla contrasts with earlier hypotheses from paleoclimatic studies suggesting an overall drying climatic trend and therefore a general decrease in overall recharge. However, this highlights the potential variability between shorter term trends determined using direct rainfall and temperature observations in discrete locations, versus trends interpreted to occur over thousands of years using temperature proxies. Further, it also reinforces the need to examine a variety of data sets to understand fully the impacts of climate variability at more localised scales and the importance of continuous climatic measurement to establish meaningful climate datasets.

3.3.2 Climate change forecasts

Fu et al. (2020) undertook an analysis of 40 global climate models (GCMs), with an emphasis on two emission scenarios, described as ‘Representative Concentration Pathways’ (RCPs). RCPs are prescribed pathways for greenhouse gases and aerosols in combination with land use changes that are employed by climate change modellers as a consistent means of describing a range of broad potential climate outcomes (Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2019). RCPs describe the radiative forcing, or extra heat the lower atmosphere will retain because of increased greenhouse gas and aerosol concentration, by the end of the 21st Century (CSIRO 2019). These scenarios included the median (RCP4.5) to high (RCP8.5) emission scenarios of greenhouse gasses. RCP4.5 is indicative of a stabilisation scenario without overshoot pathway to 4.5 Wm^{-2} (≈650 ppm CO_2 equivalent) at stabilisation after the year 2100 and RCP8.5 represents a rising radiative forcing pathway leading to 8.5 Wm^{-2} (≈1,370 ppm CO_2 equivalent) by 2100.

Fu et al. (2020) found that temperatures were projected to increase for the RCP4.5 and RCP8.5 emission scenarios. Model predictions were generally found to be in keeping with historical trends as described by Fu et al. (2020) (Table 3.1). Annual rainfall values in the GAB region were projected to decline overall in the future although the change was generally small and some models did predict increases (Fu et al., 2020) (Table 3.1).

Table 3.1: Predicted temperature and rainfall changes based on the RCP4.5 and RCP8.5 emission scenarios

Climate scenario	Year range	Temperature range (°C)	Rainfall change (%)
RCP4.5	2010 to 2054	0.61 to 1.79	−0.72 to −0.82
	2030 to 2074	0.9 to 2.39	−1.3 to −1.2
	2055 to 2099	1.16to 3.25	-−2.48 to −1.75
RCP8.5	2010 to 2054	0.76 to 2.05	−12.06 to +15.79
	2030 to 2074	1.34 to 3.3	−18.73 –to +11.63
	2055 to 2099	2.38 to 5.01	−27.8 to +14.75

Fu et al. (2020) observed that the findings of their GCM analysis contrasted with general, albeit statistically insignificant, increases in rainfall in historical records over the past 50 years. This reflects a similar disparity with respect to rainfall records and paleoclimatic data and again emphasises the importance of localised, long and continuous climatic records of various scales and sources to fully appreciate the past as well as understand what might happen in the future.

Finally, Fu et al. (2020) also noted that the lack of agreement with evapotranspiration measures and projected rainfall was difficult to assess in the context of socioeconomic impact. For instance, one may determine that groundwater demand would increase with decreasing rainfall; however, such relationships are most notable in irrigation areas, none of which are found in the SA portion of the GAB hydrogeological super-basin. In contrast, water demand for pastoralism fluctuates with fodder availability, which may be expected to correlate with rainfall. If rainfall were to consistently increase, so could water demand. However, if periods of drought were to increase, stocking rates may be more likely to fall. Such variability when modelling projected water use in future-looking modelling scenarios is worth considering when assessing cumulative impacts over time.

3.3.3 Model predictions concerning climate change

While climate change is of ancillary concern during model construction and history matching, an understanding of potential climate change-related impact in the near- and long-term future may aid design of future scenarios.

An attempt at predicting the impacts of climate change on the GAB hydrogeological super-basin was undertaken by Welsh et al. (2012) using the GABTrans model. Welsh et al. (2012) modelled recharge by using scaling factors derived from GCMs that were then applied to recharge cells. Recharge cells were defined by mapping work subsequently published by Ransley et al. (2015) and largely coincided with regions of sub-cropping and outcropping aquifer strata within the entire GAB hydrogeological super-basin. With respect to the study area that is the subject of this study, Welsh et al. (2012) demarcated the portion of GAB hydrogeological super-basin aquifer units located along the western and southwestern edge of the basin that contained either dry or unconfined groundwater conditions as 'intake beds' within their model construction. Recharge rates applied to cells to simulate the 'current day' condition were obtained by allowing rates to vary on a zonal basis between 1 and 30 mm/y during calibration, except for 2 regions where recharge rates were fixed.

Three scenarios were examined:

- An extension of 2010 climate and groundwater development unchanged to 2070.
- A predicted change in climate from 2010 to 2070, but with current development scenarios in place over the same period of time. The future scenarios included the wet extreme, median and dry extreme future climates. Welsh et al. (2012) stated that these future climate scenarios included potential groundwater recharge rates ranging from 66% of the current rate under the dry extreme climate scenario to 183% under the wet extreme climate scenario.
- A prediction of future climate and development scenarios extended from 2010 to 2070, including new groundwater extractions as well as rehabilitation of current free-flowing bores.

Welsh et al. (2012) found that in the scenarios with unchanged climate and development that groundwater extraction exceeds replenishment in most of the GAB modelled in SA. Under the second scenario, although groundwater extraction was predicted to exceed replenishment in most of the south and west of the GAB, notable exceptions were increases in groundwater level near Marla under the wet extreme climate and decreases in groundwater level over most of the intake beds under the dry extreme climate.

Under the third scenario, although Welsh et al (2012) noted groundwater level recoveries in parts of QLD and NSW based on projected bore rehabilitation, the impact in the Far North Prescribed Wells Area (FNPWA) is like that found in the second scenario.

4 Basin configuration and hydrostratigraphy

The geometry of the hydrogeological basin and the contained hydrostratigraphic units are important aspects of the conceptual model. An accurate depiction assists the estimation of groundwater flows and hydraulic parameters. However, properly understanding the basin configuration, the hydrostratigraphy and particularly the history of its formation, helps model conceptualisation beyond these fundamental requirements.

Given the size of the study area, the relationship between the stratigraphy and the hydrostratigraphy can be complex. While strata across the study area may share a lateral stratigraphic nomenclature, a different set of nomenclature may be required to distinguish hydrostratigraphic relationships and groundwater flow systems, as these are influenced by more than just stratigraphy. While stratigraphy across the GAB hydrogeological super-basin has historically served as a proxy for hydrostratigraphy, some effort has been made here to separate the concepts of stratigraphy from hydrostratigraphy.

Tectonics is a key basin configuration factor in that it not only provides the necessary accommodation space for basin sedimentation, but ongoing tectonic activity may continue to influence and shape hydrogeology after basin sedimentation ceases. This modification may take the form of uplift, down-warping or faulting, which may change the basin configuration or hydrogeological properties of contained strata over time, including changing or forming groundwater flow systems or altering hydraulic conductivity or connectivity.

Importantly, in large basins such as the GAB hydrogeological super-basin that are still considered neotectonically active (Keppel et al. 2020a; Sandiford et al. 2020), the basin configuration and hydraulic properties of strata may be constantly evolving. Therefore, the flow systems they host may in fact be a much different age to the water molecules contained within strata. Such a concept may have important ramifications when trying to determine groundwater flow velocities or the age of groundwater flow systems, particularly where proxies such as hydrochemistry are used as lines of evidence.

4.1 Setting

There are several aquifer systems captured within the study area, defined variably by groundwater age, flow systems, hydrostratigraphy and basin nomenclature. The interconnectedness or otherwise of these systems has been an open question of recent research (see for example, Howe et al. 2008; Keppel et al 2015b; Radke and Ransley, 2020). Regardless, most groundwater resources in the Far North are contained within strata of the Eromanga Basin.

As discussed in Section 1.3, the study area is designed the encompass all the Eromanga Basin found within SA and the NT and therefore captures all the confined and sub-artesian portions of the Main Eromanga Aquifer Sequence found within these states, including important regions of potential recharge. The eastern boundary extends into QLD and NSW from the SA border. This allows for lateral inflow of groundwater from the Main Eromanga Aquifer Sequence strata, located outside the study area but at a sufficient distance away from the areas of interest (Figure 4.1). Additionally, the study area encompasses Eromanga Basin strata that overlie the main Eromanga aquifer sequence, the most important of which is the main confining layers of the Rolling Downs Group (Table 4.1), which may be found over most of the study area. Above this confining layer may be found other minor aquifers and confining layers in the Eromanga Basin and Lake Eyre Basin strata (Table 4.1).

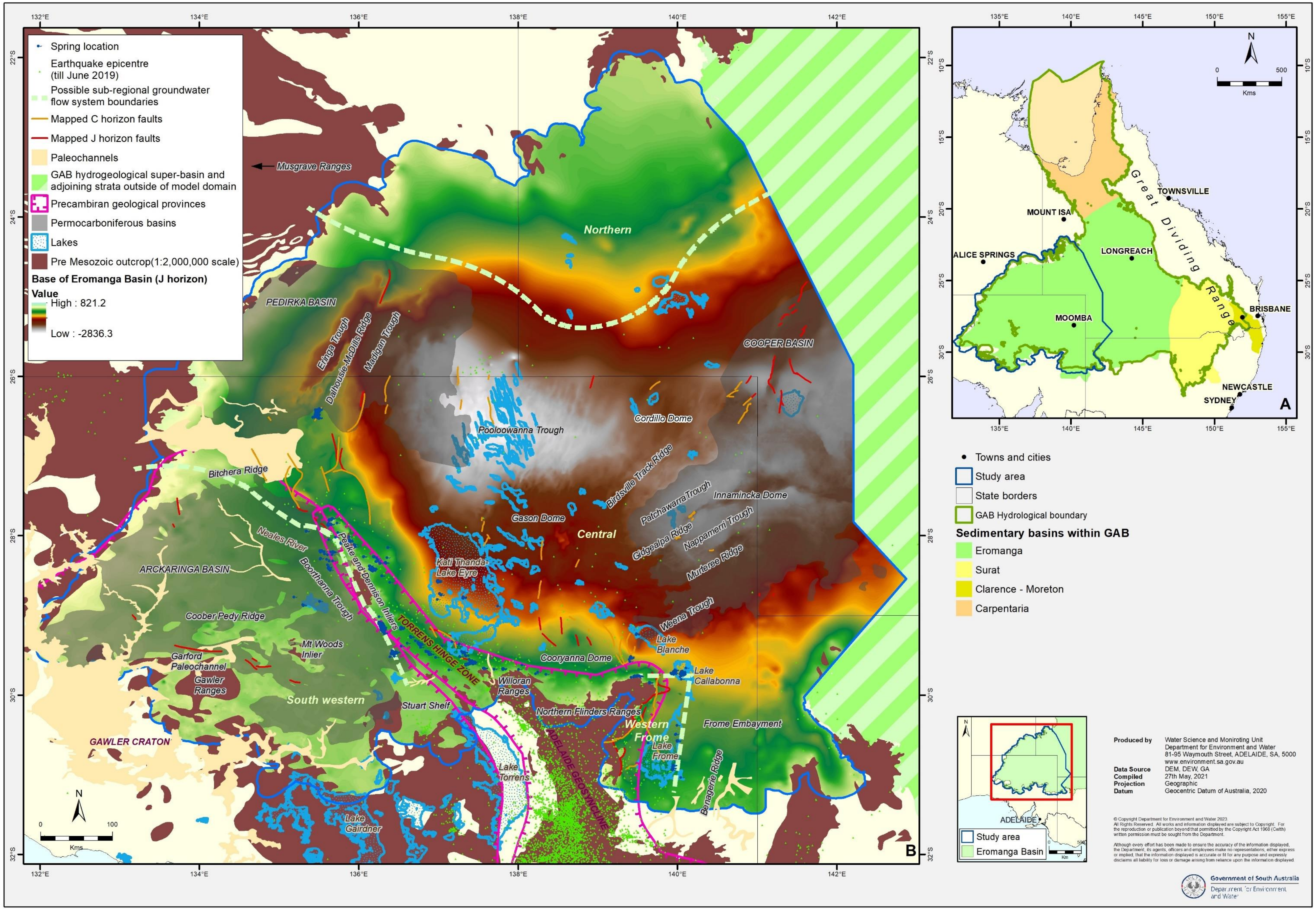

Figure 4.1: A) Sedimentary basins within GAB hydrogeological super-basin B) Structural geology and configuration underlying Mesozoic sedimentary rocks within the study area

Further, the study area encompasses regions in which important aquifers and confining layers are found underlying the main Eromanga aquifer sequence. These units are predominantly associated with Permo-Carboniferous strata associated with the Cooper, Arckaringa and Pedirka basins (Figure 4.1). These aquifer and confining layer sequences are important with respect to the possible interaction with groundwater within the main Eromanga aquifer sequence, but also because of their importance to the energy industry.

4.2 The Eromanga Basin and its relationship to the GAB

The Eromanga Basin is a Mesozoic epi-continental depocenter composed of non-marine to marine sedimentary rocks. Historically, the Eromanga Basin and chronostratigraphically equivalent basins in QLD and NSW, such as the Surat, Clarence-Moreton and Carpentaria basins, have been described collectively as the Great Artesian Basin, or GAB (Figure 4.1A). This 'hydrogeological super-basin' (Krieg et al. 1995) covers approximately 22% of the Australian land surface (Habermehl 1980), including significant areas of QLD, NSW, SA and the NT. Although the GAB hydrogeological super-basin includes sedimentary rocks from several epi-continental depressions, of these the Eromanga Basin is the largest by volume and is coincident with the GAB within the confines of the study area (Figure 4.1A). Consequently, the Eromanga Basin component of the GAB hydrogeological super-basin is the focus of this study and thus all following discussions. By extension, all the hydrostratigraphic units found within the Main Eromanga Aquifer Sequence may also be described as part of the GAB.

4.3 Eromanga Basin configuration

The formation of the Eromanga Basin was triggered when general uplift occurring within SA during the Triassic period coincided with continental down-warping to the northeast (Krieg et al. 1995; Ollier 1995; Toupin et al. 1997; Wopfner and Twidale 1967). Consequently, variations in basin subsidence or upwarping and global sea level changes during the Mesozoic Era led to the development of a series of transgressional alluvial, fluvial and marine sequences that formed the basin sediments (Krieg et al., 1995; Wopfner and Twidale, 1967). Further, volcanic activity associated with a subduction zone along the eastern margin of the Australian continent also contributed to sediment fill.

The basic configuration of the GAB hydrogeological super-basin is that of a bowl, partly defined by and progressively modified by the re-activation of several pre-depositional faults and folding. A series of mountain ranges composed of basement rocks frame the margins of the GAB hydrogeological super-basin, including the Northern Flinders and Willoran Ranges to the south, the Gawler Ranges to the south-east, the Musgrave and MacDonnell Ranges to the west and the highlands collectively known as the Great Dividing Range to the east (Figure 4.1).

Within the study area, there are several important intra-basinal structural features. The Peake and Dennison Inliers, where Precambrian basement rocks outcrop, is the most prominent surface expression of the Torrens Hinge Zone, forming the Denison and Davenport Ranges (Figure 4.1A). The Torrens Hinge Zone is a zone of structural weakness and faulting that is associated with the northern extent of the Adelaide Geosyncline. The Adelaide Geosyncline is a Neoproterozoic to Middle Cambrian basin complex in SA that underlies the central and southern portions of the study area and extends south to include the Northern Flinders Ranges.

The Adelaide Geosyncline is of particular importance to the basin configuration and by extension, the hydrodynamics inherent in Mesozoic strata within the study area (Figure 4.1B). Primarily, it divides the thicker parts of the Eromanga Basin to the east from the thinner part of the Eromanga Basin to west. This structure also serves to delineate largely confined and artesian groundwater pressures within Mesozoic aquifers to the eastern and northern parts of the study area from the largely unconfined and often dry aquifer conditions that predominate in the south-west.

To the north of the Torrens Hinge Zone, the Dalhousie-McDills Ridge forms a concealed basement high that separates the Poolowanna and Eringa trough depocenters and is coincident with the largest (by water discharge)

SA spring-system at Dalhousie Springs. Another prominent basement high is associated with the Mount Woods Inlier and the Coober Pedy Ridge. Finally, a concealed basement high with a north-east strike that separates the Poolowanna and Patchawarra trough depocenters forms the Birdsville Track Ridge. On the surface, the Birdsville Track Ridge is expressed as exposures of late Cretaceous and early Cenozoic units within low amplitude anticline structures associated with the Cordillo, Gason, Innamincka, and Cooryanna domes (Figure 4.1A).

4.4 Tectonic history and neotectonics

The influence of tectonics and neotectonics on the Eromanga Basin, as well as overlying and underlying strata is important to understand, as these recent deformation events may be dynamically affecting the flow of groundwater. This dynamic influence may:

- result from uplift, either along the margins or within the basin, which may change the direction of groundwater flow, or from active seismicity, faulting and folding, which may either form sub-basinal regions, or form conduits for inter-aquifer connectivity and spring formation
- control the distribution of artesian pressure by partially disrupting aquifer lateral connectivity in combination with impedance of vertical upward flow (Sandiford et al (2020), or through the inhibition or re-direction of lateral flow within a confined aquifer via the development of faulting.

As discussed previously, one of the most important intra-basin structural features is the Torrens Hinge Zone and associated Adelaide Geosyncline. This feature transects the study area and is coincident with the many spring occurrences and therefore the endpoint of groundwater flow within the J-K aquifer. The tectonic origins of this structure after sedimentation date back to the Cambrian Period, when several west-north-west compressive tectonic events contributed to what is now called the Delamerian Orogeny. These produced several north-south trending thrusts, north-west trending transgressive shears, recumbent folds, igneous intrusions and metamorphism (Cotton et al. 2007) as well as inverting parts of the Adelaide Geosyncline. In total, Preiss (2000) mapped 5 successive rift cycles with unique loci and orientation. Springs occurring along and near these structures indicates that the tectonic history of this region is an important influence on the hydrogeology of the Eromanga Basin.

More recently, Sandiford et al (2020) suggested that the basal traction imparted by the rapid movement of the Australian continent has had several important impacts. These include:

- causing most tectonic activity to occur on the southern side of a prominent keel observed within the lithospheric thickness near Innamincka (Figure 4.1A) and therefore within the southern half of the GAB hydrogeological super-basin
- causing variations of the mechanical properties of the sub-lithospheric mantle, which will affect the transmission and distribution of stress into the overlying plate, potentially expressing itself in the form of changes in surface elevation as well as in the pattern and location of discharge from impacted aquifers.

Further, a link between recent seismicity, spring formation and therefore impact on the hydrogeology of the study area can be made. Louden (1995) and Sandiford and Quigley (2009) have attributed this seismicity to the release of continental stress along weak zones concomitant with the Adelaide Geosyncline, which contains pre-existing faults, and zones of lithospheric heterogeneity and lithospheric buckling. Karlstrom et al. (2013) described the re-activation of pre-existing basement structures during continental-scale compression from the early Cenozoic Era to the present day as the primary control on the tectonic development and basin configuration of the GAB hydrogeological super-basin. Further, Keppel et al (2020a) noted that these areas of high seismicity are concomitant most of the mapped spring sites within the SA portion of the GAB hydrogeological super-basin (Figure 4.1A).

4.5 Stratigraphy

The geology found within the study area consists of several on-lapping intra-cratonic marine to non-marine sedimentary basins dating back to the early Phanerozoic Eon that overly metamorphic and igneous rock of Cambrian and Precambrian origin. Table 4.1 provides a summary of the major stratigraphic units found within the study area.

Table 4.1: Stratigraphy of the Far North groundwater study area

Period	Unit name	Related units	Lithology description	Depositional environment	Hydrogeological characteristics
Quaternary-Tertiary	Lake Eyre Basin	Coonarbine Formation, Eurinilla Formation, Millyera Formation, Willawortina Formation, Cadelga Limestone, Doonbara Formation, Namba Formation, Etadunna Formation, Cordillo Silcrete, Eyre Formation, Mount Sarah Sandstone	Variable sandstone, conglomerate, gravel beds, sand, silt, clay and mud units. Limestone, dolomite and silcrete horizons.	Terrestrial. Various fluvial, alluvial, colluvial, lacustrine and aeolian depositional environments and regolith overprint processes.	Major aquifers in the Eyre Formation. Leaky aquitard / partial aquifer (variation between sub formational units) in the Namba Formation.
Cretaceous	Winton Formation		Non-marine shale, siltstone, sandstone and minor coal seams.	Low energy, fluvial, lacustrine, and paludal (swamp and marsh).	Confined lenticular aquifers, discharge in eroded anticlines. Shales act as confining units.
	Mackunda Formation		Partly calcareous, fine-grained sandstone, siltstone and shale. Marks transition from marine to freshwater.	Subtidal marine and shore faces.	Confined minor aquifers within confining units, no known natural discharge.
	Oodnadatta Formation (Rolling Downs Group)	Allaru Mudstone (QLD), Woolridge Limestone Member	Laminated, claystone and siltstone, with inter-beds of fine-grained sandstone and limestone.	Low energy, shallow marine.	Confining unit with minor aquifers.
	Toolebuc Formation		Laminated carbonaceous clayey mudstone with fish fossils, calcareous clayey mudstone or coquinite with *Inoceramus* shells and clayey mudstone. Oil shale.	Low energy marine. Peak of marine transgression.	Confining unit.

Period	Unit name	Related units	Lithology description	Depositional environment	Hydrogeological characteristics
Cretaceous	Coorikiana Sandstone (Rolling Downs Group)		Predominantly carbonaceous, clayey, fine-grained sandstone and siltstone.	High energy, marine, shore face and gravel bars.	Confined minor aquifer.
	Bellinger Sandstone (Rolling Downs Group)		Interbedded fine- to coarse-grained sandstone, with minor mudstone and conglomerate.	No published depositional interpretation at time of reporting.	Possible minor aquifer. Possibly related to occurrences of artesian groundwater in a thin sandstone unit within Rolling Downs Group south of Lake Blanche and north of the Frome Embayment.
	Bulldog Shale (Rolling Downs Group)	Wallumbilla Formation (QLD)	Grey marine shaly mudstone, micaceous silt and pyrite are also present, with minor silty sands. Occasional lodestones.	Low energy, marine, cool climate.	Main confining bed for the Jurassic–Cretaceous aquifers.
	Cadna-owie Formation	Mount Anna Sandstone, Parabarana Sandstone, Trinity Well Sandstone, Livingstone Tillite, Sprigg Diamictite, Wyandra Sandstone (QLD)	Heterogeneous, mainly fine-grained sandstone and pale-grey siltstone. Coarser sandstone lenses occur in the upper part of the formation. Localised tillite and diamictite classified as member units denote significant variations in depositional environment.	Transitional from terrestrial freshwater to marine. Minor glacial sedimentation represented by member unit classifications.	A good aquifer in many parts, high yields and good water quality. May be a confining unit near the south-west Cooper Basin.
	Murta Formation		Finely interbedded siltstone, shale and fine to very fine-grained sandstone. Minor medium- to coarse-grained sandstone. Diagenetic siderite nodules and cementation in sandstone and siltstone beds are diagnostic in wireline logging.	Largely lacustrine, with several lacustrine-related facies identified.	Confining unit.
	McKinlay Member		Silty sandstone.	Transitional unit between braided fluvial deposits of the underlying Namur Sandstone and the overlying lacustrine Murta Formation.	Partial aquifer.

Period	Unit name	Related units	Lithology description	Depositional environment	Hydrogeological characteristics
Cretaceous–Jurassic	Namur Sandstone		Fine- to coarse-grained sandstone with minor interbedded siltstone and mudstone. Diagenetic calcite cement found locally in basal sequences.	Braided fluvial environment.	Major aquifer. Equivalent of the Hooray Sandstone found in QLD.
Jurassic	Algebuckina Sandstone		Fine- to coarse-grained sandstone, with granule and pebble conglomerates.	Low gradient fluvial, including rivers and floodplain. Both arid and wet climates.	Major aquifer, high yielding bores.
	Westbourne Formation		Interbedded shale, siltstone with minor sandstone. Cross bedding, cross-lamination, plant fossils and vertical burrows evident.	Lacustrine depositional environment Restricted to northern Cooper Basin region.	Largely a confining unit, possibly a minor aquifer in places.
	Adori Sandstone		Well-sorted, sub-rounded, cross-bedded fine to coarse grained sandstone. Diagenetic calcite cement found locally in basal sequences.	Low sinuosity braided fluvial environment, possible wave reworking.	Aquifer.
	Birkhead Formation		Interbedded carbonaceous siltstone, mudstone and fine- to medium-grained sandstone, with thin lenticular coal seams, silcrete and calcrete. Root mottling and bioturbation evident.	Finer grained sediments and coal deposited in lacustrine and coal-swamp environments (Lake Birkhead) that were cut by meandering fluvial channels.	Largely a confining unit. Possibly a minor aquifer in places.
Jurassic	Hutton Sandstone		Fine- to coarse-grained sandstone with minor carbonaceous siltstone and shale inter-beds and pebble conglomerate beds.	Braided fluvial with interpreted reworking by aeolian and lacustrine processes.	Aquifer.
	Poolowanna Formation		Fine- to medium-grained sandstone interbedded with laminated to massive siltstone and shale, thin discontinuous coal seams and intraclast breccia.	A meandering or anastomosing fluvial environment with minor floodplain.	Partial aquifer.

Period	Unit name	Related units	Lithology description	Depositional environment	Hydrogeological characteristics
Triassic	Simpson Basin	Peera Formation, Walkandi Formation	Shale, siltstone, minor sandstone (Peera Formation). Red-brown shale, green siltstone and fine-grained sandstone (Walkandi Formation).	Possible Lacustrine.	Confining unit.
Permo-Carboniferous	Cooper Basin	Cuddapan Formation, Morney Beds, Nappamerri Group, Gidgealpa Group	Glaciogene sediments, non-marine coal measures, lacustrine shales, conglomerate, sandstone, mudstone, siltstone.	Glaciolacustrine, terrestrial tillite, outwash, braided fluvial and lacustrine environments.	Sandstone units may be aquifers; however, over-pressurisation from gas generation may inhibit groundwater ingress and flow-through.
Permo-Carboniferous	Arckaringa Basin	Mount Toondina Formation, Stuart Range Formation, Boorthanna Formation	Mt Toondina Formation: Upper unit: grey carbonaceous shale, coal and interbedded grey sandstone, siltstone and sandy shale. Lower unit: shale, siltstone and sandstone Stuart Range Formation: Grey mudstone, siltstone and shale Boorthanna Formation: Upper unit: interbedded marine clastic rocks, (silt to boulders) Lower unit: glaciogene sandy to bouldery claystone and diamictite, intercalated with shale and carbonate units	Glaciogene through transgressional marine, with youngest units fluvio-lacustrine.	Mount Toondina and Boorthanna Formations contain aquifers. Stuart Range Formation is a confining unit.
Permo-Carboniferous	Pedirka Basin	Purni Formation. Crown Point Formation	Purni Formation: Interbedded sands, silts and clays, as well as coal beds. Crown Point Formation: Sandstone and shale	Fluvial and paludal (swamp) environments in Purni, glacio-fluvial and glacio-lacustrine in Crown Point Formation.	Sandstone and coal seams are potential aquifers, Claystone and shale potential confining units.
Pre-Carboniferous	Crystalline basement	Warburton Basin, Adelaide Geosyncline	Metasedimentary rocks ranging from greenschist through to gneissic grade, granitoid intrusives, basic dykes and sills.	NA	Fractured rock aquifers present where mechanical deformation permits.

4.6 Hydrostratigraphy

4.6.1 The Eromanga Basin/Great Artesian Basin super-basin

In SA, the Cadna-owie Formation, the Algebuckina Sandstone, and their lateral equivalents form the most important aquifers in the SA portion of the GAB hydrogeological super-basin with respect to both economically based extraction and environmental dependence (Figure 4.1, Figure 4.3). Although the Cadna-owie Formation is generally regarded as an aquifer through much of the study area, there are important exceptions to this interpretation. Lithological heterogeneity as well as burial-induced diagenesis may affect the classification, to the point where this unit can be a leaky aquitard (Ransley and Smerdon 2012). For example, Radke et al. (2000) interpreted that aquifer horizons over the deeper parts of the Cooper Basin had reduced permeability and porosity because of burial pressure and diagenesis based on observed near-stagnant groundwater flow.

Underlying the Cadna-owie Formation in areas outside the Cooper Basin region, the Algebuckina Sandstone (in SA) or the De Souza Sandstone (in the NT) is a thicker, fine- to coarse-grained sandstone, with granule and pebble conglomerates of a generally terrestrial origin. In deeper parts, such as near the Cooper Basin, the Algebuckina Sandstone may laterally grade into several different stratigraphic units, including the Hooray, Namur, Adori and Hutton sandstones, as well as intra-aquifer confining units such as the Murta, Westbourne and Birkhead formations.

Historically, the Cadna-owie Formation, Algebuckina Sandstone, and lateral-equivalent units have been treated as a single unit in historical conceptual and numerical groundwater models (Radke et al., 2000; Welsh, 2000). For example, in Habermehl (1980), Seidel (1980) and Love et al. (2013a and b), a collective term of the 'J' (Jurassic) aquifer is used. Such collective nomenclatures can be considered an oversimplification, particularly in the Cooper Basin region. This may in part be driven by a lack of information of these units, as most hydrogeological data, particularly in SA, originates from either the Cadna-owie Formation, Algebuckina Sandstone or Namur Sandstone. An important tenet of this modelling project is the discrete representation of these intra-aquifer confining units.

Table 4.2 presents a summary of aquifer and confining unit nomenclature used for this modelling study. The Cadna-owie Formation, the Algebuckina Sandstone, and their lateral equivalents, plus the sub-basinal Hutton-Poolowanna aquifer, and including intervening confining units, is referred to as the 'Main Eromanga Aquifer Sequence'. This collective term is largely used to describe the main sequence of strata being represented in model construction, and thus captures all strata within the upper and lower vertical limits of the model (Table 4.2).

Table 4.2: Summary of hydrostratigraphic unit nomenclature

Collective Term	Western Study area		Cooper Basin Region, study area	
	Formation	**Hydrostratigraphic Units**	**Formation**	**Hydrostratigraphic Units:**
Main confining units	Rolling Downs Group	Main confining units	Rolling Downs Group	Main confining units
Main Eromanga Aquifer Sequence	Cadna-owie Formation (and lateral equivalents)	J-K aquifer	Cadna-owie Formation	Intra-sequence confining units
	Algebuckina Sandstone		Murta Formation	
			McKinlay Member	
			Adori Sandstone	J-K aquifer
			Westbourne Formation*	
			Namur Sandstone	
			Birkhead Formation	Intra-sequence confining unit
			Hutton Sandstone	Hutton-Poolowanna aquifer
			Poolowanna Formation	
Basement	Pre-Jurassic	Basement	Pre-Jurassic	Basement

*Possible minor intra-aquifer confining unit

Within the Main Eromanga Aquifer Sequence, the most important definition for the purposes of conceptualization is that of the 'J-K aquifer.' The term 'J-K aquifer' primarily refers to a combined unit consisting of the Cadna-owie Formation, where mapped as an aquifer, and the Algebuckina, Adori and Namur Sandstones (Figure 4.3). Most of the hydrogeological information about the GAB from within SA and wider study area comes from these formations and specifically the first two, which are in conformable contact everywhere except where the Murta Formation occurs. Although conceptualized here as a single unit to aid model construction, sub-regional lithological variation as well as structural deformation may contribute to modification of hydraulic properties and basin configuration, which may have led to the development of semi-discrete sub-basinal regions. Such semi-discrete sub-basins within the wider GAB may be interpretable based on lithology, structure, hydraulic properties and hydrochemistry. With respect to the GAB hydrogeological super-basin and how our conceptualisation of aquifer and confining layer units were determined, Norton and Rollet (2022) and Rollett et al. (2022) calculated sand/shale ratios from geophysics logs obtained from key wells to interpolate the lithological distribution and the thickness of predominantly sand and shale units across the GAB. These works demonstrate that at the super-basin scale the South Australian portion of the Main Eromanga Aquifer Sequence is predominantly composed of sand units when compared to laterally equivalent units found to the east and in particular the Surat Basin (Figure 4.2). This lithological distribution has been attributed to differences in depositional systems between the western Eromanga Basin to chronologically equivalent basinal environments further east. Cotton et al. (2007) summarised depositional interpretations for the Hutton Sandstone that suggested fluvial transport of sediments originating in the south-west of the basin and extending to the north and east where sediments were redistributed through other, lower energy processes.

At the scale of the study area, examples of possible sub-basinal regions include the largely unconfined south-western Eromanga Basin (Howe et al. 2008) (Figure 4.1B) and within the north-eastern portion of the study area. Both flow systems coincide with areas where the Main Eromanga Aquifer Sequence is relatively shallow and thin compared to thicker sequence found toward the centre of the study area. Smaller, semi-discrete groundwater flow systems may also be interpreted as sub-basinal regions in the Wellfield area (Figure 1.1) or the western side of the Frome Embayment (Figure 4.1A). In these cases, basin configuration, proximity to areas of possible mountain system recharge or localised basement highs may contribute to the formation of such flow systems. These sub regions are discussed further in Volume 6, where hydrochemical evidence for these is presented. Hydrostratigraphic nomenclature used in this study is designed to encompass regional scale hydrostratigraphy while allowing flexibility to discuss sub-regional scale discontinuity.

By extension, the Hutton Sandstone and the Poolowanna Formation are being treated as a separate hydrogeological unit, referred to as the Hutton–Poolowanna aquifer. Although the Hutton Sandstone and Poolowanna Formation are also lateral equivalents of the Algebuckina Sandstone, they are sub-basinal in extent. They are also less hydraulically connected with other strata compared to the Namur and Adori Sandstones given the presence, thickness and extent of the overlying Birkhead Formation confining unit (Figure 4.3). These differences in nomenclature can be described, with the Hutton–Poolowanna aquifer and intra-sequence confining units predominantly found in the Cooper Basin region, whereas in the Western Eromanga Basin, the J-K aquifer predominates (Table 4.2).

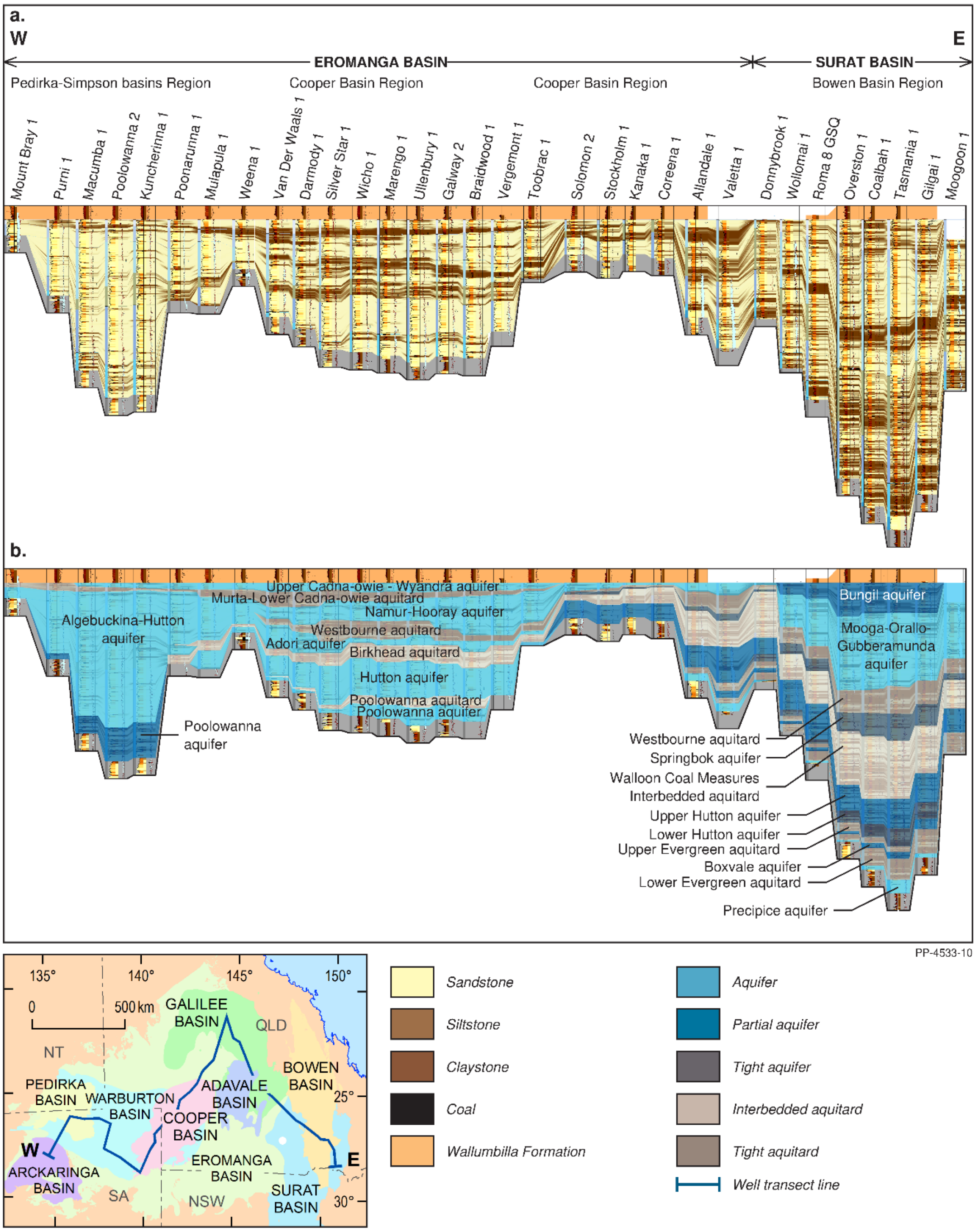

Figure 4.2: Example cross-section across the GAB showing the lithology variability within and between aquifers

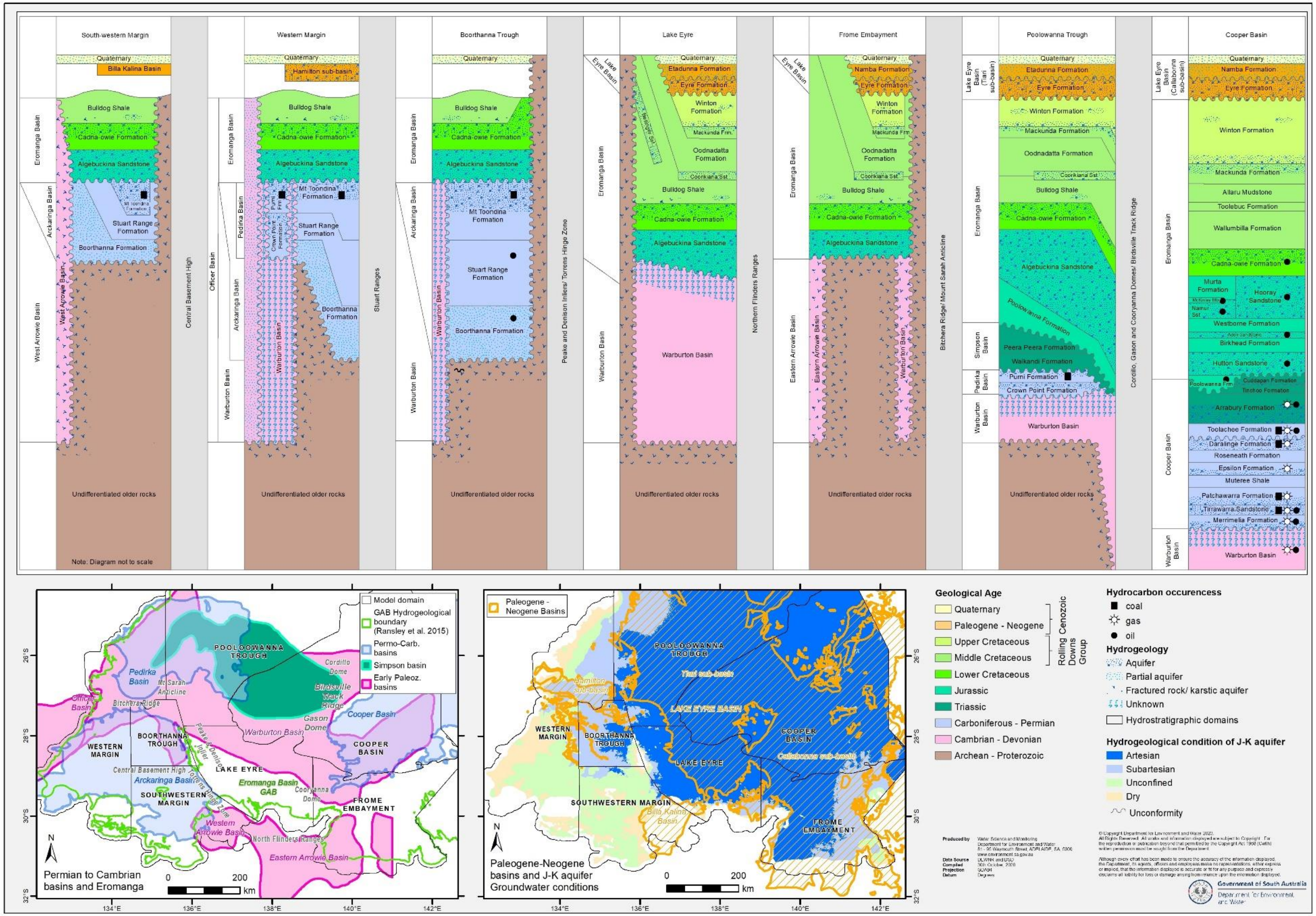

Figure 4.3: Hydrostratigraphy of the SA portion of the Far North groundwater study area

5 Inter-basin hydrostratigraphy and vertical connectivity

Inter-aquifer connectivity refers to how groundwater migrates between aquifers. The conceptual model needs to consider connectivity to aquifers outside the Main Eromanga Aquifer Sequence. This assists with:

- lateral and vertical boundary conditions
- identification of subregional groundwater flow systems.

5.1 Units overlying the Main Eromanga Aquifer Sequence

5.1.1 Rolling Downs Group

For a very large portion of the study area, the Rolling Downs Group overlies the Main Eromanga Aquifer Sequence (Table 4.1 and Figure 5.1). The Rolling Downs Group is composed of shaly mudstone units of low permeability that were deposited in deep-water marine environments (Isbell 1957) (Table 4.1, Figure 4.3). The Bulldog Shale and Oodnadatta Formations outcrop extensively near the western margin of the GAB, whereas the Wallumbilla Formation and Allaru Mudstone occur at depth in the central portions of the basin near the borders of SA and QLD. This extensive relationship is ultimately what provides the confining pressure that promotes artesian groundwater conditions in the eastern and central parts of the study area.

Where this main confining unit is absent or breached, such as in the western region, the strata that composes the J-K aquifer may either outcrop or come into contact with alluvial aquifers of the modern hydrological system. Such areas might be a zone of potential recharge to the J-K aquifer.

Whilst the Rolling Downs Group is predominantly a confining layer, there are minor aquifers or partial aquifers found with it. From oldest to youngest, these sequences are: Bellinger Sandstone, Coorikiana Sandstone, and the Winton and Mackunda formations. The Bellinger Sandstone is a recently named unit found near the Frome Embayment (Alley and Hoare 2017) (Figure 4.1), whilst the other units are predominantly found north-east of the Torrens Hinge Zone, where Eromanga Basin strata become much thicker (Figure 4.1, Figure 5.1).

The Coorikiana and Bellinger Sandstone units are minor aquifers and can be artesian in places (Harrington et al. 2013; Keppel et al. 2016; Keppel et al. 2020b). The subsurface extents and configuration of these upper Eromanga Basin strata has not been adequately determined to assess their relationships to one another, or to the J-K aquifer.

The Winton and Mackunda formations are the youngest units of the Rolling Downs Group. These formations were deposited during marine regressions through to terrestrial depositional environments (Table 4.1, Figure 4.3). The marine calcareous sandstone, siltstone and shale of the Mackunda Formation and the non-marine shale, siltstone and sandstone of the Winton Formation also represent the youngest units of Mesozoic Eromanga Basin. Although typically sub-artesian and with variable salinity, sandstone sequences within the Winton and Mackunda formations are important aquifers in Central Queensland due to their relatively shallow depth (Golder 2015).

Limited connectivity is considered possible with these younger Rolling Downs Group aquifers, although it is likely to be restricted to where faulting has either juxtaposed aquifers or provided a conduit.

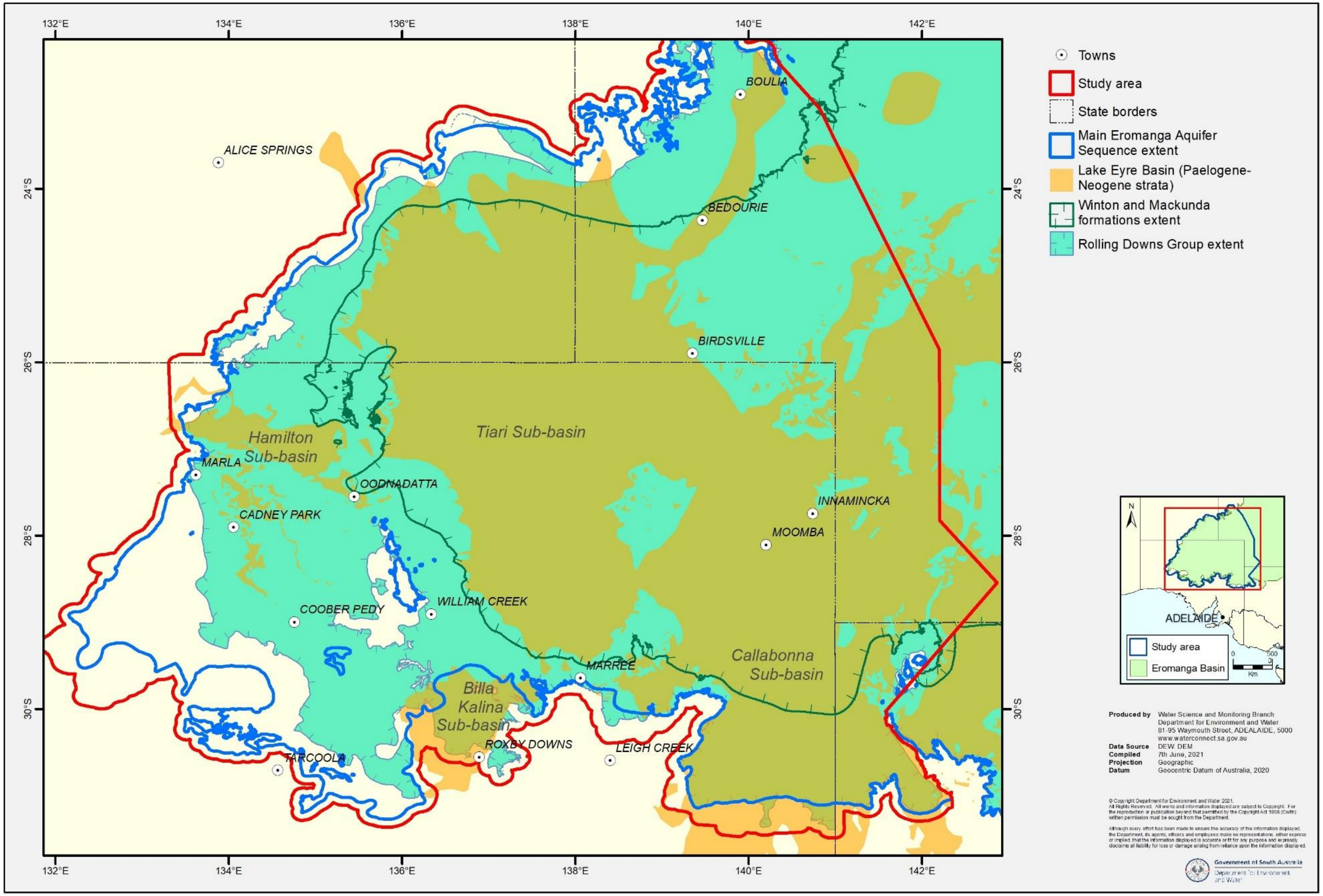

Figure 5.1: Extents of important strata overlying the Main Eromanga Aquifer Sequence

5.1.2 Cenozoic strata

Unconformably overlying the Rolling Downs Group are terrestrial sedimentary units of the Cenozoic Lake Eyre geological basin. Variations in sedimentation and resultant stratigraphy within the Lake Eyre geological basin has been caused by the Birdsville Track Ridge dividing the wider Lake Eyre geological basin into two large sub-basins called the Tiari to the north-west and the Callabonna to the south-east (Table 4.1, Figure 5.1). Within both these sub-basins, the interbedded sandstone, shale, and lignite beds of the Eyre Formation form an important aquifer. Overlying the Eyre Formation are the Namba Formation in the Callabonna Sub-basin and the Etadunna Formation in the Tiari Sub-basin. Both units may contain minor aquifers with groundwater of highly variable salinity, as well as finer grained sedimentary rocks that may form confining units (Table 4.1). Other minor sub-basins within the western portion of the study area also exist, namely the Billa Kalina and the Hamilton (Figure 5.1). Notably, aquifers within the Hamilton Sub-basin are an important local groundwater resource for stock and domestic purposes (Keppel et al. 2017).

Where Rolling Downs Group strata is missing or thin and groundwater conditions in the J-K aquifer are unconfined, the latter becomes receptive to recharge. Often such regions are difficult to identify because of the lithological similarity between stratigraphic units of the Mesozoic and Cenozoic Eras. Such areas typically occur near the margins of the Eromanga Basin, or intra-basin regions where Mesozoic strata can become thinner, as well as near the Peake and Denison Inlier (Figure 4.1A). Figure 5.2 provides one such example located near the Garford Paleochannel west of Coober Pedy; here the confining layer of the Rolling Downs Group is missing and Mesozoic and Cenozoic sandstone both occur unconformably over Permo-Carboniferous claystone basement. In this example it is conceivable that the Mesozoic and Cenozoic sandstone layers are acting as a single hydrostratigraphic unit that is receptive to local recharge.

Where the rocks of the J-K aquifer outcrop, the groundwater found in these areas is interpreted to coincide with the phreatic water table (Figure 5.3). However, for a predominant portion of the study area, the water table is associated with near-surface aquifer units found within Cenozoic sediments. The highly variable and localised nature of these units means that we do not assume that groundwater flow is continuous across the subregion. However, the phreatic surface typically reflects the regional topography, with areas of high groundwater elevation found near the Musgrave Ranges and the Central Australian Plateau to the north-west and west respectively. As with other aquifers, differences in elevation between the phreatic water table and the potentiometric surface of the Eromanga Basin in this region may be used to interpret the potential for upward or downward leakage from one to the other. Whether such potential for leakage occurs is dependent on the demonstration of a conduit for flow and evidence of leakage.

5.2 Units underlying the Main Eromanga Aquifer Sequence

Sedimentary rocks of several Permo-Carboniferous basins underlie the Mesozoic age Main Eromanga Aquifer Sequence within the study area (Table 4.1, Figure 4.3). The Cooper, Arckaringa and Pedirka basins not only contain some coarser grained sedimentary sequences that in places are in contact with the Main Eromanga Aquifer Sequence, but they also contain appreciable amounts of coal and hydrocarbon source rocks that have been targeted by the energy industry (Department of Manufacturing, Innovation, Trade, Resources and Energy, 2012).

Below the Cooper Basin are metasediments and basalts of the Warburton Basin, and granitoids of the Big Lake Suite (Figure 4.3). The tectonic history and chronostratigraphy of rocks underlying the Cooper Basin have been discussed as important with respect to generating the appropriate thermal gradient to allow for the formation of oil (Meixner et al. 1999; Hall, et al. 2016) In contrast, Beardsmore (2004) suggested the very thick coals and their low thermal conductivities could account for much of the thermal signature in the Cooper Basin region. By extension, any heat source or resultant thermal gradient is expected to affect groundwater flow in the overlying aquifers.

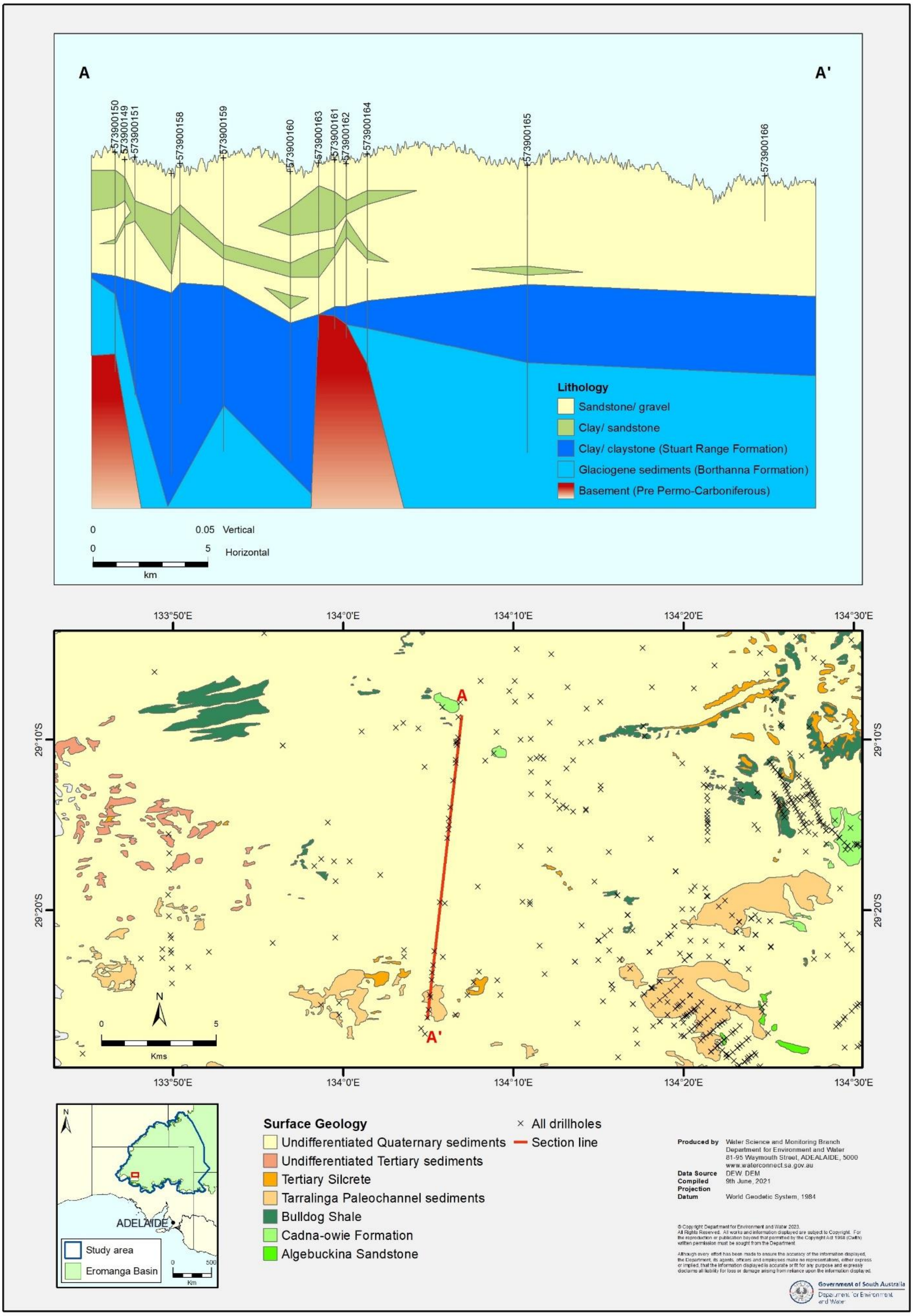

Figure 5.2: Cross-section showing lithological variation in Quaternary to Permian sedimentary rocks near the Garford Paleochannel.

5.2.1 'Unconformity'aquifers or aquitards.

Possibly the most important inter-aquifer relationship between the Main Eromanga Aquifer Sequence and underlying units is where exposure has altered the hydrogeological properties of pre-Mesozoic rocks prior to the deposition of Mesozoic sedimentary rocks, regardless of the former's stratigraphic interpretation. Such 'regolith' or 'unconformity' aquifers underlying the Main Eromanga Aquifer Sequence may be very important around the margins of the Eromanga Basin, where recharge to or discharge from the J-K aquifer is more likely to occur. One such area occurs near Marree, near the southern margin of the basin (Figure 4.1A). Here, the hydrochemistry of water from springs is very similar to that of J-K aquifer groundwater, but drilling logs suggest no J-K aquifer strata is present. Pressures in nearby wells are also like those in the J-K aquifer. Given the proximity to the Northern Flinders Ranges, we hypothesise that the unconformity between Mesozoic and Precambrian rocks is at least partly composed of either immature alluvial fan deposits sourced from the nearby ranges to the south, or a permeable weathering horizon that has not been removed by erosion prior to Mesozoic sedimentation. Logging data supports the occurrence of both, which indicates large particulate fragments (for example, 'boulders') as well as discolouration in keeping with weathering.

However, with respect to the study area, the hydrogeology of the unconformity zone between the Main Eromanga Aquifer Sequence and underlying rocks is uncertain away from the margins of the basin. This uncertainty stems from a lack of drilling data, which is required to confirm the presence of such aquifers and to determine their importance to groundwater flow and storage. Indeed, the 'transition zone' representative of the unconformity may in fact be an impediment to flow, as interpreted by Pandey et al. (2020) in the Surat Basin, QLD, between the GAB Aquifer and the Condamine Alluvium.

5.2.2 Interconnectivity relationship with Permo-Carboniferous basins

Within the margins of the Eromanga Basin, the inter-aquifer relationships between the Main Eromanga Aquifer Sequence and underlying strata are complex. Recent assessment of the lithology and the structural configuration of stratigraphy within the Cooper, Arckaringa and Pedirka basins suggest there is potentially connectivity between the aquifers in the Main Eromanga Aquifer Sequence and aquifers within these Permian basins. Of note is that there are discrete hydrostratigraphic units with groundwater flow systems within the Mount Toondina and Boorthanna Formations of the Arckaringa Basin, the Purni and Crown Point Formations of the Pedirka Basin and the Gidgealpa Group of the Cooper Basin. These formations are generally composed of interbedded sandstone, siltstone, and shale, with intermittent coal in the younger formations (Table 4.1).

5.2.2.1 Pedirka and Simpson Basin

Ransley and Smerdon (2012) interpret the Pedirka and Simpson Basins (Figure 4.3, Figure 5.4) as adjoining the J-K aquifer via predominantly partial aquifers, although regional scale mapping in the same document suggests connection is via leaky aquitard. For the Pedirka Basin, interpretation of 'partial aquifer' appears justified given the heterogeneous lithology inherent in both the Purni and Crown Point Formations (Table 4.1). Whilst Fulton et al. (2015) found that the Purni Formation could be highly connected to the overlying Cadna-owie Formation, where any effective confining unit is absent at a local scale, the lithological heterogeneity may lower the bulk hydraulic conductivity at a regional scale.

Hydraulic connectivity between the aquifers in the Pedirka Basin and the J-K aquifer is interpreted to be limited to where a thick sequence of fine-grained Triassic sediments of the Simpson Basin separate the two in structural lows and basin depocenters such as the Madigan and Poolowanna Troughs (Figure 4.1A, Figure 4.3 and Figure 5.4). While little is known concerning the hydrogeological characteristics of the Simpson Basin, current interpretation suggests it will behave as an aquitard and this limits the connectivity between Eromanga and Pedirka basin aquifers.

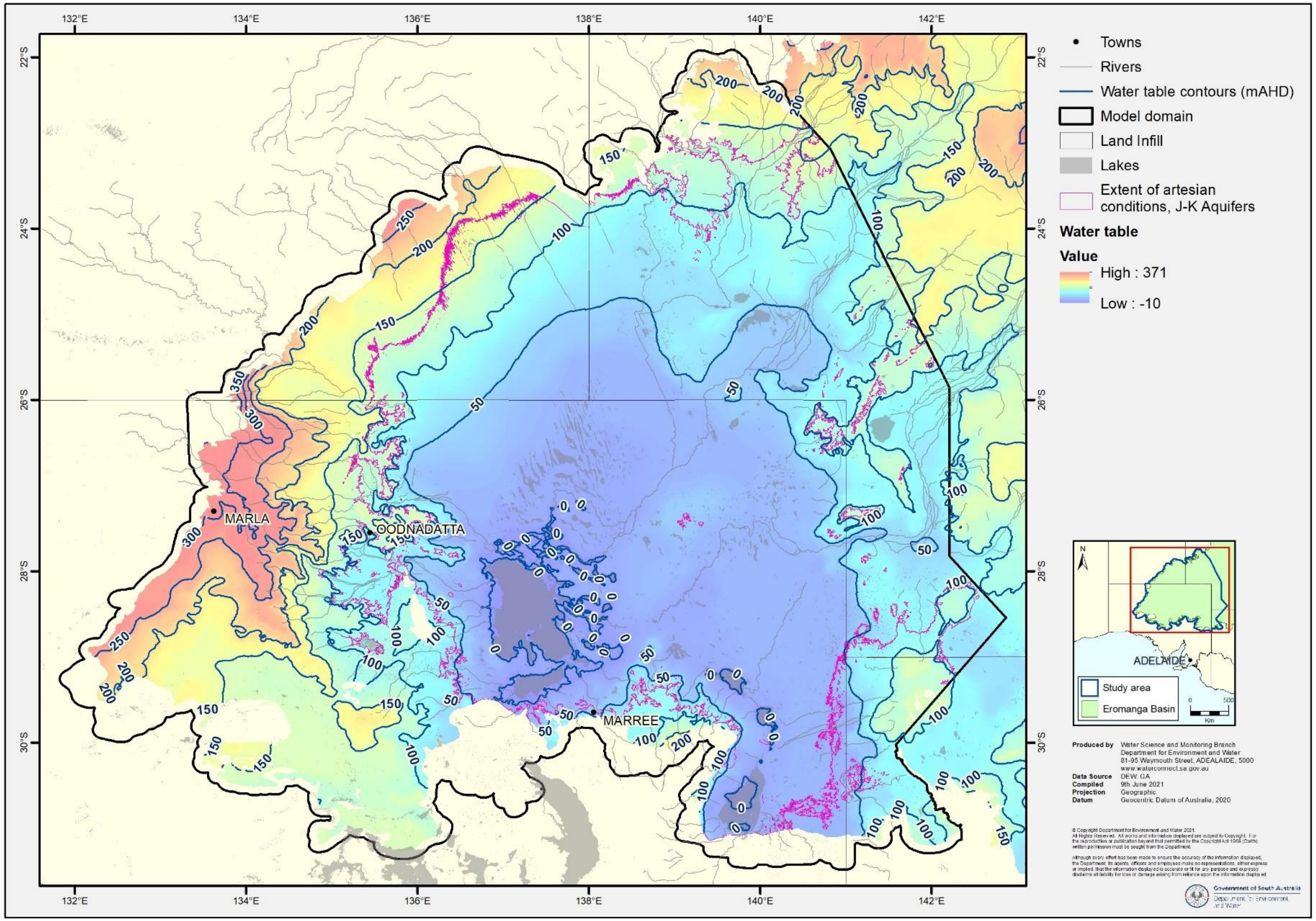

Figure 5.3: Phreatic surface of the study area

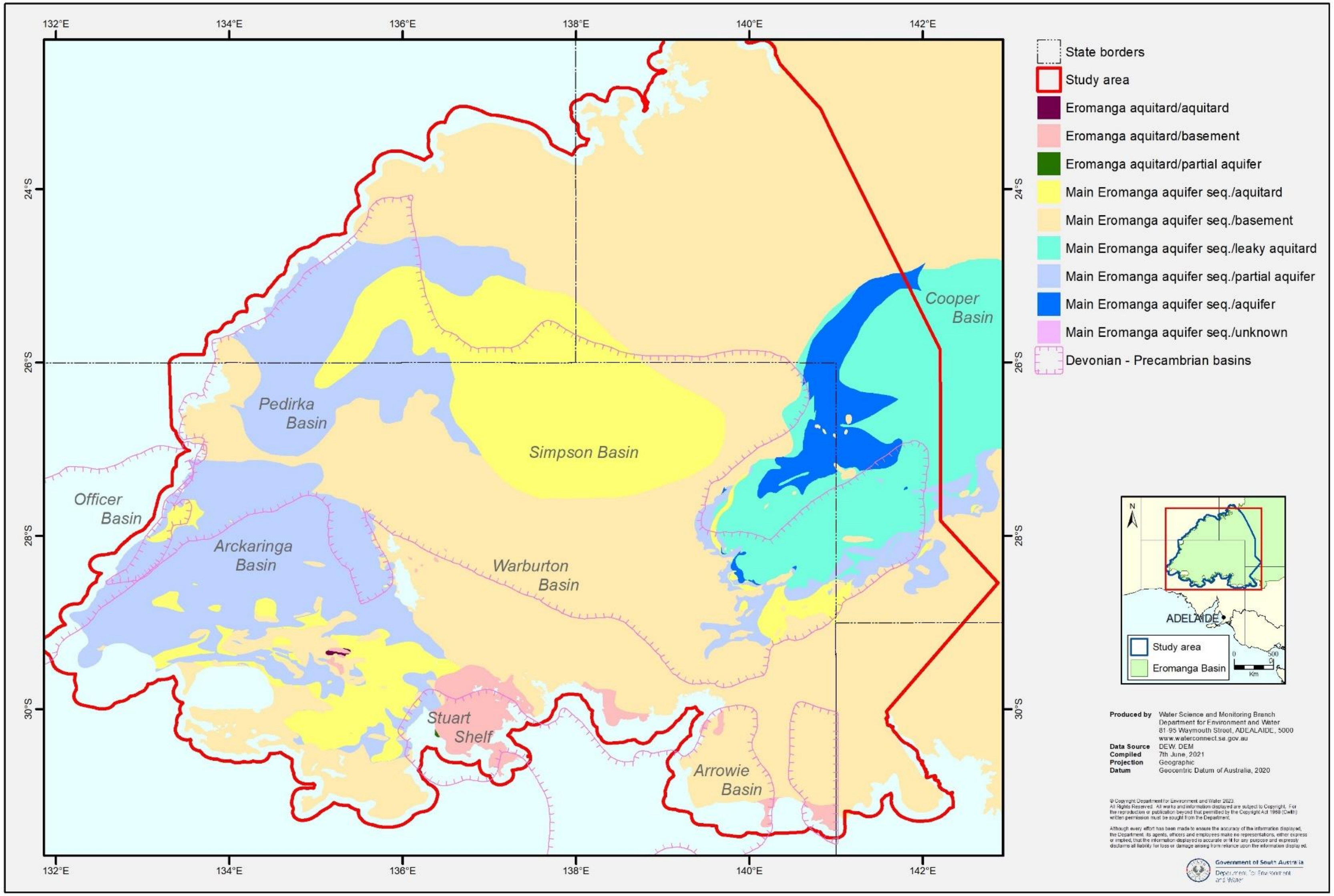

Figure 5.4: Hydrogeological connectivity between GAB aquifer and underlying basins.

5.2.2.2 Arckaringa Basin

Ransley and Smerdon (2012) described the hydrogeological units of the Arckaringa Basin in contact with the J-K aquifer equivalent units as either 'Aquifers or 'Partial aquifers', particularly noting coarser grained sedimentary rocks in the Mt Toondina and Boorthanna Formations (Figure 4.3, Figure 5.4). In support of the notion of inter-aquifer connectivity, Keppel et al. (2015b) presented seismic and logging evidence for a lithological connection between sandier units of the J-K aquifer and the Mount Toondina Formation in the Boorthanna Trough region, particularly where paleochannels are present at the unconformity between the two aquifers. Such paleochannels may crosscut several intra-formational strata, thus increasing the likelihood of connectivity between aquifer units of the J-K aquifer and underlying strata. Figure 5.5A, which was first presented in Keppel et al. (2015b) shows a section across the northern margin of the Boorthanna Trough. Large channels incised into the Permian succession are filled with chaotic, semi-transparent seismic facies identical to that of the Algebuckina Sandstone. Underlying the paleochannel is a fault displacing pre-Permo-Carboniferous strata.

The Stuart Range Formation is an important confining unit present within the Arckaringa Basin, potentially limiting connectivity between aquifers in the underlying Boorthanna Formation and the overlying Mt Toondina Formation and the J-K aquifer where the Mt Toondina Formation is absent (Figure 5.4). Aquaterra REM (2005) and SKM (2009) infer that the Stuart Range Formation acts as an effective barrier to downward leakage. Pumping test data presented in SKM (2009) and Lyons and Hulme (2010) highlight the limited connectivity between Boorthanna and unconfined aquifers in the Eromanga Basin. In support of this notion, Kleinig et al. (2015) suggests a very low value for the vertical hydraulic conductivity (*Kv*) of the Stuart Range Formation.

Kellett et al. (1999) and Belperio (2005) described the Stuart Range Formation as a leaky aquitard that separates the GAB and Boorthanna Formation aquifers. Further, Priestley et al. (2017b) used density corrected hydraulic head data and several isotopic tracers to provide hydrochemical evidence for inter-aquifer leakage into the J-K aquifers through the Stuart Range Formation. However, Priestley et al. (2017b) did not have sufficient evidence to identify the cause of leakage conclusively, only noting that aquitard thinning or focussed leakage surrounding fault zones as possible explanations.

Finally, SKM (2009), Aquaterra (2009) suggest that the Stuart Range Formation potentially provides sufficient leakage to enable drawdown stability in groundwater production wells located in the underlying Boorthanna Formation. Evidence for this comes from the way in which water levels stabilise and recover after anomalous pumping rates from the Boorthanna Formation (OZ Minerals, 2018). While SKM (2009) and Aquaterra (2009) interpretations are not directly related to the GAB, leakage from the Stuart Range Formation into aquifers with either natural or induced lower pressures as indicated by groundwater monitoring works (OZ Minerals, 2018) has relevance. Additionally, Purczel (2015) used numerical modelling to describe a conceptualisation of lateral regional inflow to and outflow from the Arckaringa Basin aquifers through the J-K aquifer and basement, although the model constructed was deliberately simplistic and considered first order.

5.2.2.3 Cooper Basin Region

Much of the oil and gas produced from the Cooper Basin region comes from reservoir rocks found in Eromanga Basin strata, with Cooper Basin strata acting as source rock (Figure 4.3). In particular, the same porosity and permeability characteristics that make aquifers within the Main Eromanga Aquifer Sequence good aquifers also translate to reservoir rock characteristics. Cross-formational flow between Cooper Basin strata and the overlying Eromanga Basin is recognised as an important mechanism to explain variations in hydrocarbon prospectively (Youngs, 1971) and trap formation for petroleum hydrocarbons (Moriarty and Williams, 1986; Schulz Rohjan, 1993). Further, groundwater flushing of underlying Cooper Basin source rock due to connectivity with groundwater within the Eromanga Basin aquifers has also been interpreted (Altmann and Gordon, 2004; Dubsky and McPhail 2001; Youngs, 1971). Connectivity may be lithologically controlled or due to structural deformation. Kellett et al., (2012) suggested that the best developed connectivity between the Eromanga and Cooper Basin aquifer units occurs along the northern margin of the Cooper Basin, near the SA and QLD border (Figure 5.4).

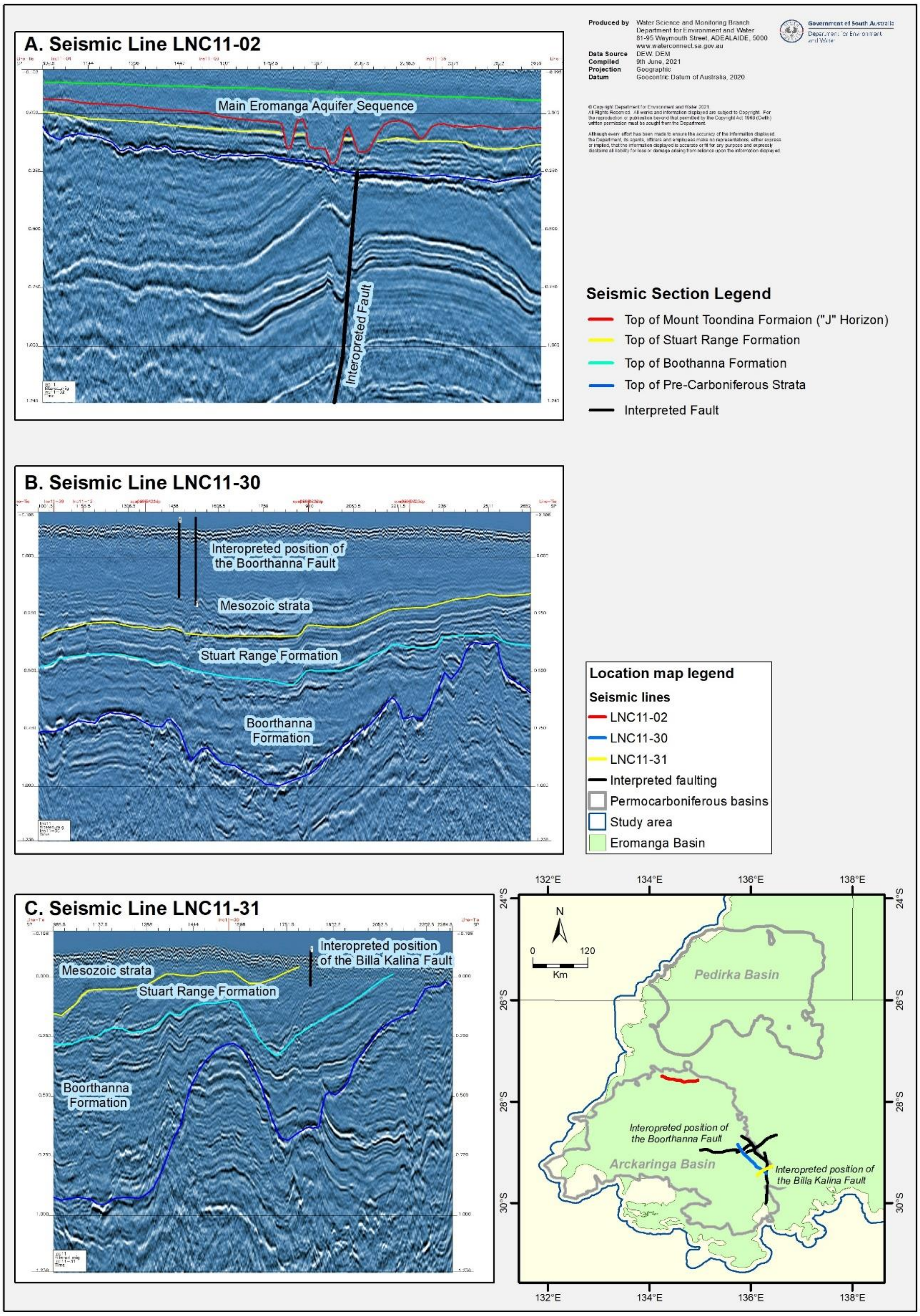

Figure 5.5: Selected seismic lines from within the study area. One shot point is approximately 30 metres. A) Section across the northern margin of the Boorthanna Trough. B) and C) Interpreted seismic reflection section across the previously interpreted positions of the Boorthanna and Billa Kalina Faults)

More broadly, Bentley et al. (1986) suggested that the discrepancy between $^{36}Cl/Cl$ derived ages and those derived from modelling found in a portion of southwestern QLD could be explained by upward leakage of saline groundwater into aquifers of the GAB hydrogeological super-basin where an underlying confining unit was absent.

5.2.2.4 *Stuart Shelf*

An important non-GAB group of groundwater flow systems within the study area are those within fractured rock and limestone aquifers in the Stuart Shelf region, Western Arrowie Basin (Figure 5.4). These are largely found underneath aquitard units of the Rolling Downs Group (Bulldog Shale, Table 4.1 and Figure 5.4). Aquifer units of particular interest include the Andamooka Limestone, and the underlying Tent Hill Formation, which includes the Arcoona Quartzite, Yarloo Shale, and Corraberra Sandstone. These aquifers are the most well known in the Stuart Shelf and are the subject of several studies (for example, Broken Hill Pty (BHP) 2009a; BHP 2009b; Kellett et al. 1999). Other aquifers noted in the region include the Pandurra Formation and the Nucaleena Formation (basal conglomerate). The Tregolana Shale is a noted aquitard (BHP 2009a).

BHP (2011) and Kellett et al. (1999) described Stuart Shelf aquifers as part of a low flow, localised flow system that has short flow lines and that have total flows of less than 4 ML/d. With respect to generalised regional scale flow, BHP (2009a) described an east and north-east flow path towards northern Lake Torrens. The groundwater gradient within the Stuart Shelf section of this region was approximately 7×10^{-4}. BHP (2009a), Kellett et al. (1999), Howe et al. (2008) and Lyons and Hulme (2010) all suggest that there is a lateral connectivity between the Stuart Shelf and aquifers in the south-eastern corner of the Arckaringa Basin. A groundwater-divide between the J-K aquifer to the north and east and the Stuart Shelf aquifers concomitant with the GAB spring line has been conceptualised by BHP (2011), thus separating the two groundwater-systems.

5.2.2.5 *Early Paleozoic Basins*

The hydrogeological relationships between the Main Eromanga Aquifer Sequence and strata within the Warburton, Officer and Arrowie Basins is less clear because appropriate hydrogeological information is lacking (Figure 4.3, Figure 5.4). Our understanding of the hydrogeology of the Warburton Basin, which underlies a large portion of the Main Eromanga Aquifer Sequence in the central and eastern portion of the Far North Prescribed Wells Area (FNPWA), is poor (Figure 5.4). Likewise, although fractured rock aquifers occur in the Precambrian basement units, most of this information comes from areas where these units occur at shallow depth. Our understanding of the hydrogeological properties of these basement units at depth where they underlie the Main Eromanga Aquifer Sequence is also poor.

5.2.3 Inter-aquifer connectivity and faulting

Faulting provides an important form of inter-aquifer connectivity, as it can locally negate the confining characteristics of aquitards or enhance aquifer characteristics. However, faulting can produce heterogeneous groundwater flow characteristics and it can be difficult interpreting their impact on inter-aquifer connectivity. Faulting may either increase or decrease permeability and effective porosity, or can do both within the same fault zone, for example diminishing lateral groundwater flow across fault zones but increasing flow vertically and along fault zones. Although large regional fault-zones are most likely to be where preferential flow paths and therefore inter-aquifer connectivity forms, this may not necessarily be the only instance. For example, Ransley and Smerdon (2012) noted that across the thicker and deeper parts of the GAB hydrogeological super-basin, such as within the Eromanga Basin depocenter near the Cooper Basin, polygonal faulting has deformed the confining unit of the Eromanga Basin and could provide a means for vertical upward leakage into shallower strata (Figure 5.4).

Chapter 7 provides further discussion concerning the impact of faulting on hydrogeology considered for this study. Faults mapped during structure-surface interpretation are presented in Figure 4.1.

6 Model layer discretization and development

This chapter describes how our hydrostratigraphic conceptualisation was adapted during model layer construction and how the top and bottom surfaces used to define these model layers were developed.

The model layer structure was based on:

- a simplified, but robust, representation of the essential hydrostratigraphic units described in Chapter 4
- a description of the vertical resolution required to simulate the important hydrogeological processes identified and described during this study (for example, recharge, discharge and through-flow).

Model layer surfaces and isopachs describing hydrostratigraphic units within the Eromanga Basin in SA, the NT, south-west QLD and north-west NSW were generated based on a compilation of data for input into the numerical groundwater model. Data sources included:

- water well, mineral exploration and petroleum drilling records
- seismic data
- Updated and integrated existing structure surfaces including the previously interpreted 'C' Horizon (top of Cadna-owie Formation and lateral equivalents) by Sampson et al. (2013), the Hydrogeological Atlas of the Great Artesian Basin (Ransley et al., 2015) and numerous local, tenement scale structure surfaces sourced from the petroleum industry.

6.1 Choice of hydrostratigaphic layers

The stratigraphic formations and members were grouped into six hydrostratigraphic layers, based on relative hydrogeological connectivity, mapping resolution and importance with respect to extraction of groundwater (Figure 6.1, Figure 6.2 and Figure 6.3; Table 6.1). Layers were generated for the tops of the Cadna-owie Formation ('C' Horizon), Murta Formation ('Dm' Horizon), McKinlay Member (McKinlay Horizon), Namur Sandstone ('Dn' Horizon), Hutton Sandstone ('H' Horizon), and the base of the Poolowanna Formation or top of the Pre-Jurassic basement strata ('J' Horizon). Alternative names in parentheses were developed during seismic interpretation works to denote seismic reflector horizons. A seventh structure surface was developed, the McKinlay Member, but this was later integrated into the Murta Formation.

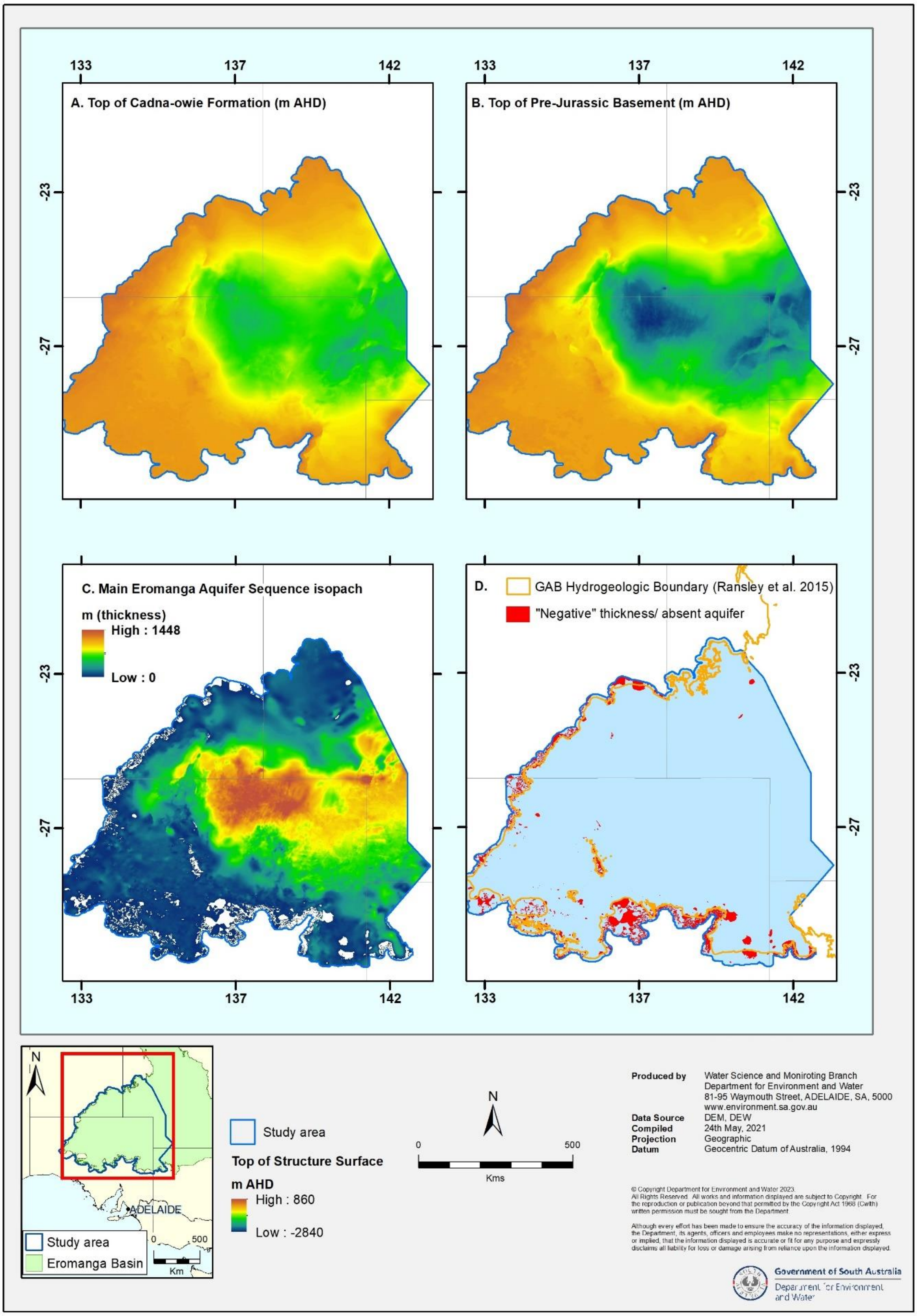

Figure 6.1: Intra-aquifer structure surfaces developed for study area. A) Top of the Cadna owie Formation (layer 1). B) Top of the Pre-Jurassic Basement (layer 6). C) Isopach of the Main Eromanga Aquifer Sequence. D) Structure surface quality control data indicating where a “negative” thickness exists, indicative of an absence of Main Eromanga Aquifer Sequence strata.

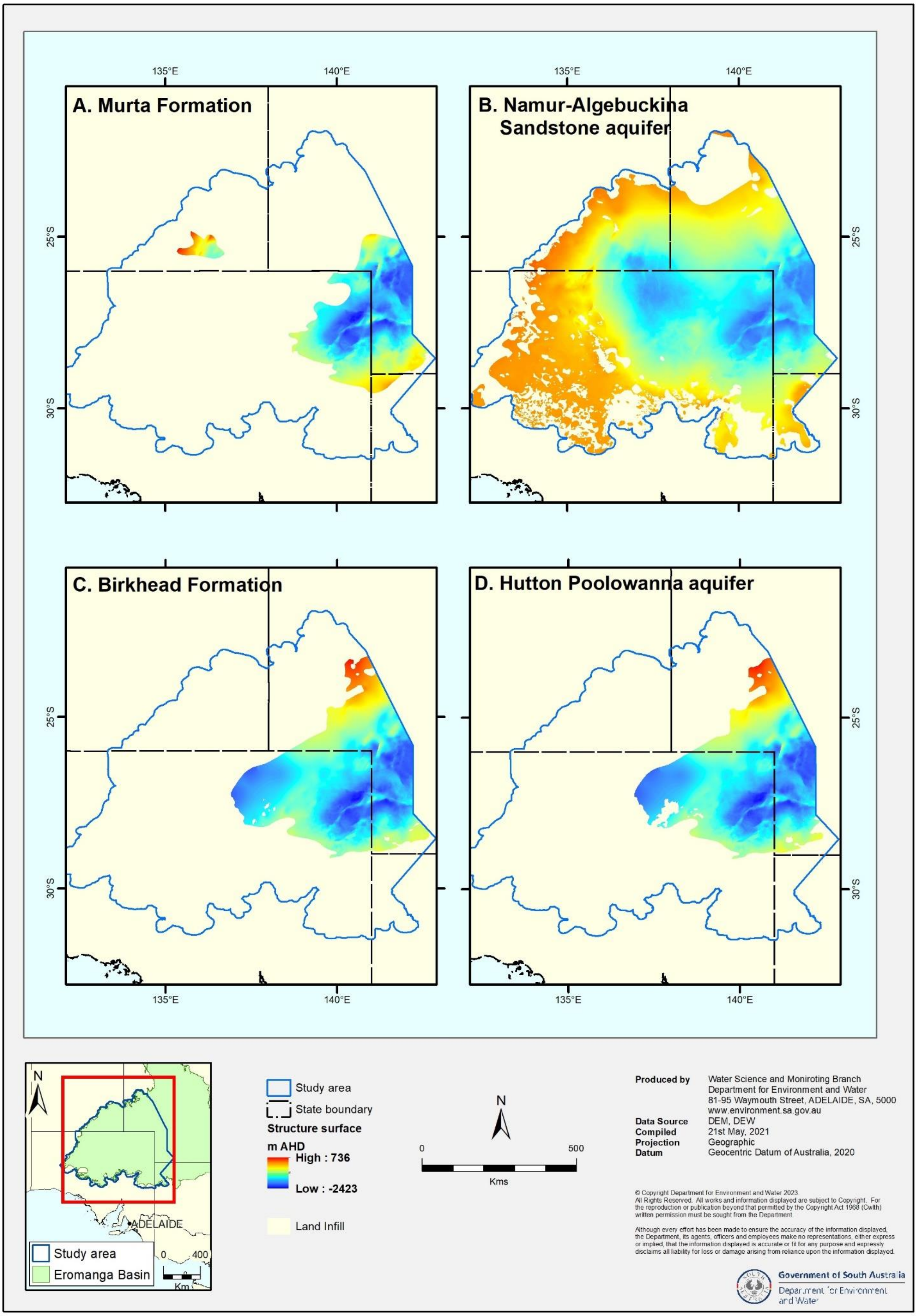

Figure 6.2: Intra-aquifer structure surfaces developed for study area (sub-regional aquifers and aquitards).

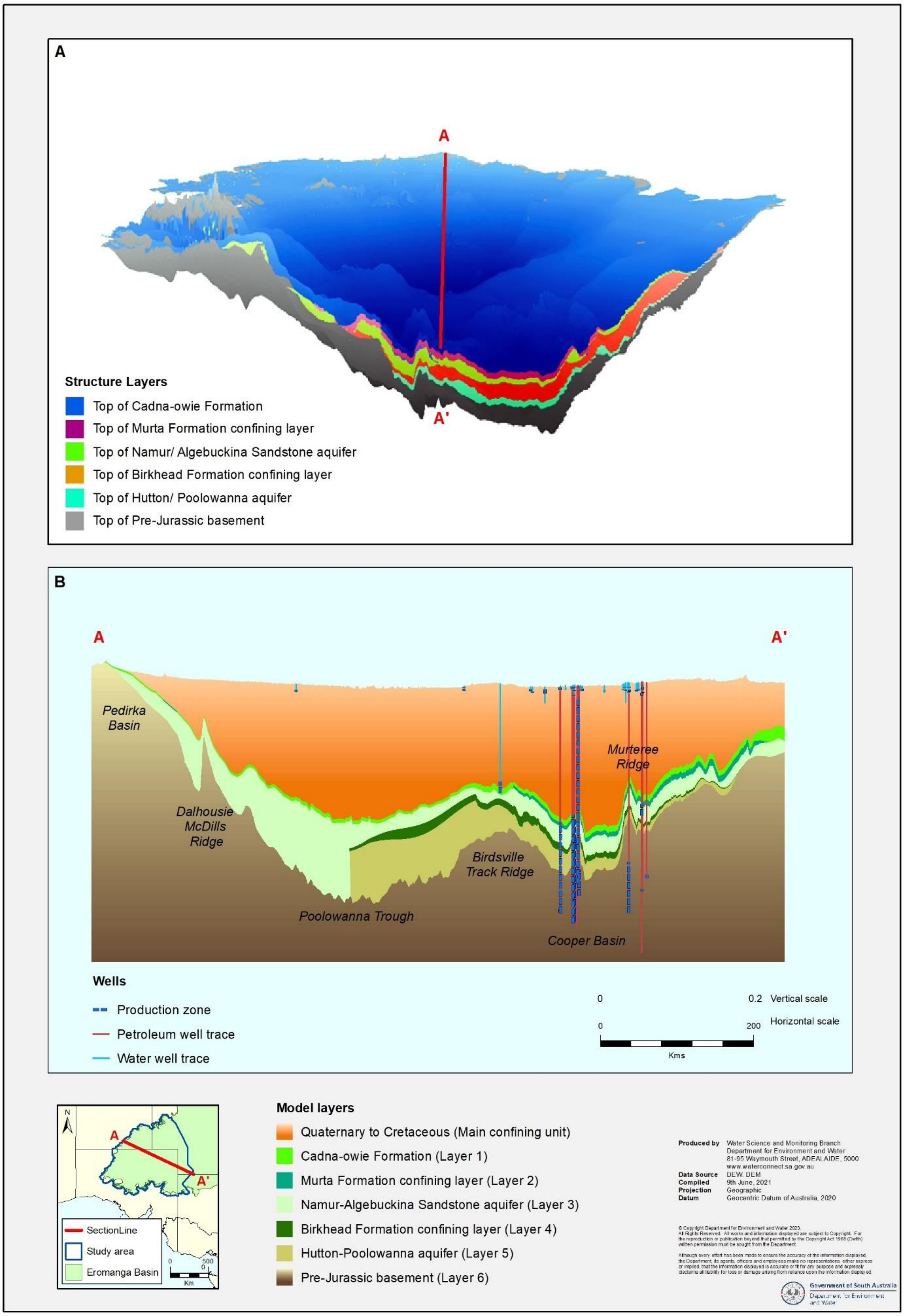

Figure 6.3: A) 3D projection of structure surface used in numerical model. B) Cross-section through study area showing model layers and key structures.

Table 6.1: Summary of hydrostratigraphic unit nomenclature and relationship to model layer design

Collective term	Western study area					Cooper Basin Region study area					Whole of study area	
	Stratigraphic unit	Hydrostratigraphic Unit	Model layer name	Hydrogeological characteristic	Qualitative permeability	Stratigraphic unit	Hydrostratigraphic unit	Model layer name	Hydrogeological characteristic	Qualitative permeability	[a]Max. thick. (m)	[a]Ave. thick. (m)
Main confining units	**Rolling Downs Group**	**Main confining unit**		**Confining unit**	**Low**	**Rolling Downs Group**	**Main confining units**		**Confining unit**	**Low**	NA	NA
'C' Horizon												
Main Eromanga Aquifer Sequence	Cadna-owie Formation (and lateral equivalents)	J-K aquifer	Cadna-owie Formation (layer 1)	Partial aquifer/aquifer	Medium	Cadna-owie Formation	Intra-sequence confining unit	Cadna-owie Formation (Layer 1)	Leaky aquitard	Low	689[b]	42
	Algebuckina Sandstone		Namur–Algebuckina Sandstone aquifer, (layer 3)	Aquifer	High	Murta Formation and McKinlay Member	Intra-sequence confining unit	Murta Formation confining unit (Layer 2)	Low permeability confining unit. McKinlay Member included initially as conservative option; however, an alternative conceptualisation to include within Layer 3 is an option	Low	122	49
						Adori Sandstone, Westbourne Formation, Namur Sandstone	J-K aquifer	Namur–Algebuckina Sandstone aquifer (Layer 3)	Aquifer	High	1259	211
						Birkhead Formation	Intra-sequence confining unit	Birkhead Formation confining unit (Layer 4)	Low permeability confining unit	Low	225	72
						Hutton Sandstone and Poolowanna Formation	Hutton–Poolowanna aquifer	Hutton–Poolowanna aquifer (Layer 5)	Aquifer	Medium	855	256
'J' Horizon												
Basement	Pre-Jurassic	Basement	Pre-Jurassic Basement (layer 6)	Partial aquifer. A designated thickness specified below layer 3 with variable boundary conditions to allow for broad upward or downward leakage. Base of layer 6 is a no-flow boundary	Variable	Pre-Jurassic	Basement	Pre-Jurassic Basement (layer 6)	A designated thickness specified below layer 5 with variable boundary conditions to allow for broad upward or downward leakage. Base of layer 6 is a no flow boundary	Variable	NA	User defined

Note: Table shading reflects hydrogeological properties of model layers. [a] Depths based off isopach interpolation. [b] Maximum thickness was interpolated in close vicinity to a mapped fault but cannot be confirmed. Confirmed thickness of 357 m based off intersection found in Well Unit no. 684200195.

The model layers comprise the following broad sequences (Figure 6.3):

- one partial aquifer sequence that extends across the entire study area (Cadna-owie Formation)
- an intra-aquifer confining unit in the Cooper Basin region and parts of the Pedirka Basin region (Murta Formation)
- a major aquifer sequence that extends across most of the study area (Namur–Algebuckina Sandstone aquifer).
- a deeper intra-aquifer confining unit limited to the Cooper Basin region (Birkhead Formation)
- one deep aquifer unit limited to the Cooper Basin region (Hutton–Poolowanna Aquifer)
- an extensive basement unit with variable hydrological characteristics.

To allow for a more complex representation of hydrogeological relationships, a 'basement' unit representative of Pre-Jurassic strata is included in the model design as layer 6. The basement unit has a designated thickness and is modelled with variable boundary conditions to allow for broad upward or downward leakage that is consistent with the spatial distribution of underlying hydrostratigraphic units as described in Chapter 4. Underlying the basement unit is a no-flow boundary.

Similarly, for the confining units above the Cadna-owie Formation (layer 1) that exhibit generally very low permeability, head-dependent flow boundaries represent zones of preferential or diffuse discharge in some areas, such as around springs and some fault zones, with no-flow conditions specified in other areas.

Figure 6.1 displays the structure surfaces used to describe the top of the Cadna-owie Formation (or the 'C-Horizon', representing the top of layer 1) and the top of Pre-Jurassic strata ('J-Horizon', representing the top of layer 6).

Notable features identified during structure surface development included several basement highs that render the J-K aquifer thin or absent. Prominent basement highs include those associated with the Benagerie Ridge, near the northern margin of the Frome Embayment and those associated with the Mount Woods and Peake and Denison Inliers (Figure 4.1; Figure 6.1). Several areas of absent aquifer were also mapped within the far western extent of the study area where Mesozoic strata is typically thin and so such absences are expected. However, difficulties in identifying stratigraphic boundaries in lithologies of similar hydraulic conductivity such as sand were noted. Where feasible, a pragmatic approach was applied to include highly conductive units in one of the aquifer-model layers, unless such units were logged otherwise. Similarly, many areas where the Namur–Algebuckina Sandstone aquifer was mapped as absent were identified within the far west of the study area. This was expected as available logging only occasionally discriminated between the Cadna-owie Formation and the Algebuckina Sandstone (Figure 6.2).

Appendix B present several cross sections describing the morphology of structure.

6.2 Layer construction

Novak (2020) (Appendix C) presents a detailed description of data sources, methodology, limitations, and lessons learned during the construction of structure surfaces used to define the model layers. The following is a summary of work undertaken.

6.2.1 Review of water wells, mineral exploration and petroleum data.

As a first step, stratigraphic and hydrostratigraphic logs were reviewed as required to ensure that the source-databases (SA Geodata, SARIG and PEPS SA) were consistent. Where stratigraphic or hydrostratigraphic logs were not available, lithology and drillers logs were identified in the databases and where possible, a hydrostratigraphic log was developed. These new hydrostratigraphic logs were developed with reference to surrounding geological logs, surface geology mapping and associated company reports. A literature review was then conducted to determine if drill-hole data existed, which had not yet been entered into the databases. These additional logs were entered into SA Geodata.

6.2.2 Review and interpretation of seismic data

Previous structure-surface interpretations by Sampson et al. (2013) and Ransley et al. (2015) were reviewed and where required, re-interpretation of formation picks from seismic data for all key structure surfaces was undertaken. Open-file and closed-file seismic data were sourced from the petroleum and mining industry. Typically, depth picks were used to allow for rapid correlation against well data. If required, time data was integrated or tied in where depth picks were not available. For this version, seismic data were reviewed for quality control purposes. Workflows were created to sequence concurrent drill hole, seismic and outcropping geology ties. Where required, validation of structure surfaces against drill-hole logs occurred for quality control purposes.

6.2.3 Outcropping-geology (J-K aquifer strata and Basement)

Surface geology mapping at 1:100,000 scale (Geological Survey of South Australia 2012) as *ArcMAP*™ shapefiles was used to identify the location of outcropping J-K aquifer strata and Pre-Jurassic Basement strata. In turn, data was used at the top of the Pre-Jurassic basement ('J' Horizon) and the top of the Cadna-owie Formation ('C' Horizon) structure-surface construction to provide a more accurate slope vector near the margins of the Eromanga Basin. Using *ArcMAP*™, polygons for the 2 broad outcrop types were selected from the surface geology shapefiles and saved into new separate shapefiles. From here, polygons were dissolved and then an internal buffer polygon with an arbitrary thickness of 500 m created. The edges of the buffer polygon file were then converted to points located every 100 m along the edge. Elevation data were then assigned to each point based on the SRTM-H 1-second DEM. Each outcropping point (either GAB aquifer or basement) was assigned a depth to formation of zero metres. These points were then used to extrapolate the structure surfaces to land surface.

6.2.4 Surface compilation issues and quality control

Draft surfaces were provided by DEM to DEW in July, October and December 2019 for validation, quality checking and subsequent correction prior to incorporation into the model. Issues included:

- There were negative isopach thicknesses, where a deeper structure surface breached a shallower surface. Validation determined whether this represented a true absence of aquifer material (that is, a fully penetrating basement high) or whether an error or lack of data was causing the algorithm employed to form a negative isopach. As basement highs can be associated with faulting or spring/groundwater-dependent ecosystem (GDE) formation, ensuring such features were properly validated was important.
- Further, occurrences of GAB springs in regions where the Main Eromanga Aquifer Sequence was validated as being absent required a conceptualisation refinement to include a 'J2' Horizon. We describe the 'J2' Horizon as the base of a regolith aquifer developed in basement rocks near the margins of the GAB hydrogeological super-basin that is in lateral connection to aquifers within the Main Eromanga Aquifer Sequence and that has similar aquifer properties.
- There were unrealistic thicknesses at the margin of some model layers. Surface margins were validated and checked if they indicated formations were unrealistically thick at the margins (that is, where the formation isopachs either did not 'pinch out', or determination of unconformity relationships with basement or 'J' Horizon were realistic).

- Some spatial extents of intra-aquifer horizons differed materially from previous interpretations. Where this occurred, validation and quality checking of data was undertaken. Such validation was often related to that undertaken for isopach thickness at the margins of structure surfaces as described above. In particular, where the extents of certain horizons indicated potential vertical connectivity between aquifer units within the study area, such occurrences have been validated.
- There were issues about interpretations of zones of high gradient. Where structure surfaces were found to have a steep gradient, evidence was sought as to whether such gradients were indicative of a fault. Typically, if no evidence of faulting could be found, continuity of the formation across the zone of steep gradient was favoured. These issues could be from one of several sources, including:
  - errors in original stratigraphic interpretation of drilling logs, listed drill hole location or elevation data
  - poor lithological or interpretive geology logs for Neocretaceous to Quaternary sequences
  - heterogeneous distribution of drilling and seismic data
  - poor quality drill-hole logging or seismic data, or a lack of data in key areas
  - Difficulties encountered while attempting to stitch previously generated structure-surface horizons together, both from the public domain and those generated privately by companies operating in the region and provided to DEM
  - inherent error found within previous structure-surface horizons.

7 Faulting

At a fundamental level, faults are important to understand with respect to hydrogeology because the deformation and displacement can materially affect the porosity and permeability of the rock and hence the potential hydraulic connectivity between juxtaposed aquifers and/or aquitards. These impacts include:

- influencing the basic configuration of the basin (Chapter 4)
- developing significant heterogeneity of hydraulic properties
- forming spring conduits and other zones of natural groundwater discharge to the surface.

Faults have the potential to affect three-dimensional groundwater flow systems by forming preferential flow pathways (via fault-parallel fracture transmissivity), and/or impermeable barriers or leaky barriers to groundwater flow (via reduced across-fault permeability), and/or providing connectivity from one aquifer to another, or limiting it, depending on juxtaposition displacements (Murray et al. 2018; McCallum et al. 2018).

This section provides a brief overview of selected research into fault systems and groundwater flow over the last 20 to 30 years, culminating in the findings of studies directly relevant to the GAB hydrogeological super-basin. In particular, this chapter includes brief summaries of relevant studies concerning appropriate methodologies for the description and conceptualisation of faulting within a hydrogeological setting (Underschultz et al. 2018) and depictions within a numerical groundwater model (McCallum et al. 2018).

It is currently not the intension to represent faulting in the model realistically given the sparsity of relevant hydrogeological information and the processing requirements needed. Rather the model may be used to investigate fault-related uncertainties where appropriate.

7.1 Faulting and groundwater flow – theory

Babiker and Gudmundsson (2004) indicate that the most likely faults and shear zones to conduct groundwater are those that have been most recently active. Gudmundsson (2000) and Babiker and Gudmundsson (2004) found that permeability increases within the fault zone greatly once a fault becomes active. This can lead to changes in the potentiometric surface-spring yield (if faulting is associated with the formation of springs), and base flow in connected streams. Activity within a fault zone achieves this by creating new fractures, as well as reopening old fractures within the fault zone, thus increasing the hydraulic conductivity of the deformed rock. Further, the current tectonic stress field imposed on strata within the study area may influence hydrodynamics. Barton et al. (1995) presented evidence that the permeability of critically stressed faults concomitant with current stress fields was much higher than in inactive faults and associated fracturing in crystalline rock. Although much of the strata within the study area may be considered more ductile, being largely composed of variably consolidated sedimentary rock, appreciation of the neotectonic-derived current stresses is still considered important.

Flow through a fault zone depends upon the structural configuration of the fault and the related aquifer/aquitard system, combined with variations in the thickness of the fault zone and the composition of the fault core (Caine et al. 1996; Celico et al. 2006; Murray et al. 2018). Bredehoeft et al. (1992) and Fairley and Hinds (2004) described how faults and the associated damage zone surrounding them can simultaneously act as barriers to lateral flow while acting as conduits to vertical flow, with this being dependent upon the relative permeability of the fault and associated damage zone in relation to the confined aquifer. Further, these fluid flow properties do not remain stable over time. Antonellini and Aydin (1994), Bense et al. (2003) and Celico et al. (2006) described how precipitation of minerals or grain-size reduction within a fault zone due to cataclasis or grain-scale mixing may lower permeability. In contrast, subsidiary structures within the damage zone of a fault may enhance permeability (Bense et al. 2003; Curewitz and Karson 1997; Goddard and Evans 1995). In this way, a fault zone with a low permeability core may develop, surrounded by a high permeability damage zone compared to the surrounding protolith, thus leading to the situations where, although inhibition of lateral flow may occur if the fault is perpendicular to the flow, vertical flow may be enhanced (Figure 7.1 from McCallum et al,. 2018 after Bense et al. 2003). Likewise, where the strike of the fault is parallel to flow, preferential enhancement of lateral flow may occur near the fault core. Consequently, examination of hydraulic head data either side of a fault plane may display large steps in head, either over short distances or over linear trends indicative of fault zone influence.

Finally, the form of deformation imparted on a protolith will depend on the nature of the protolith (that is, whether the protolith is unconsolidated or consolidated, crystalline or detrital, fine or coarse grained) and the depth of burial, which affects the pressure under which deformation occurs. Greater depths will result in more cataclastic deformation, whereas shallow depths may result in particulate flow deformation. Additionally, grain re-orientation caused by the impact of directional deformation may increase the anisotropy of permeability (Bense et al. 2003).

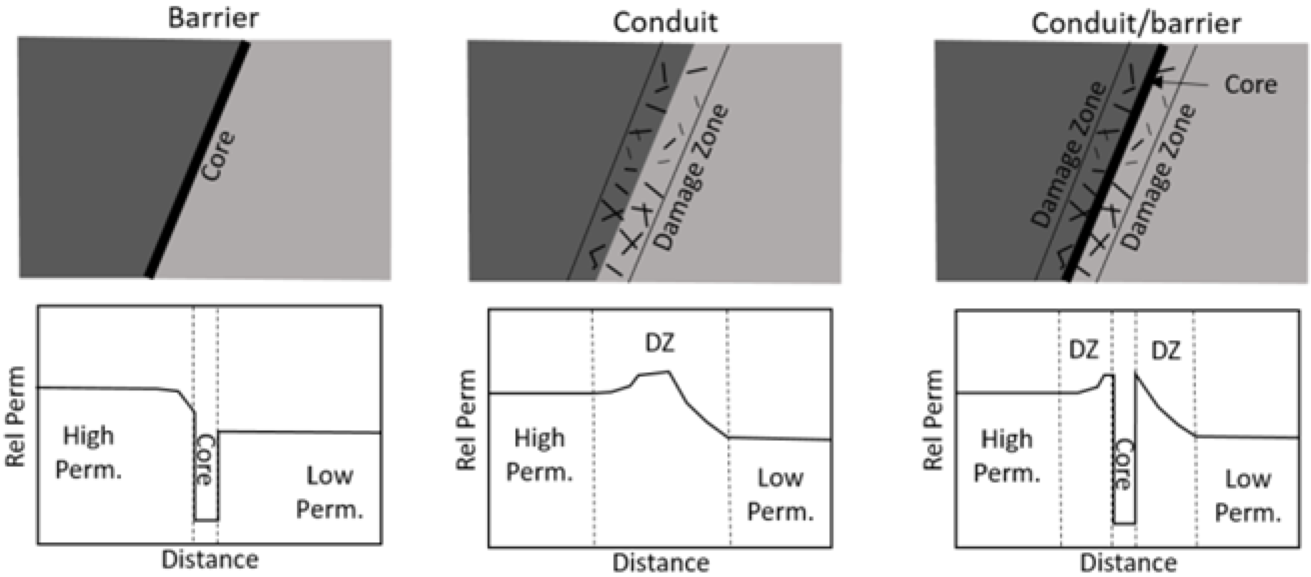

Figure 7.1: Schematic description of a fault, highlighting the fault core and damage zone and its relationship to porosity and permeability differences

7.2 Tools for modelling the influence of faulting on groundwater flow

At a macroscale, the degree of juxtaposition between aquitard and aquifer units and the rheology of deformed strata within the fault zone are fundamental characteristics of fault configuration and can be used to assess the potential for lateral groundwater flow across a fault zone. Juxtaposition analysis describes the relationship between strata either side of a fault plane. Where the facies type and lithology are known, juxtaposition analysis can quantify the degree to which disparate rock types onlap and thus describe the potential for breaks in the confining unit or the capacity for lateral cross-fault plane or vertical flow. Allan (1989) developed a diagrammatical juxtaposition quantification technique that has since been used in the petroleum exploration industry for the assessment of fault-controlled reservoir seals. Groundwater researchers are now adopting the technique as a means of determining the hydraulic properties of fault zones and planes (Underschultz et al. 2018).

Further to juxtaposition analysis, determining whether a pressure differential exists either side of a fault plane may further quantify hydraulic properties. For example, the Shale Gouge Ratio calculation can be used to estimate the proportion of fine-grained sediments from the wall rock entrained across the core of the fault (Underschultz et al. 2018). Such fine-grained sediments, described as a proportion of shale, may form a membrane seal across the fault plan, thus inhibiting lateral flow and therefore causing a fluid pressure differential either side of the fault plane to form.

Finally, the depiction of such complexity within a numerical groundwater model requires consideration. Modern modelling packages such as MODFLOW-USG have enabled the idealised numerical depiction of ever more complex faulting configurations.

For example, McCallum et al. (2018) discussed at length the use of the control volume finite difference technique within the unstructured-grid functionality of the modelling software package MOFLOW-USG for such a purpose. Further, McCallum et al. (2018) discussed how various options for depicting faulting configurations represent a trade-off between accuracy, such as the continuum approach, where fault zone thicknesses are represented with actual cells, and processing time such as employment of conductance terms to describe groundwater flow behaviour through the fault. However, the scale of faulting and the appropriateness of the evidence used to interpret the existence or otherwise of faulting needs careful consideration. This is discussed further in Chapter 8.

7.3 Faulting, groundwater flow and the wider Great Artesian Basin

Within the wider GAB, Senior and Habermehl (1980) and Radke et al. (2000) have discussed offset displacement where aquifers are juxtaposed against aquitards conceptually, while Mavromtidis (2008) and Smerdon and Ransley (2012) summarized how fault displacement affects basin configuration in the central Eromanga Basin region. These authors suggested that fault displacement of Eromanga Basin strata can range from tens to hundreds of metres. Consequently, faulting plays an important role in shaping the basin configuration as well as potentially influencing groundwater flow at a sub-regional scale However, field-based data and investigations specifically examining the influence of faulting on groundwater flow are sparse. A numerical modelling-based study by Smerdon and Turnadge (2015) examined the influence of faulting in a largely hypothetical way, which suggested that disruption of flow by faults acting as low-permeable barriers may significantly impact heads down-gradient.

Additionally, faulting and minor jointing are important mechanisms for spring conduit formation. At a regional scale, GAB springs are closely associated with the Torrens Hinge Zone and along the margins of the Adelaide Geosyncline (Karlstrom et al 2013). This association indicates that deep faults that perhaps initially formed as normal faults in the Neoproterozoic Era (Preiss 1987) are providing the basis for modern spring conduit formation. Complementary to this, several authors including Aldam and Kuang (1988), Waclawik et al. (2008), Karlstrom et al. (2013) and Keppel et al. (2020a) have summarised and presented evidence that GAB springs found within the study area may be an expression of neotectonic activity, particularly given the close spatial association between springs and seismic activity (Figure 4.1B). Further, active faulting may be required to maintain spring flow (Hancock et al. 1999), as chemical precipitation, alteration or mechanical blocking may reduce groundwater flow within the spring conduit over time. Consequently, Underschultz et al. (2018) suggests that this causal link between spring conduit formation and active faulting means that spring observation data such as discharge flux, temperature and hydrochemistry may be used to calibrate and validate the hydraulic characteristics estimated for related fault zones.

A further possibility for spring conduit formation that is not directly related to faulting is hydraulic fracturing in response to internal overpressure of fluids (Gudmundsson and Brenner 2001; Gudmundsson et al. 2002). Fluid overpressures may exacerbate any pre-existing planes of weakness, such as fractures, faults or even fissility, but also feature extensional mode ‘I’ cracks that are not necessarily conformable to an underlying stress regime. Langbein et al. (1993) and Uysal et al. (2009) also noted hydraulic fracturing is often associated with extensive brecciation. With respect to springs found within the study area, Keppel et al. (2020a) noted in a study encompassing a very limited number of spring sites that no such brecciation was observed and all mapped fractures and lineaments appeared conformable to the underlying east–west stress regime interpreted by Reynolds et al. (2006), Hillis et al. (1998) and Hillis and Reynolds (2000). This led to the conclusions that the formation of springs included in the study were more likely directly related to neotectonic deformation. Consequently, while the possibility remains for spring formation via hydraulic fracturing, assessment of supportive evidence is required before such an interpretation can be made.

Whilst it has been stated that it is currently not the intension to represent faulting in the model realistically, the potential for faulting to influence regional scale groundwater flow and to heavily influence the location of springs is recognised. With respect to spring formation, as the model is not explicitly depicting strata above the Main Eromanga Aquifer Sequence, the requirement to depict explicitly groundwater movement through fault-related spring conduits developed in these horizons has been removed. Consequently, spring depiction will be initially undertaken simply as a means of replicating discharge from the system.

8 Data gaps and recommendations

Through the processes of data compilation, analysis and literature review, several critical data gaps were made apparent, both with respect to raw data as well as conceptual understanding of the basin configuration, hydrostratigraphy and relevant structural geology. The following section provides a discussion of the data gaps considered important with respect to the development of a conceptual hydrogeological model and ultimately the numerical model construction.

8.1 Formation heterogeneity and lithology-based conceptualisation

Model development aims to capture the key hydrostratigraphic variability found within the Main Eromanga Aquifer Sequence, by separating and modelling the main intra-sequence units found in the Cooper Basin region. However, there are other areas and sources of aquifer heterogeneity that may not be captured sufficiently to describe within a modelling context at this time. This heterogeneity is largely related to lithological variability found within individual stratigraphic formations.

Stratigraphic interpretation has commonly been used for hydrogeological description and numerical model construction for the GAB hydrogeological super-basin, largely because, at a regional scale, the GAB aquifers have been interpreted to be sufficiently homogenous for this to be considered representative. However, heterogeneity related to either lithological or post-deposition diagenesis within the Main Eromanga Aquifer Sequence has been recognised previously such as by Radke et al. (2000) and Kellett et al. (2012) describing the Cadna-owie Formation as a confining unit near the Cooper Basin region, as distinct from its usual classification as an aquifer.

The issue of intra-formational heterogeneity may be of relevance in places where overlying or underlying units may share hydrogeological characteristics like the Main Eromanga Aquifer Sequence and thereby increase the extent of the aquifer beyond its stratigraphic constraints. For example, Permian sequences, such as those found in the Mount Toondina Formation or Purni Formation (Table 4.1) may have quite variable lithologies indicative of a heterogeneous depositional energy environment, including coarser grained sequences. Examples of where this may occur are discussed in Chapter 5.

The apparent variability of lithology and diagenetic history within stratigraphic sequences within the study area contrasts with historical assumptions regarding the use of stratigraphy as a means of describing hydrogeological homogeneity. Such variability is more apparent within Permian units underlying the Eromanga Basin, as well as basin margin areas where depositional energy predominantly favoured coarser grained sediments. The impact of shifting the modelling focus to capturing lithological variability in such areas, as opposed to a stratigraphic-based discretisation and then assigning hydraulic properties has not been tested. Consequently, there is scope for small-scale uncertainty analysis testing of this alternative conceptualisation or using a 2-dimensional model first to assess the potential impact this may have on the determination of aquifer scale, groundwater volumes and the interpretation of groundwater flow systems.

8.1.1 Mapping lithological heterogeneity

The possible deficiency of stratigraphic-based vertical discretization to fully capture material variations in lithology and post-depositional diagenesis may fail to sufficiently represent the permeability. This may lead to misrepresentation of hydraulic parameterization in model design and construction and therefore the hydrodynamics and storage of the hydrogeological system being represented. A method for potentially improving how such hydraulic heterogeneity can be mapped and incorporated into modelling was detailed by Herckenrath et al. (2015) and Schoning and Herckenrath (2017). In these studies, the permeability of the study area covering a large portion of the Surat Basin in QLD (Figure 4.1A) was explicitly interpreted using lithological logging, petrophysical, drill stem test (DST), as well as core and pumping test data. Specifically, petrophysical logs, DST, and other data were used to estimate and constrain initial input permeabilities and other stochastic parameters per lithofacies unit within each stratigraphic formation depicted within several groundwater flow models called 'numerical permeameters.'

These smaller models were then used to extrapolate these small-scale permeability determinations into stochastic distributions of permeability within a stochastic discretization of lithology at a regional scale for input into a regional-scale model.

While this method has enormous potential to improve the accuracy and precision with which vertical discretization within a study area is achieved, we note that this method is still potentially subject to the same concerns with respect to the heterogeneous distribution of available data across the study area, as well as the quality of data. Data required for such an analysis are likely to be currently restricted to several specific areas. Most notably in SA, these restricted areas coincide with petroleum hydrocarbon exploration and extraction. Beyond this relatively confined area, the availability of similar data sets is sparse. In the study presented by Herckenrath et al (2015), most relevant data was sourced from a confined area within the central and southern parts of the study area and appear to be confined by geology central to coal and petroleum hydrocarbon exploration and development. Further, lithology logging data used to develop stochastic distributions of lithofacies and to allow extrapolation of small-scale permeability test data may be of poor or coarse quality and consequently any extrapolated permeability estimation may be still misapplied. In the absence of a more comprehensive review, such a methodology may be best employed in specific areas within the current study area where its application may be undertaken with a reasonable degree of confidence and where the resultant extrapolations realistically depict permeability.

Further, such analysis requires specialised software and user knowledge to allow its application to occur in an efficient and cost-effective manner (see for example, Schoning and Herckenrath 2017). The technology and expertise are currently available within research and the petrochemical industries but is currently not directly available to DEW.

Nevertheless, the importance of the Cooper Basin region as a focus for groundwater impact assessment makes such methodologies worthy of future consideration once initial model construction is complete and potential improvements to the vertical discretization in model construction can be more readily identified.

8.2 Other aquifers

One of the largest gaps in knowledge concerns the Neocretaceous portion of the Eromanga Basin and Tertiary (Paleogene to Neogene) basin aquifers, as well as known aquifer systems underlying the Main Eromanga Aquifer Sequence. With respect to aquifers in the Neocretaceous portion of the Eromanga Basin and the Tertiary basin aquifers, these units have not received as much research attention in SA as those within the Main Eromanga Aquifer Sequence. This is despite these aquifers having the following characteristics:

- a large number of operational wells in these basins and associated aquifers, currently thought to be in the hundreds
- known use of supplies of groundwater for potable to industrial purposes, both in SA and QLD (se for example, Golder Associates 2015)
- growing evidence for the reliance of spring environments on groundwater from these aquifers
- long-term recognition of the potential affects that saline groundwater found in these aquifers may have, including leakage into the aquifers found within the J-K aquifer resulting from a loss of pressure due to extraction
- hydrochemical evidence suggesting artesian groundwater discharge into shallow aquifers in a few localised instances (Costelloe et al. 2012).

Understanding the roles these upper aquifers play in the study area is important in relation to fully appreciating the hydrodynamics of the region. Assumptions regarding the discharge of groundwater from the J-K aquifer, particularly in areas away from the margins of the GAB hydrogeological super-basin, necessitate consideration of some form of interaction with these units. Costelloe et al. (2011) and Costelloe et al. (2015) suggested this when discussing the disparity between the eastern and western J-K aquifer, using remotely estimated evaporative discharge rates from basin margin areas.

Central to this task is obtaining a better idea of the basinal structure, hydraulic relationships, and consequently the hydrostratigraphic characteristics of the larger shallow aquifers. As described in Golder Associates (2015), some hydraulic connectivity is likely between aquifers in the Quaternary, Tertiary and Neocretaceous Eromanga aquifers, although the exact nature of this connectivity remains unknown. Prior to mapping of these stratigraphic units, a review of existing logging as found in SA Geodata and PEPS SA, geophysical logging and other data and isopach mapping completed by Sampson et al. (2013) and Ransley et al. (2015) is recommended.

Similarly, we anticipate the role of underlying aquifers, particularly stratigraphic units currently described as partial aquifers found in Permian basins, to be important. Data concerning the hydraulic properties and in some cases structure of these basins is still somewhat limited. Typically, most data concerning structure was collected where hydrocarbon exploration has been undertaken. Further, detailed hydrogeological information has been obtained from localised areas, most notably near the Prominent Hill mine within the south-eastern Arckaringa Basin. Central to issues concerning the extent of Permo-Carboniferous strata within these basins is correct interpretation and identification in logging.

8.3 Faulting

As discussed in Chapter 7, the presence of faults or low permeability structural features can control groundwater flow conditions, at least on a local scale. As shown by Smerdon et al. (2012) and Smerdon and Turnadge (2015), the development of potentiometric surfaces for GAB hydrogeological super-basin aquifers assumes that 1) faults act as barriers to continuous groundwater flow, and that 2) groundwater flow that is continuous across faults could impact localised potentiometric surface elevation by ±50 m.

The first potential issue to overcome concerning the depiction of faulting in a numerical groundwater model is determining if there is sufficient evidence for the existence of a fault. The most common methodology to map faulting at a basin-wide scale is seismic geophysics. Using such data, Sampson et al. (2013) and Keppel et al. (2015b) illustrated that many historically mapped faults are merely steeply dipping strata rather than the aquifer being juxtaposed against low permeability units as modelled by Smerdon et al. (2012) and Smerdon and Turnadge (2015) (Figure 5.5). However, the scale at which such methods are applied and the depths targeted may render such surveys inappropriate for smaller-scale faulting (Dee et al. 2007). For example, fault-interpretation work under specific spring vents in the Neales River and Lake Blanche regions presented by Keppel et al. (2015a) and Keppel et al. (2016) suggested the scale of movement along the fault structure directly related to spring formation is small compared to regional structures to which such springs may be related.

Further, the presence of springs, although sufficient to determine the likely mechanical deformation of underlying strata and vertical migration of groundwater, may be insufficient to infer other groundwater flow impacts, such as the juxtaposition of aquifer and aquitard horizons or the development of barriers to lateral flow. This might be the case in the previously described Boorthanna and Billa Kalina faults. The Billa Kalina and Francis Swamp springs are located near these faults and are therefore indicative of tectonic deformation despite a lack of evidence in seismic geophysics data (Figure 5.5B and Figure 5.5C). The hydraulic effects of such localised deformation and their relationship to springs and surrounding undeformed strata requires an appropriate scaled mapping technique and a concomitant numerical groundwater model for adequate depiction. In other words, such localised fault-related hydraulics are unlikely to be adequately replicated in a regional scale model, nor indeed is it necessary to, for the purpose of best practice regional assessment (Barnett et al. 2012).

With respect to groundwater conceptualisation, a few important tenets were applied to judge the potential impact of faulting on groundwater flow and to representing causal impact pathways (Mallants et al, 2018) in a numerical model, including:

(1) Is there sufficient evidence to determine the existence of a fault?

(2) What evidence is there to suggest the fault is having a material impact on groundwater flow?

(3) Is this impact important to replicate in a regional numerical model?

Other impacts such as the development of significant hydraulic heterogeneity may require more thorough discretisation and numerical representation within the study area. However, sufficiently representative approximation of the hydraulic properties of a fault zone requires data that may be unavailable. This data gap may be at least partially addressed during modelling using uncertainty analysis, although the limitations of such an approach should be made clear if used.

9 Closing remarks, modelling assumptions and conclusions

9.1 Topography and surface drainage

The topography of the study area is typically very flat (Figure 2.1). Topographic variation is largely derived by the rivers and creek-lines that typically drain toward the center of the study area and towards one of the large playa lakes. The largest of these lakes is Kati Thanda–Lake Eyre at approximately 9,500 km^2. Kati Thanda–Lake Eyre is also the lowest point topographically within Australia, below sea level at approximately −15 m AHD.

The study area is largely bordered by highlands and plateaus. The more prominent highlands include the Northern Flinders, Wiloran and the Gawler Ranges on the southern margin, the Musgrave, and MacDonnell Ranges to the north-west, the Goyder and Hamilton Ranges to the north-east and the Barrier Ranges to the south-east. Within the study area, the Denison and Davenport Ranges, which are synonymous with the Precambrian, Peake and Denison Inliers, form the most prominent highland and are located to the west of Kati Thanda–Lake Eyre. Further to the west, the low escarpments of the Stuart Range mark the western margin of the Lake Eyre hydrological basin.

Rivers, creeks, and lakes in the region are ephemeral, with highly episodic, short-lived flow events driven by either heavy monsoonal rains or heavy winter rains associated with La Niña events in the Pacific Ocean.

The Great Artesian Basin (GAB) springs are the most recognised and one of the most important types of groundwater dependent ecosystem (GDE) found within the study area. The GAB springs are of great ecological, Cultural, and economic importance. GAB springs isolation within an otherwise arid environment makes them ecological 'hotspots' where endemic flora and fauna have evolved over very long periods of time. Other GDEs found within the study area are associated with riparian vegetation near rivers and creeks. Usually, these GDEs are thought to be dependent on shallow occurrences of groundwater.

9.2 Climate

The climate is predominantly hot and arid. Generally, the northern and eastern portions of the study area are hotter than the southern and western portions. Rainfall occurrence within the study area is sporadic, whereas the intensity of rainfall can vary considerably. The predominant source of rainfall within most of the study area are weak winter cold fronts, however the northern portions appear to be somewhat influenced by summer monsoonal rains. Evaporations rates are generally greater than precipitation rates, ranging between 2,000 and 3,600 mm/y, whereas rainfall is generally less than 250 mm/y for the entire study area.

Australia has been undergoing a period of long-term drying linked with changes in paleoclimate, which is likely to have affected long-term recharge rates to the GAB hydrogeological super-basin. Patterns in historical weather data indicate a general increase in temperature and rainfall across the GAB hydrogeological super-basin, although only the temperature increase is statistically meaningful. Statistically significant increases in rainfall within the study area are restricted to near Marla. Future climate change modelling indicates impacts to the GAB hydrogeological super-basin, but these are largely restricted to areas interpreted as recharge zones. The uncertainty regarding localised climate change emphasises the need for a variety of well-constrained datasets to describe paleoclimate over a variety of scales.

9.3 Stratigraphy, hydrostratigraphy and model layer construction

In SA, the Cadna-owie Formation, the Algebuckina Sandstone, and their lateral equivalents form the most important aquifers in the SA portion of the GAB hydrogeological super-basin with respect to both industry and ecology.

The Cadna-owie Formation is a relatively thin, marine and near-shore transgressional unit of inter-layered siltstone and sandstone deposited in the Cretaceous period. Although the Cadna-owie Formation is generally regarded as an aquifer through much of the study area, there are important exceptions to this interpretation. Lithological heterogeneity as well as burial-induced diagenesis may affect the classification, to the point where this unit can be an aquitard or a leaky aquitard in places. This may be particularly relevant in the Cooper Basin region.

Underlying the Cadna-owie Formation, the Algebuckina Sandstone is a relatively thicker, fine to coarse-grained sandstone, with granule and pebble conglomerates of a generally terrestrial origin. In deeper parts, such as near the Cooper Basin, the Algebuckina Sandstone may laterally grade into a few different stratigraphic units, including the Namur, Adori and Hutton sandstone units, as well as intra-aquifer confining units such as the Murta, Westbourne and Birkhead formations.

With respect to hydrostratigraphy, most of the strata lying between the top of the Cadna-owie Formation and the base of Jurassic strata has traditionally been referred to as a single aquifer unit. In this report, it is referred to as the Main Eromanga Aquifer Sequence but has been given other names previously. The historical nomenclature is regarded as an oversimplification as the Murta and Birkhead formations, and to a lesser extent the Westbourne Formation, have aquitard or leaky aquitard characteristics. Nevertheless, most hydrogeological information from the Main Eromanga Aquifer Sequence in SA and the NT comes from the Cadna-owie Formation, the Algebuckina Sandstone (or DeSouza Sandstone in the NT) and the laterally extensive Namur Sandstone and Adori Sandstone. Consequently, these units have been discussed together using a hydrostratigraphic nomenclature of the J-K aquifer. Although the name is suggestive of a singular unit, lithological variations as well as structural deformation contributing to modification of hydraulic properties and basin configuration, may have led to the development of semi-discrete sub-basinal regions with distinct hydraulic and hydrochemical characteristics. For the purposes of this study, the Hutton Sandstone and Poolowanna Formations have been described as a separate sub-basinal aquifer, separated vertically from the J-K aquifer by the Birkhead Formation confining unit.

In total, six hydrostratigraphic layers were developed. The layer surfaces were generated for the tops of the Cadna-owie Formation (‘C’ Horizon), Murta Formation (‘Dm’ Horizon), McKinlay Member (McKinlay Horizon), Namur Sandstone (‘Dn’ Horizon), Hutton Sandstone (‘H’ Horizon), and the base of the Poolowanna Formation/top of the Pre-Jurassic Basement strata (‘J’ Horizon). The McKinlay Member was integrated into the Murta Formation after surface construction was completed.

Groupings of geological formations and members into the six hydrostratigraphic layers are based on relative hydrogeological connectivity, mapping resolution and importance with respect to extraction of groundwater.

The hydrostratigraphic layers comprise the following broad sequences:

- one partial aquifer sequence that extends across the entire study area (Cadna-owie Formation)
- an intra-aquifer confining unit in the Cooper Basin region and parts of the Pedirka Basin region (Murta Formation)
- a major aquifer sequences that extends across most of the study area (Namur–Algebuckina Sandstone aquifer)
- a deeper intra-aquifer confining unit limited to the Cooper Basin region (Birkhead Formation)
- one deep aquifer unit limited to the Cooper Basin region (Hutton–Poolowanna aquifer)
- an extensive basement unit with variable hydrological characteristics.

To allow for a more complex representation of hydrogeological relationships, a unit representative of Pre-Jurassic (basement) strata is included. This unit is designed with a specified thickness and with variable boundary conditions. Head-dependent flow boundaries are designed to represent zones of preferential or diffuse discharge in the confining units above the Cadna-owie Formation that have very low permeability. Specifically, this is employed in areas around springs and some fault zones, while no-flow conditions are specified in other areas.

Within these units there may be sources of aquifer heterogeneity that are still insufficiently captured. This heterogeneity is largely related to lithological or diagenetic alteration found within individual stratigraphic formations. The issue of intra-formational heterogeneity may be relevant in places where overlying or underlying units share hydrogeological characteristics like the J-K aquifer and thereby increase the extent of the aquifer beyond its stratigraphic constraints. The apparent variability of lithology and diagenetic history within stratigraphic sequences within the study area contrasts with historical assumptions regarding the use of stratigraphy as a means of describing hydrogeological homogeneity. There is scope to use existing petrophysical, logging and other borehole data to extrapolate lithologic-based permeability across the study area using stochastic-based modelling; however, this is currently beyond the scope of this project.

9.4 Inter aquifer connectivity

Cross-formational flow between the Main Eromanga Aquifer Sequence and aquifer units within the underlying Permian basinal sedimentary rocks occurs where an effective confining unit is absent. Connectivity between these may be enhanced:

- where sandstone-filled paleochannels exist at the unconformity between the GAB and underlying Permian basinal sediments of the Mount Toondina Formation (Table 4.1), or
- where structural deformation such as faulting or jointing has either enhanced porosity or displaced different hydrostratigraphic aquifer units into contact.

Evidence for interconnectivity between the Cooper and Eromanga basins has been highlighted by the petroleum industry. Evidence for this includes migration of hydrocarbons from the Cooper Basin into overlying Eromanga Basin strata, and calcium carbonate precipitation caused by mixing of groundwater and hydrocarbon flushing from Cooper Basin strata.

Cross-formational flow can occur between the J-K aquifer and aquifer units within the overlying Cretaceous/Cenozoic basinal sedimentary rocks where an effective confining unit is absent. This is most likely to be the case in areas interpreted to be in recharge zones on the margins of the basin or within drainage channels that have eroded the confining units in the Rolling Downs Group. Similarly, connectivity may be changed where structural deformation such as faulting or jointing has either enhanced porosity or displaced different hydrostratigraphic aquifer units into contact. This may be evident in regions where fault structures have been mapped or structure-related springs occur or in regions where deformation-related secondary porosity occurs.

In the deeper parts of the Eromanga Basin where Mesozoic strata overlies either Precambrian crystalline basement or strata from the Warburton Basin, the hydrogeological relationship is currently uncertain.

Understanding the roles the upper aquifers play in the study area is important in relation to fully appreciating the hydrodynamics of the region, particularly given its location between the J-K aquifer and the surficial environment. Central to this task is obtaining a better idea of the basinal structure, hydraulic relationships, and consequently the hydrostratigraphic characteristics of the larger shallow aquifers. Similarly, it is anticipated that the role of underlying aquifers, particularly stratigraphic units currently described as partial aquifers found in Permian basins, may be important.

10 Appendices

Appendix A Elevation determination methodologies found in SAGeodata

Table 10-1: Elevation determination methodologies found in SAGeodata and explanation of confidence

Survey method description	Confidence
GPS Differential	High
GPS Multi Base Wide Area Differential	High
GPS Single Base Wide Area Differential	High
GPS Real-time Differential (nav level)	High
GPS Svy Grade- Real Time Kinematic (RTK)/Kinematic	High
GPS Survey Grade (kinematic/static)	High
GPS Survey Grade – Static	High
Surveying	Medium
Digital Elevation Model (DEM) (1s SRTM-H)*	Medium
Controlled AMG/MGA map	Low
(DISUSED) Calculated	Low
Digitised	Low
Sourced from documents (PLANS, ENV, RB etc.)	Low
Google Earth image	Low
Google Maps image	Low
Undifferentiated GPS (GPS)	Low
GPS type unknown (GPSUN)	Low
Digital image	Low
(DISUSED) Inferred	Low
(DISUSED) Map plot	Low
(DISUSED) Provisional (estimated) (PRO)	Low
(DISUSED) Unknown (UKN)	Low

Notes:

High: Generally, these methods have vertical and horizontal accuracies in the order of centimetres.

Medium: Surveyed – note that surveys are often historic (pre-2000) and of unknown quality. Generally, these methods could be expected to have vertical and horizontal accuracies in the order of tens of centimetres to metres. DEM: Vertical and horizontal error in the order of metres (<10 m).

Low: These codes reflect a range of methods that include being informed by coarse scale maps (MAP and DEM), calculated by unknown methods (CAL and INFER), low quality GPS methods (GPS and GPSUN) and unknown or provisional (UKN and PRO). Generally, these methods could be expected to have vertical and horizontal accuracies in the order of metres to tens of metres.

*Elevation sourced determined and used in preference to low confidence methods

Appendix B Selected hydrostratigraphic cross-sections through the study area

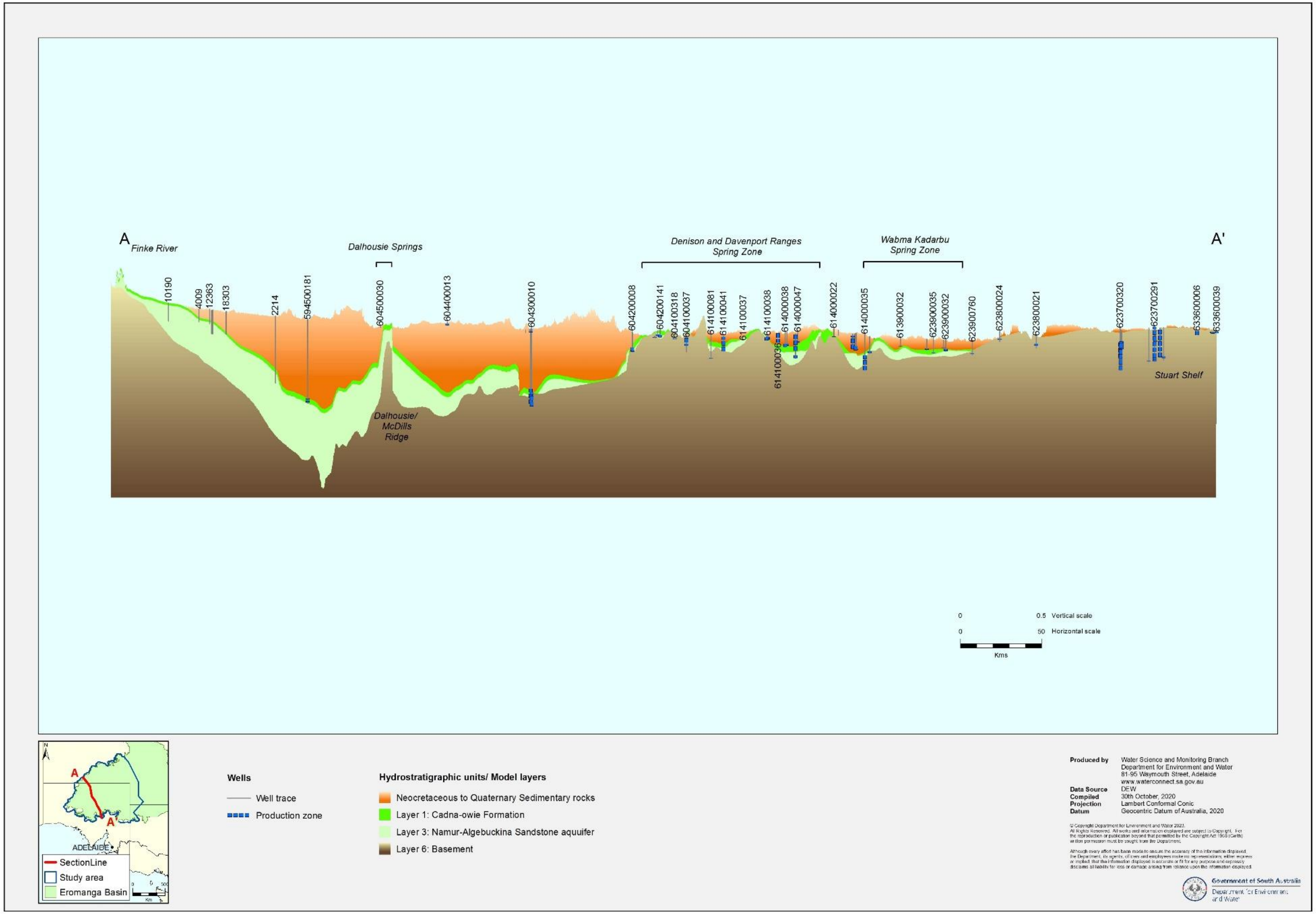

Figure 10.1: Cross-section Finke River to Stuart Shelf

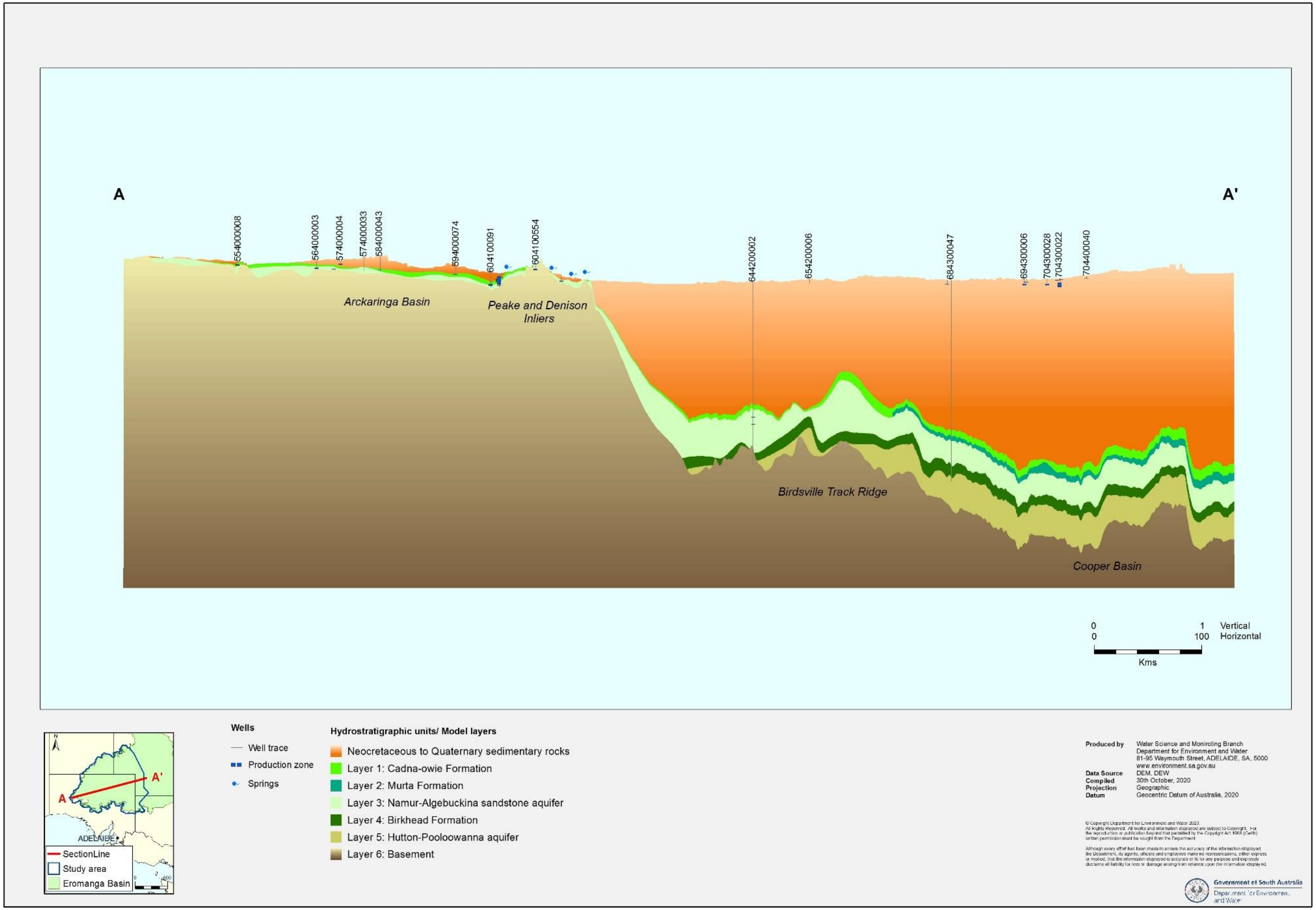

Figure 10.2: Cross-section Arckaringa Basin to Cooper Basin

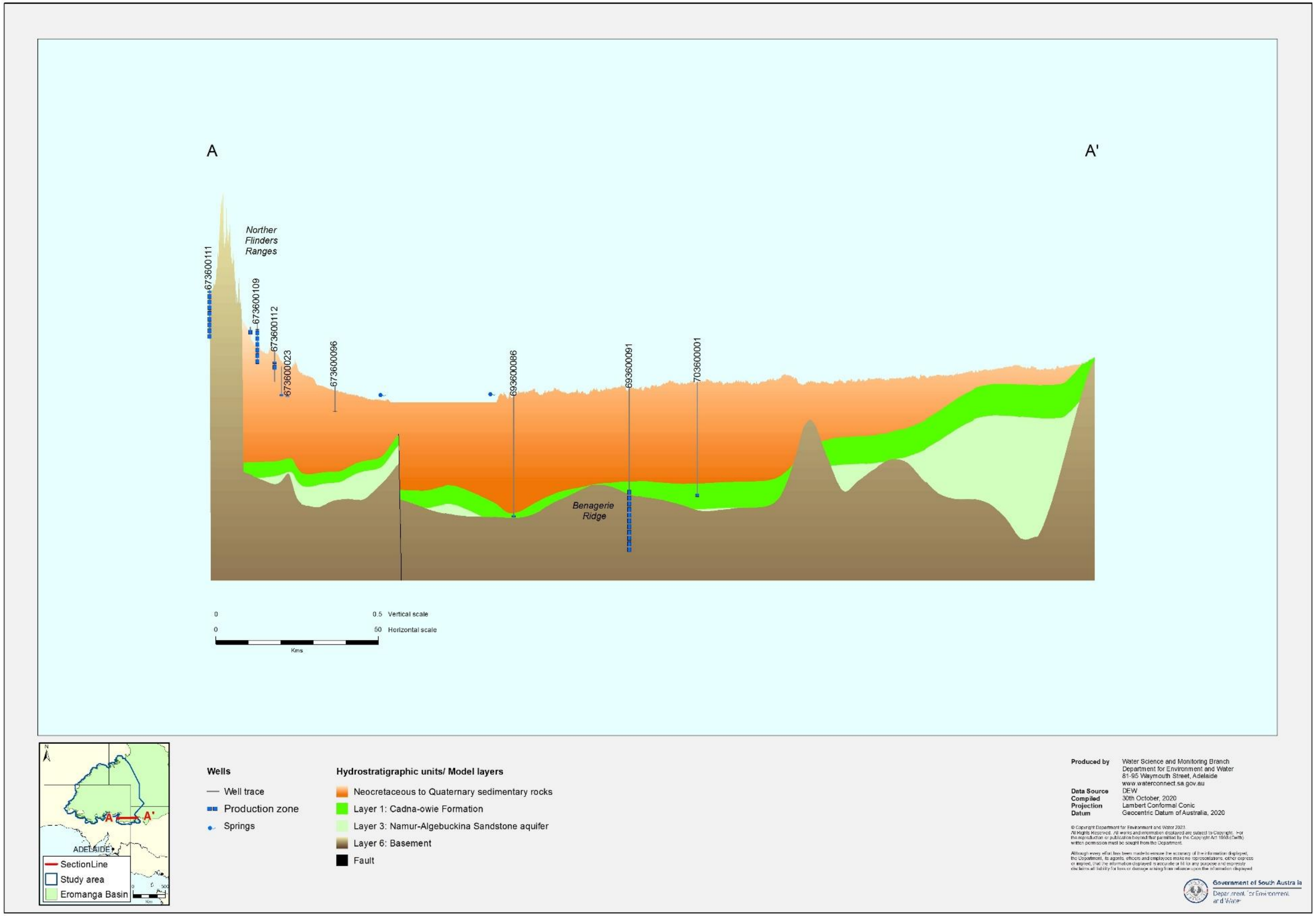

Figure 10.3: Cross-section Frome Embayment

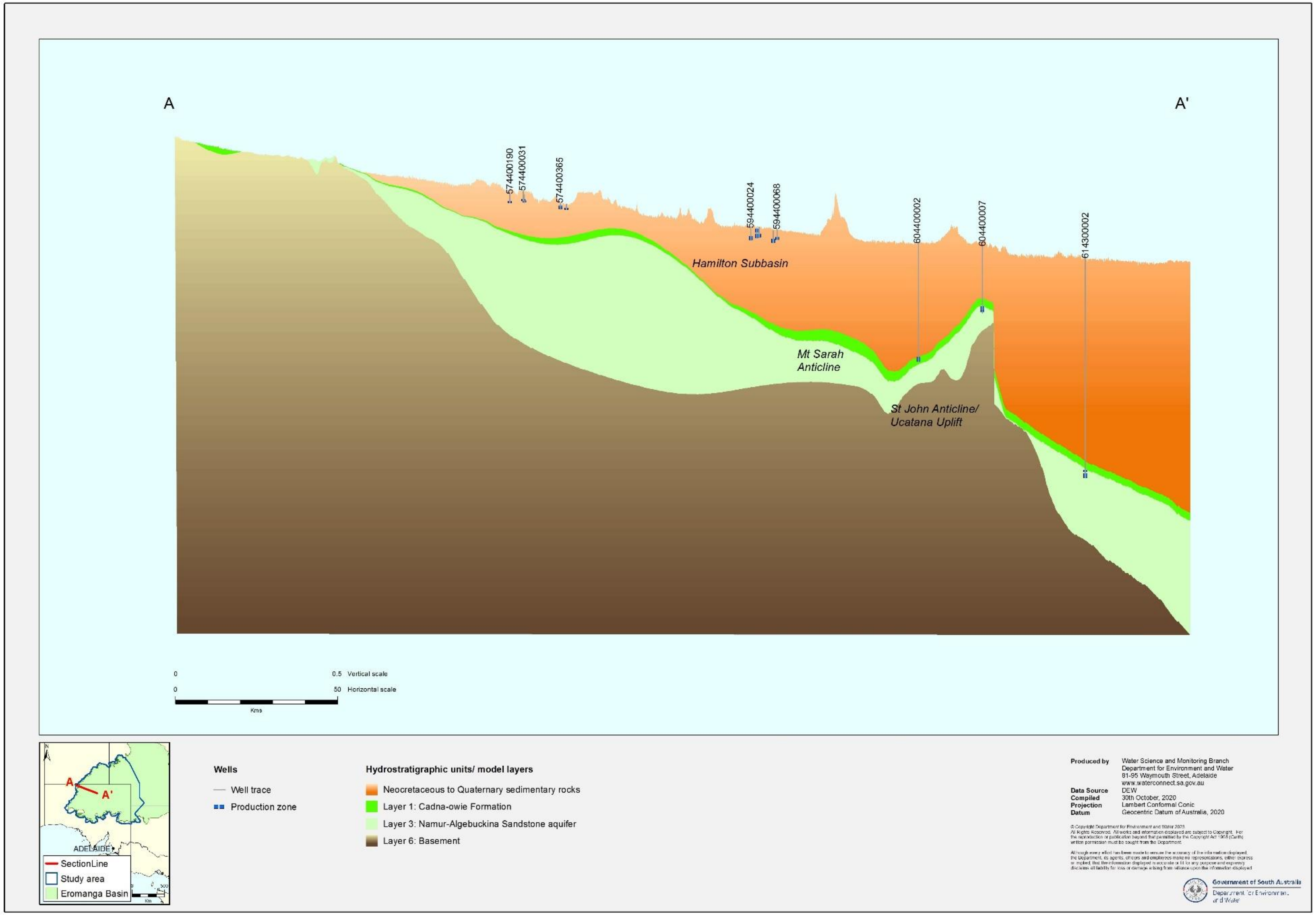

Figure 10.4: Cross-section Hamilton Sub-basin

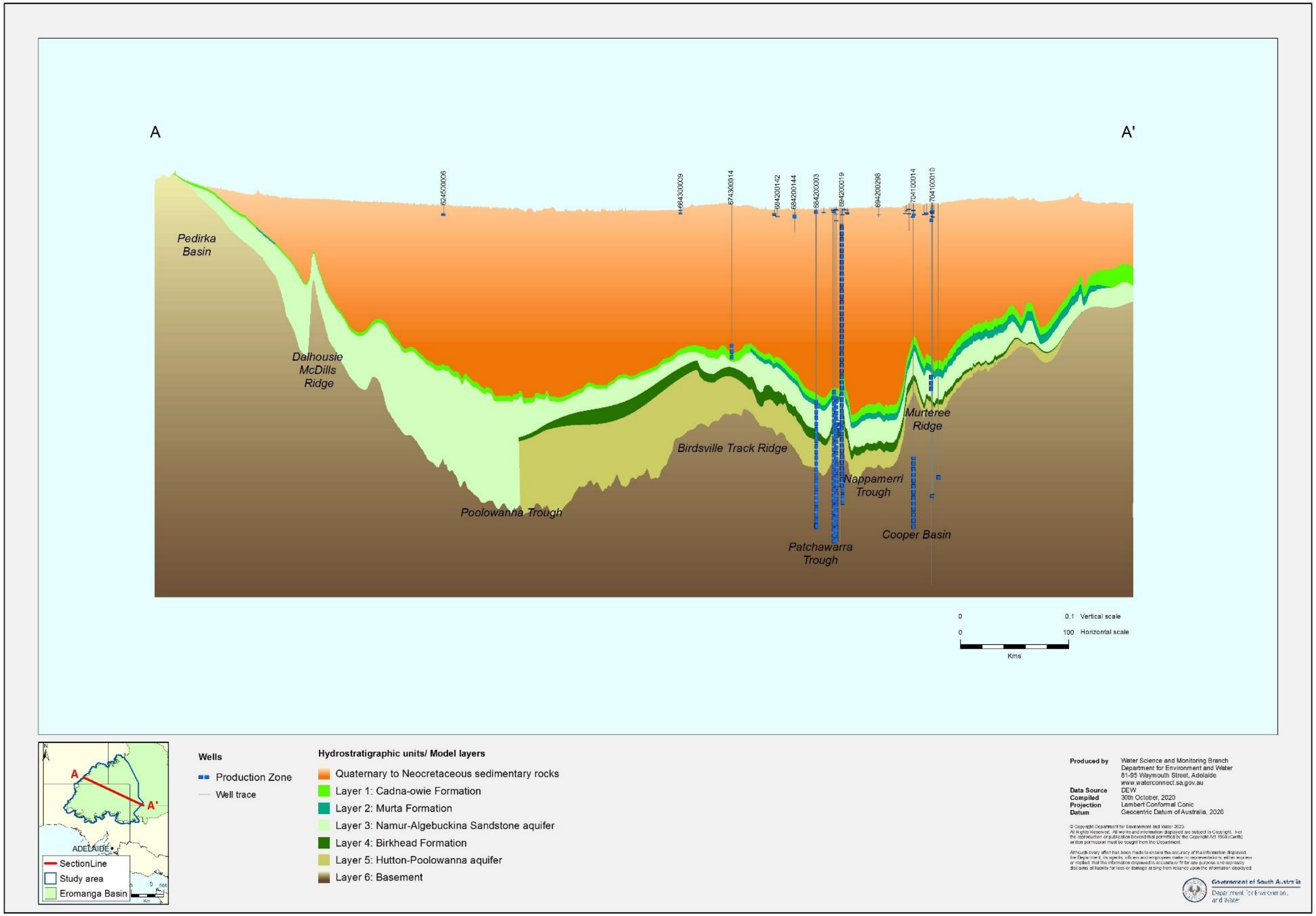

Figure 10.5: Pedirka Basin to Cooper Basin cross section

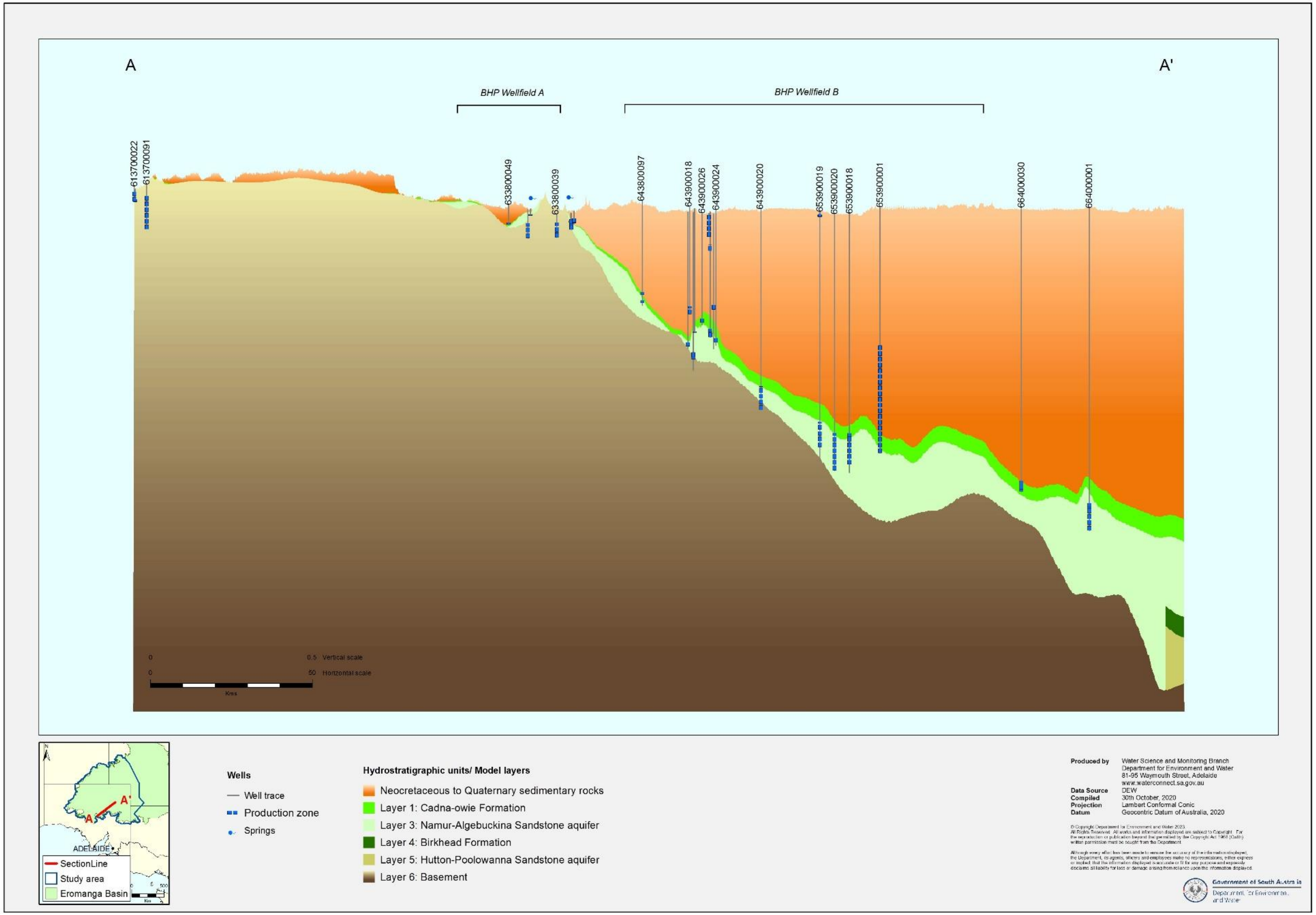

Figure 10.6: Cross-section Southern Kati Thanda–Lake Eyre South

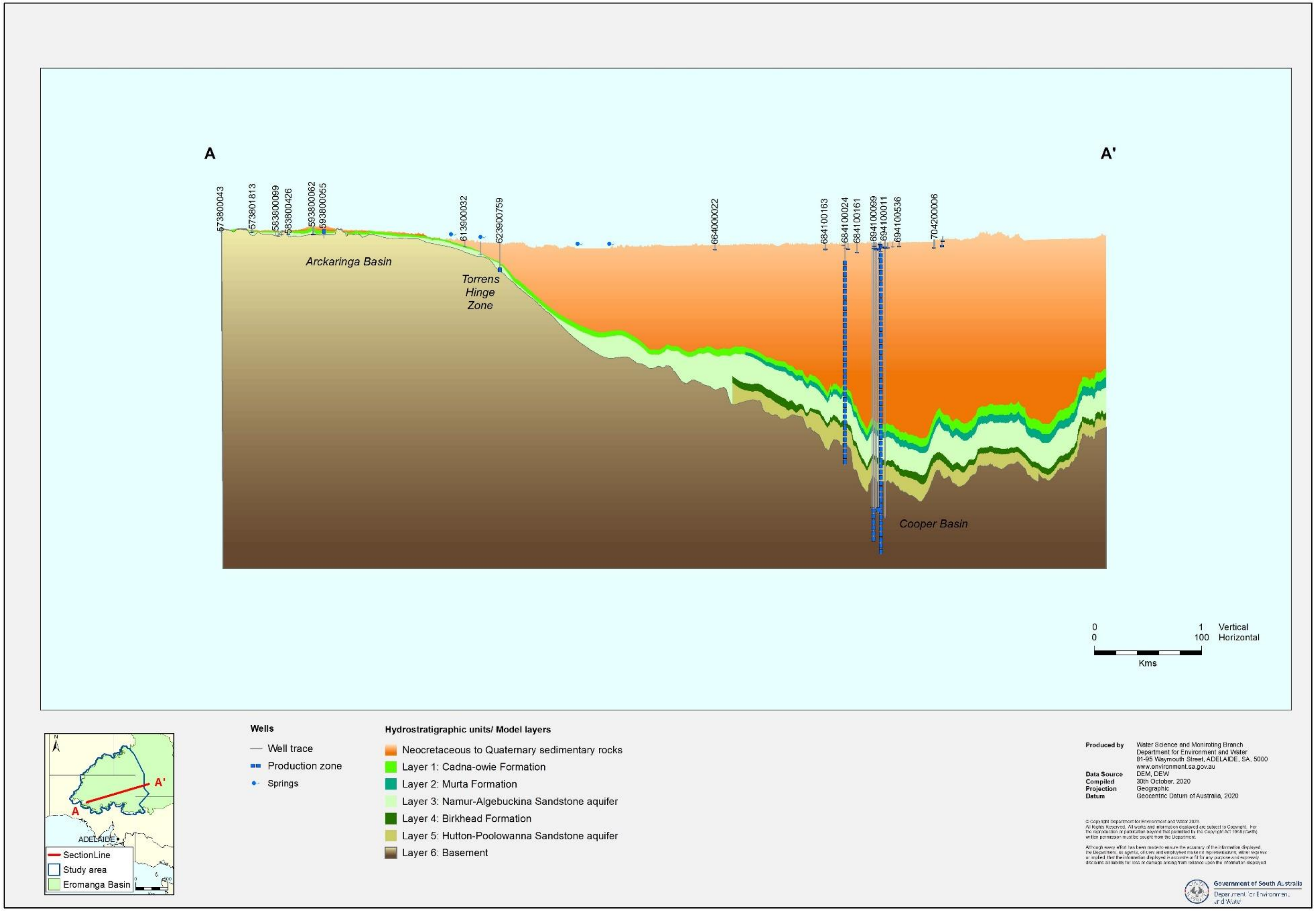

Figure 10.7: Cross-section Arckaringa Basin to Cooper Basin

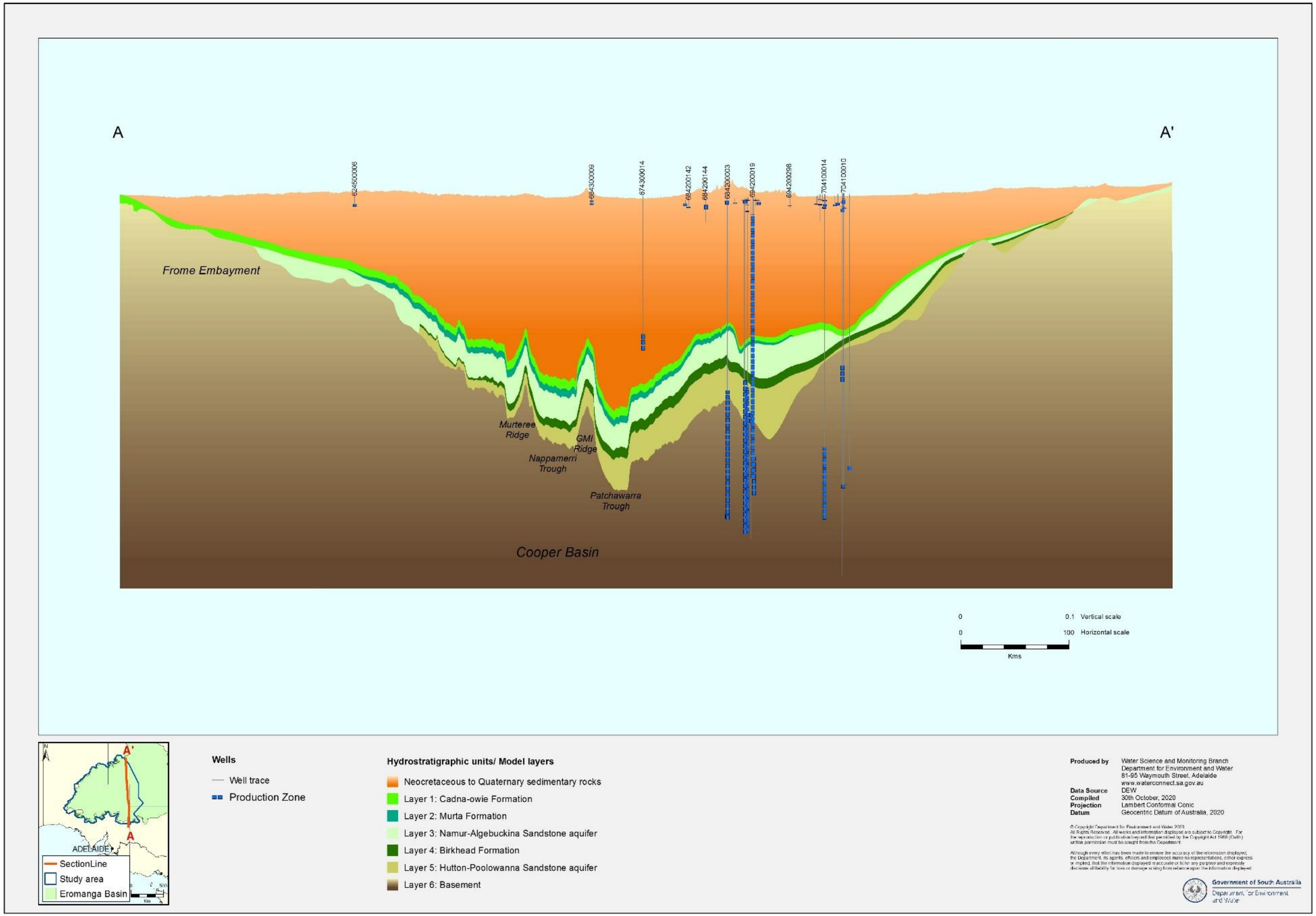

Figure 10.8: Frome Embayment to south-west QLD cross section

Appendix C Novak, M (2020) 2020 Eromanga Basin Seismic Structural Surfaces Mapping Project – Extension and Update for the Far North Prescribed Wells Area. DEM Technical report.

2020 Eromanga Basin Seismic Structural Surfaces Mapping Project – Extension and Update for the Far North Prescribed Wells Area

Martin Nok[1]

365 [1] AusGeos Pty Ltd

1 Introduction

In December 2018, the South Australian Department for Energy and Mining (DEM) contracted AusGeos Pty Ltd to consolidate/validate geophysical and geological datasets and produce a series of depth structure maps of key aquifers and aquitards that would be incorporated into a transient groundwater model of the South Australian portion of the Great Artesian Basin that is being developed by the South Australian Department for Environment and Water (DEW) in conjunction with DEM.

10.1 Basin configuration, tectonics and faulting

The Eromanga Basin, which is part of the GAB hydrogeological super-basin, can be described as having a bowl shape that is partly defined and modified by faulting.

A series of mountain ranges composed of basement rocks frame the western and southern margins of the Eromanga Basin. The Torrens Hinge Zone divides the Eromanga Basin into the relatively thin and shallow portions to the west from the relatively deep and thick portions to the east. The Torrens Hinge Zone and the related Adelaide Geosyncline are a relatively seismically active region, with this activity potentially translating into fault and fracture deformation within overlying aquifer strata. Many of the GAB springs and regions of pronounced diffuse discharge to shallow water tables that occur within the study area overlap with regions either overlying or adjacent to the Adelaide Geosyncline or the Torrens Hinge Zone. This zone also hosts a number of mapped regional structures, including the Peake and Denison Inliers and the Dalhousie-McDills Ridge.

A numbel of important subregional depocenters and basement highs occur within the study area. The Dalhousie-McDills Ridge separates the Poolowanna and Eringa Trough depocenters. Another prominent basement high is associated with the Mount Woods Inlier and the Coober Pedy Ridge. Finally, a concealed basement high with a north-south strike that separates the Poolowanna and Patchawarra Trough depocenters forms the Birdsville Track Ridge. Other zones of structural deformity have been mapped more recently, including within the northern Frome Embayment and between the Dalhousie–McDills Ridge and the Denison and Davenport Ranges.

Neotectonics and faulting are important with respect to shaping the basin configuration as well as imparting fault-related changes to hydraulic conductivity. One of the important expressions of this with respect to supporting endemic ecology within the region is through the development of springs, either via uplift and erosion stripping away confining unit rocks or by faulting and fracturing causing spring conduit formation. Further aeolian deflation and denudation driven by neotectonic upwarping may also contribute to diffuse discharge.

Evidence for faulting, as well as the evidence to assign a hydraulic condition on the zone of rock impacted by faulting, may be either difficult to discern or generally absent. Methods traditionally used to depict faulting at a regional scale may not have sufficient resolution to depict all faults that have meaningful impact on hydrogeology. The presence of springs, although sufficient to determine the likely mechanical deformation of underlying strata and vertical migration of groundwater, may be insufficient to infer other groundwater flow impacts. In other words, such localised fault-related hydraulics are unlikely to be adequately replicated in a regional scale model, and nor are they required to be, for the purpose of regional assessment.

Consequently, it is currently not the intention to represent faulting in the model realistically given the sparsity of relevant hydrogeological information and the processing requirements needed.

This report provides an overview of the methodology adopted for the project, data sources, limitations, assumptions and conclusions. Importantly, it provides a dataflow and directory of data-files and should be used in conjunction with Department for Environment and Water (2020), Far North Prescribed Wells Area Groundwater Model project, DEW Technical report 2020/XX, Government of South Australia, Department for Environment and Water, Adelaide as a first point of reference for future groundwater models.

2 PROJECT OVERVIEW

In early 2018 the South Australian Department for Environment and Water and the South Australian Department for Energy and Mining formed a Steering Committee with representation from Santos, Beach Energy and Senex Energy to oversee the development of a new transient groundwater model to inform future water allocation decisions for the Far North Prescribed Wells Area (FNPWA).

This new numerical model aims to address gaps identified in the pre-existing models and to provide confidence to decision makers regarding the management of water in the FNPWA.

The study area encompasses the limits of the GAB within SA, the NT and a buffer zone extending up to 300 km in places across the border in QLD to include important spring sites, covering a total area of 725,000 km^2 (Figure 1).

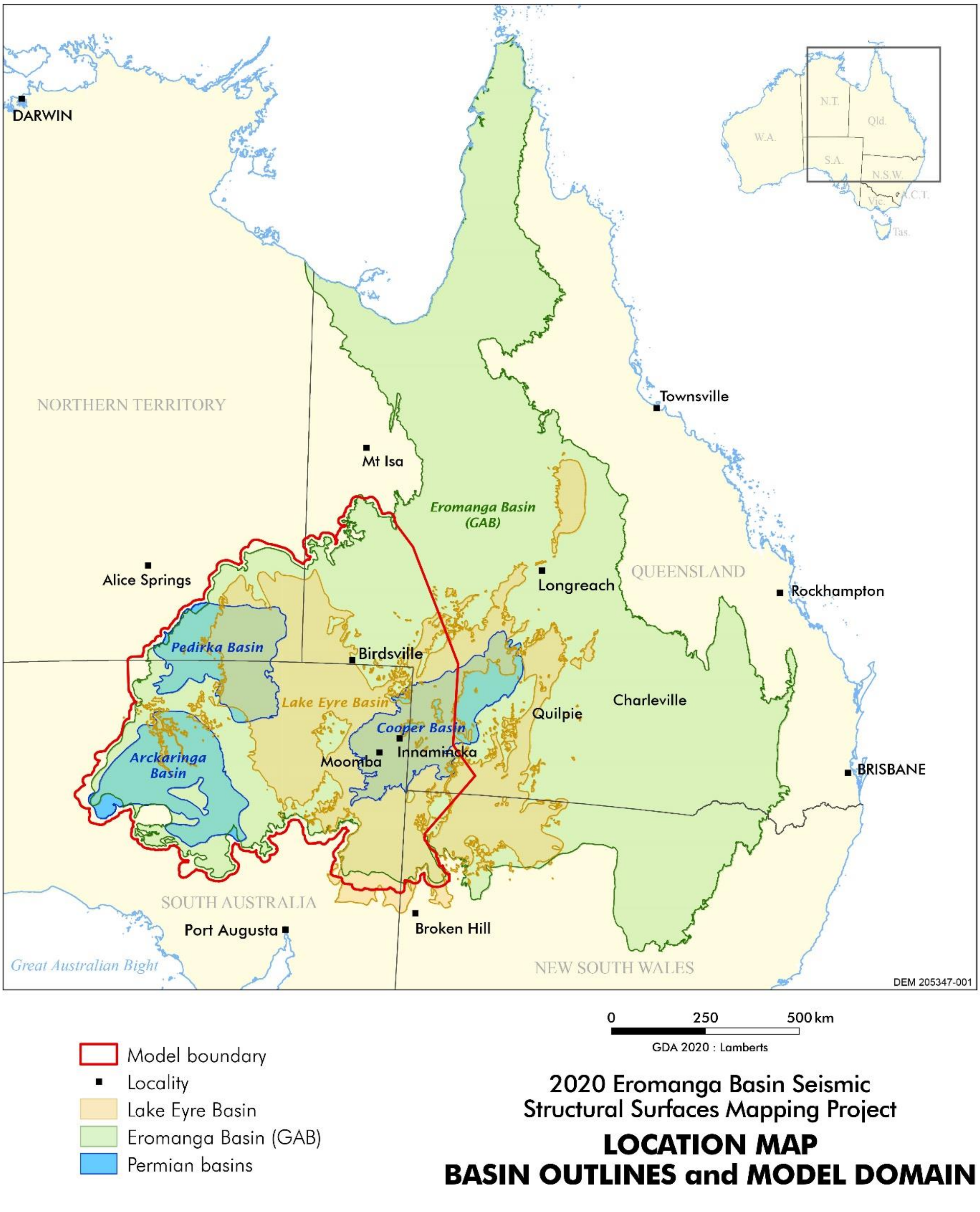

Figure 10-9. Regional location map for this study showing basin outlines and study area

A major component of this new groundwater model is the provision of updated stratigraphic surfaces for key geological units, incorporating key seismic horizons and stratigraphic surfaces last mapped by DEW and GA in the 2012 Geoscience Australia Great Artesian Basin Water Resource Assessment (GABWRA) project (Ransley and Smerdon, 2012) and updated by Ransley et.al. 2015.

This report details the merging of the pre-existing GABWRA stratigraphic surfaces, company seismic horizon and well data from South Australia, Queensland and Northern Territory and water bore data to develop 7 key horizons that represent major aquifers and aquitards of the basin (Figure 2).

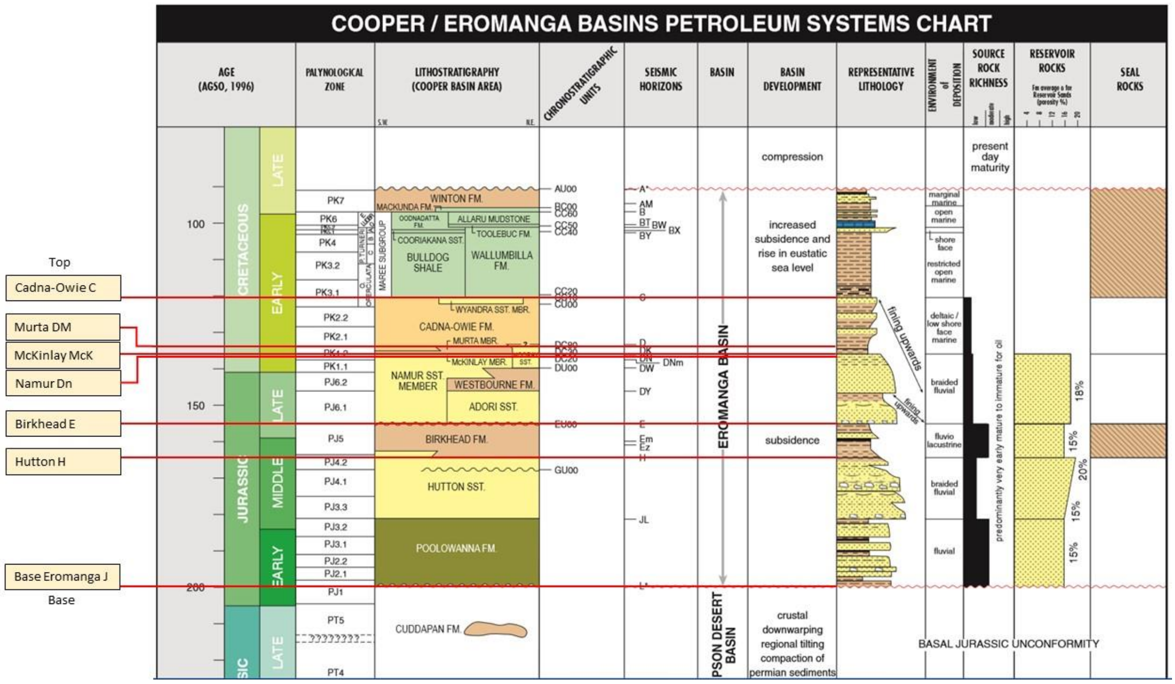

Figure 2. Cooper / Eromanga Basins Petroleum Systems Chart (after Santos)

3 DATA SOURCES

3.1 DATA SOURCES – WELLS

Well data were supplied by DEW, oil industry and collated by DEM from internal and Queensland databases. This dataset provided the main control to which all depth surfaces in this project were tied. Upwards of 12,000 wells from DEW, 4,000 from Santos, and 2,200 from Petroleum Exploration and Production System (PEPS) were loaded as well as additional data from Queensland Petroleum Exploration Data (QPED) database (Figure 3).

3.1.1 DEW

Well data compiled by DEW contributed the largest collection of wells. The DEW dataset comprised mineral wells, water bores, some exploration wells and all wells located in Northern Territory.

Exploration wells contained in the DEW dataset were superseded by more recent data extracted from the PEPS database and by data received from industry.

All well data with well header (name and location) and formation data (formation tops and depths) were provided by DEW in spreadsheet form.

3.1.2 DEM

Well data stored in PEPS contributed a significant dataset to the WAP project. Extraction filters excluded wells with an inclination greater than 10 degrees. Stored formation tops for Cadna-owie and Hutton and their sub-sea depths in metres were extracted for each well, with well name, top-hole X,Y and KB elevation, and written to Excel spreadsheets.

Relevant formation tops, listed in Table 1, from base Cadna-owie Fm to base Poolowanna Fm / Base Eromanga Basin were extracted from PEPS, and combined with equivalent data from the Santos dataset and the QPED online database using Excel spreadsheets.

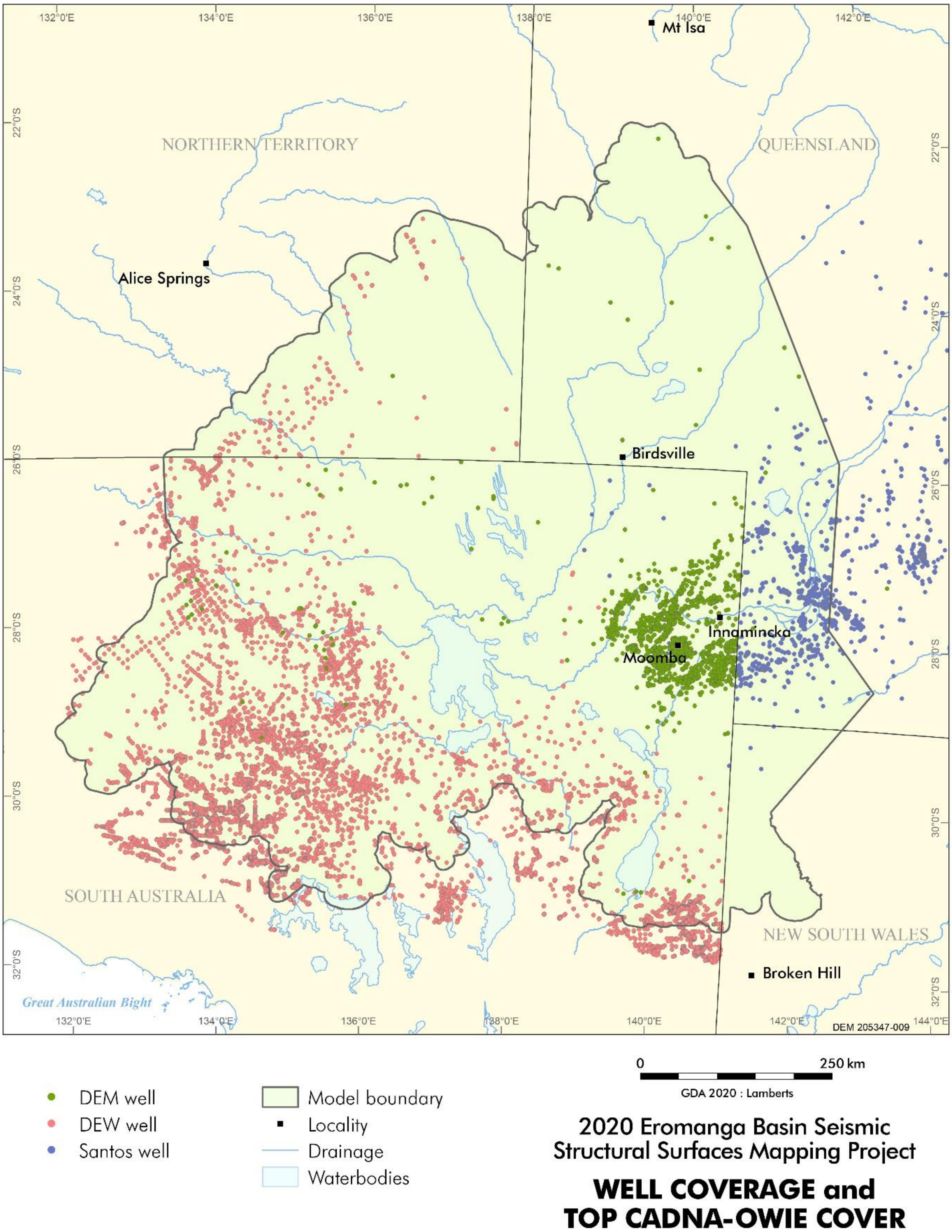

Figure 3. Location of wells (at Top Cadna-owie horizon) used for developing surfaces

3.1.3 SANTOS

A number of South Australian operators provided well datasets for this project. The Santos dataset was the most extensive with over 4,000 wells. The datasets contained both well identifying information and formation tops & depths. The Santos datasets were received in spreadsheet format between 18th January and 22nd January 2019 defining their currency to some date before those dates. The dataset contained a number of blank entries representing either missing or redacted data.

3.1.4 QLD

Queensland well data were extracted from the QPED database during the well compilation stage of the project around March / April 2019 and saved in Excel spreadsheets.

3.1.5 Deviation data

Well formation top data in the PEPS database contained deviation labels but did not contain deviation corrections. Filters were used to extract only vertical and 'slightly deviated' wells, meaning those generally having inclinations less than 10 degrees.

A few deviated South Australian wells were included in the study where they had deviation data loaded from previous work.

Santos' well dataset was assessed to contain TVD depth data corrected for deviation (applying deviation surveys), but without additional location data for tops in deviated wells. This location error while present in the data was deemed minor.

Additional well formation top data in the QPED database also did not contain deviation corrections. All these wells included in the study were considered to be close to vertical.

No deviation data had been used within the DEW dataset. Consequently many exploration wells within the DEW dataset were replaced by correctly deviated wells from the industry dataset.

3.2 DATA SOURCES – OUTCROPS

Outcrop points were supplied by DEW. The datasets comprised field data of first occurrence of basement outcrop and a further outcrop point 500 m beyond the first outcrop for grid stabilisation purposes. 465,614 points in SA and NT and 38,892 points in NSW were loaded. Outcrop data were treated as well data in the gridding and contouring processes.

3.3 DATA SOURCES – SPRINGS

Location data of 5152 known spring locations were provided by DEW and loaded into the project database (Figure 4). Ground spring data were used to verify the mapped extents of aquifers.

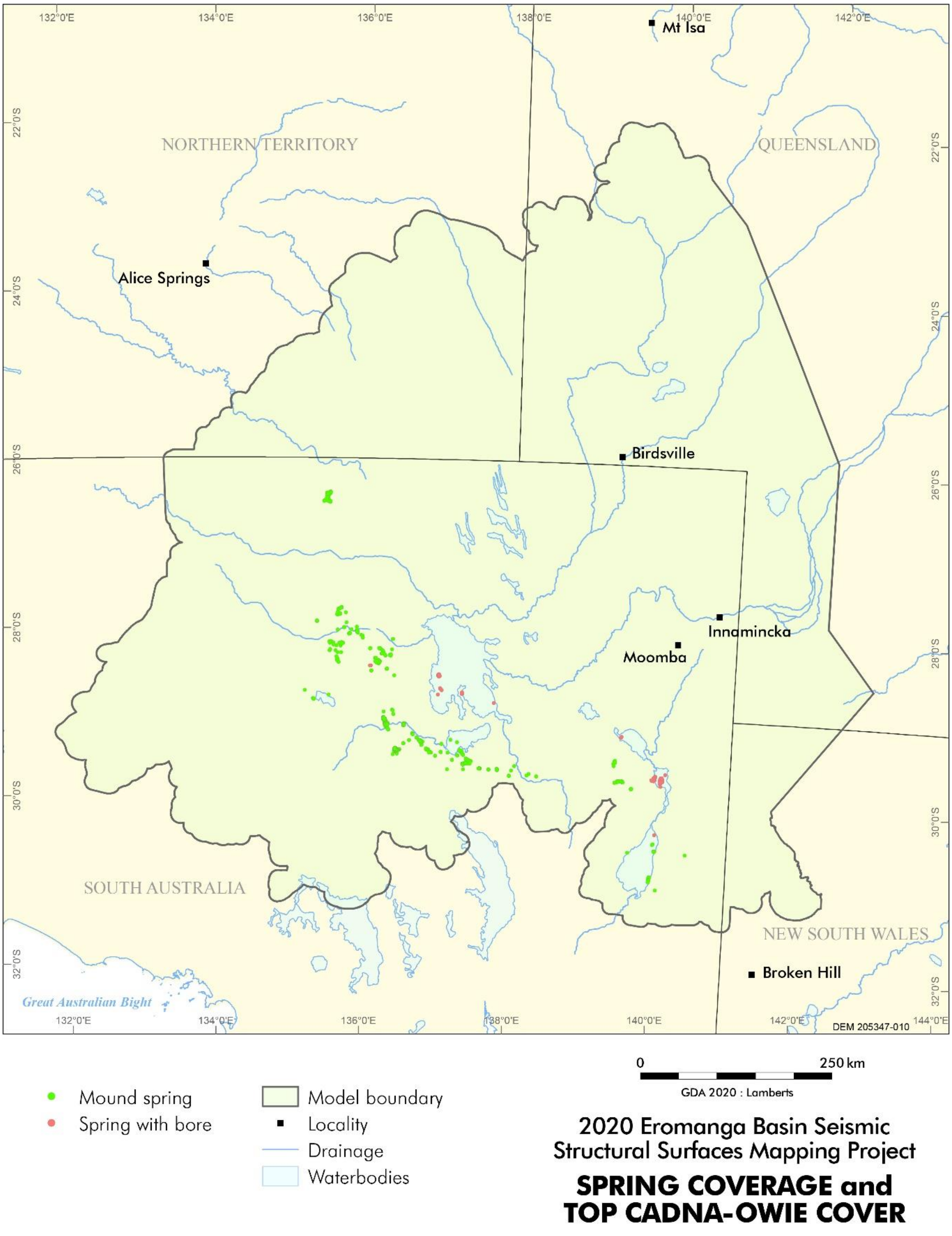

Figure 4. Location of springs used in model

3.4 DATA SO—RCES - DEPTH SURFACES

3.4.1 Geoscience Australia (GA)

Four depth surfaces were obtained from the 2012 GABWRA project for use in this project (Ransley and Smerdon, 2012).

i. Lay—r 01 - 3-second Digital Elevation Model surface
ii. Lay—r 04 - Base of Rolling Downs Group surface
iii. Lay—r 06 - Base of Injune Creek Group surface
iv. Lay—r 10 - Base of Jurassic-Cretaceous sequence surface

Layers 04, 06 and 10 were used to provide data in areas not covered by the other data sources.

3.4.2 Santos

Santos provided a number of surfaces in time and depth. The following three surfaces in depth were used for the construction of the appropriate depth grids:

i. Near_Top_Cadna-owie_DEPTH_SS_Tied_ReferenceWells
ii. Near_Top_Hutton_DEPTH_SS_Tied_RefWells
iii. Near_Base_Eromanga_DEPTH_SS_Tied_RefWells

3.4.3 Senex

Senex Energy provided 11 surfaces. After detailed analysis much of the extent of the Senex grids was also covered by the Santos grids. The western parts of the Senex grids were found to be at odds with the WAP2012 grids and it was decided not to use the Senex grids in the construction of the appropriate depth grids.

3.4.4 Beach

Beach Energy provided a limited number of depth grids. These were split by historical permits and, for data originating from 3D interpretations, the grids were confined to the extents of their 3D data. Consequently the Beach data offered a number of small patches of depth data which restricted their value for a large regional study. In addition the Beach data covered similar areas to the Santos data which was more extensive and continuous. The Beach depth surfaces were assessed to provide minimal additional information over the Santos datasets and it was decided not to use the Beach grids in the construction of the appropriate depth grids.

3.5 METHODOLOGY – WELLS

3.5.1 Data loading

Header data for wells including well name, location, KB elevation and other support information were loaded to *Petrosys™*. For each well, depth information converted to subsea (negative below MSL, positive above MSL) was loaded for the each surface in the study.

3.5.2 Data QC/QA

Well data were extensively quality controlled using a number of methods.

Where multiple sources for the same data were available, depth and location data were cross-checked to identify differences. Large differences were followed up to seek an explanation and to identify the correct data. Where a confident reason for differences was found the correct result was used.

This data QC effort identified a number of wells which had incorrect depth or location data either due to keying in errors or due to other causes such as metric/imperial unit errors.

In some cases depth differences stemmed from different log interpretations. These were reviewed by experienced staff within DEW and DEM and corrected if necessary.

Differences in depth of less than 8 m were generally acceptable.

3.5.3 Deviated wells

Deviated wells were identified and a determination was made as follows:

- Wells with inclinations less than 10 degrees were used uncorrected (without correction for well deviation).
- Wells deviated > 10 degrees with the correct deviation applied to depth (regardless of corrections to sub-surface location) were used.
- Deviated wells > 10 degrees that had not been corrected for depth were generally removed. This applied mainly to recently drilled development wells in areas with adequate well density.
- In a number of cases where a well was deemed valuable but had not been corrected for deviation, and a deviation survey existed, rather than discard such wells, the depth and location data were re-calculated from the deviation survey.

3.5.4 Inconsistent Names

Some effort was required to reconcile various well naming styles adopted by the different providers of data. Examples included different numbering systems such as WellName 001 vs. WellName 1, different applications of hyphens and spaces in well names; use of different side-track abbreviations such as ST1 and DW1; and so on.

3.5.5 Parked wells

Errors in well data that could not be adequately resolved led to wells being separated from the live dataset into a ‘parked’ category. Over time some of these wells could be resolved and returned to the live dataset. A small collection of wells remained ‘parked’ and these wells were not used to construct the final surfaces.

3.6 METHODS – SURFACES

3.6.1 Data loading

At the start of the project 400 m by 400 m gridding was chosen as the working and final grid spacing for all surfaces. All incoming surfaces were resampled to this grid spacing using Petrosys™.

A Datum / Projection CRS of **GDA94** / **SA Lambert** was chosen for this project and all incoming surfaces were converted to this Datum / Projection using Petrosys™.

A project AOI was established and surfaces extending beyond this area were clipped/constrained to this AOI also within Petrosys™.

3.6.2 Data QC/QA

A considerable effort was dedicated to quality control of all surfaces throughout the project. Incoming surfaces were checked upon loading to Petrosys™. Surfaces were checked after tying to wells which provided a powerful means of checking the well data and resolving the most visible errors. The surfaces were also checked relative to faults, visually against seismic data, relative to outcrops and springs. The surfaces were investigated for interaction (crossing and excessive thinning) with other surfaces using isopachs constructed between adjacent surfaces. Isopachs were constructed and used to QC the surfaces at various stages of completion. Final checks were performed after the final well tie, before the implementation of dummy wells. Further surface checks were performed after the final tie to all wells, including dummy wells, and in ArcGIS after export from Petrosys™ and prior to handover to the modelling part of the project.

3.6.3 Input Surface Problems & resolution

Various concerns were noted with some of the input surface, and were resolved as follows:

Original surfaces from the GABWRA website were found to contain an artificial 'mesh' type pattern. This was resolved by the GA team and a new set of corrected surfaces were provided for this project.

In a few cases, surfaces received from the operators deviated along their periphery from other corresponding surfaces in the project. As would be expected, surfaces received from the operators were consistently more detailed than either the WAP2012 or the GA surfaces. However in some parts outside the operators' core exploration and development areas, larger differences were noted. Surfaces in these areas were observed to be unconstrained by wells, assumed to be extrapolated from the operators' core areas, and of lower importance. These discrepancies were resolved by incorporating dummy wells along the margin of those surfaces provided by Santos to minimise the deviations prior to the merge of the surfaces.

Surfaces provided by Senex were noted to contain surface irregularities along their western edge. As the Santos grids largely overlayed the Senex grids, Senex grids were not used in the construction of the final surfaces.

3.6.4 Input surface priorities

Once the input depth grids were selected, for a number of the required surfaces multiple input surfaces were available, each with a different spatial extent. Because of the higher detail/resolution of the surface provided by industry it was necessary to merge individual surfaces in a way that retained the highest level of detail in the final product. To do this, prior—ties - based on the quality and detail of each surface – were defined as follows:

- The highest priority was given to the **Santos** surfaces. Where a Santos surface was available it was used.
- The second priority was given to the **WAP2012** surfaces. Where the WAP surface existed outside the Santos surface it was used.
- The lowest priority was assigned to the **GABWRA** surfaces. These surfaces were used to fill in all missing areas within the AOI.

Only these three sources provided input into the construction of the final surfaces.

3.6.5 Tie to wells

All surfaces were tied to wells before proceeding with further steps.

3.6.6 Surface merging

Where grids from multiple sources were available and needed to be merged, such grids, once approved, were merged according to the above priority sequence. Typically a 'Feathering Distance' of 15 km was used to blend surfaces at their join to reduce undesirable edge features.

In some cases, control (dummy) wells were added to constrain surfaces beyond the feathering distance to reduce edge effects further. These locations were generally characterised by very sparse well densities.

3.6.7 Re-tie to wells

A further tie to wells was performed before checking for crossing and closely approaching surfaces. Isopachs were found most expedient for locating crossing and closely approaching surfaces.

3.6.8 Isopachs

Throughout the construction process isopachs were used to check the integrity of surfaces. The CadnaIie (C) to Base Eromanga (J) isopach was essential in defining the key Western edge of the GAB, but also along the Northern and Southern margins, and around the various known outcrops. Isopachs were also used to QC the surfaces in known spring locations.

3.6.9 Outcrop data

A detailed outcrop dataset representing the line of first occurrence of outcropped basement, comprising X, Y location and elevation above MSL data, was supplied by DEW. Cadna-owie and Base Eromanga surfaces were tied to this elevation data during the same well tie process as the verified well data.

In addition X, Y, and elevation data of points 500 m inboard of the first line of outcrops were provided by DEW. The objective was that the basement surface would attain a slope more closely corresponding to the assumed basement form near the outcrop edge of the GAB by concurrently tying to both outcrop datasets. Inspection of the results showed that these two surfaces honoured the provided outcrop data within the capability of the selected gridding parameters and the gridding algorithm.

3.6.10 Faults

Surfaces provided by Santos and the WAP2012 contained large interpreted faults. Additional fault interpretation was not specified in the scope of this work. All provided (prior interpreted) faults were kept. Many faults were checked against seismic data. In a few cases, where faulting was required to stabilise surfaces or insert a clearly missed fault, such faults were added.

3.6.11 Control features (faults)

In some complex areas, typically near steeply rising basement, where stabilising original C and J surfaces was particularly challenging and where these surfaces crossed, removing substantial areas of the GAB section needed for this study, 'control faults' were added to correct this problem. One such location was the structurally complex area west of Lake Frome.

3.6.12 Extent of surfaces

The final extent of surfaces was determined according to the following methodologies.

Lithostratigraphy

The generalised lithostratigraphy of the Cooper / Eromanga Basin is shown in Figure 2.

All surfaces selected for this study and for input to modelling, are labelled in Figure 2 and listed in Table 1. The surface abbreviations and any equivalent formation names are also listed in Table 1.

Surface Abbreviation	Surface Name	Equivalent Formations
C	Top Cadna-owie Fm.	
DM	Top Murta Fm	
McK	Top McKinlay Mbr.	
Dn	Top Namur Sst.	Algebuckina Sst., Longsight Sst., Hooray Sst., De Souza Sst.
E	Top Birkhead Fm.	
H	Top Hutton Sst.	
J	Base Eromanga Basin	

Table 10-2. Surfaces selected for this study with abbreviations, names and equivalent formation names

Sequence and method of surface construction

Surfaces were constructed in the following sequence:

1st Cadna-owie

2nd Base Eromanga

3rd Hutton

4th Birkhead

5th Namur

6th Murta

7th McKinlay

The general method used for construction of each surface is listed below

- The Cadna-owie surface was constructed by merging available Santos, WAP2012 and GABWRA Cadna-owie surfaces into one surface and tying to available well and outcrop data. Cadna-owie was the uppermost surface in the sequence and thus formed the top envelope for all other surfaces.
- The Base Eromanga surface was constructed by merging available Santos, WAP2012 and GABWRA Base Eromanga surfaces into one surface and tying to available well and outcrop data. Base Eromanga was the lowermost surface in the sequence and it formed the base envelope for all other surfaces.
- The Hutton surface was constructed by merging available Santos, WAP2012 and GABWRA Hutton surfaces into one surface and tying to available well and outcrop data.
- The Birkhead surface was constructed from the Hutton surface by phantoming from the Hutton surface and tying to all Birkhead wells. Amount of shift was calculated by gridding of the Birkhead thickness at wells. Or put another way, the Hutton surface was bulk-shifted by the calculated Birkhead-to-Hutton well isopach and tied to every Top Birkhead Fm depth in the well dataset.
- The Namur surface was constructed from the Cadna-owie surface by phantoming down from the Cadna-owie surface and tying to all Namur wells. Amount of shift was calculated by gridding of the Cadna-owie to Namur well isopach.
- The Murta surface was calculated as the mid-point of the Cadna-owie and Namur surfaces and tying to all Murta wells. The midpoint was derived using the equation (Cadna-owie + Namur)/2.
- The McKinlay was calculated as a midpoint of the Namur and Murta surfaces and tying to all McKinlay wells. The midpoint was derived using the equation (Murta + Namur)/2.

Clipping by other surfaces

The spatial extent of all surfaces was defined in three ways. Primarily the extent of surfaces was set by their juxtaposition to other surfaces. Truncation of surfaces conformed to a sequence stratigraphic framework defined below.

<u>Stratigraphic Framework</u>

- Top Cadna-owie formationIrface (C) terminates against Base Eromanga surface (J). The clipping of the C surface by the J surfaces was however not performed in Petrosys™. Both surfaces were provided to the modelling team together with the locus of the intersection of the two surfaces (zero thickness of the C-J isopach). The DEW modelling team were able to define the exact GAB termination point using the implied intersection of the C and J surfaces and the team's detailed geologic knowledge from maps, satellite data and field work.

- Top Cadna-owie formation surface also terminates against top Algebuckina where Algebuckina sandstone is present.
- Top Algebuckina Sandstone terminates against Base Eromanga surface. Similarly for the Longsight, Hooray and De Souza sandstones which are equivalent to Algebuckina.
- Top Murta surface does not terminate against any other surfaces but undergoes a facies change to the Algebuckina Sandstone west of the Birdsville Track Ridge.
- Top McKinlay surface does not terminate against any other surfaces but the upper boundary intertongues with the Murta Formation.
- Top Hutton surface truncates against Base Eromanga, or passes laterally into the Algebuckina Sandstone when the Birkhead Formation is absent.
- Top Birkhead surface truncates against Base Eromanga, or undergoes a facies change to Algebuckina Sandstone at the same point as the Hutton Sandstone to the west of the Birdsville Track Ridge.
- Top Namur surface does not terminate against any other surfaces but is a lateral equivalent of the Algebuckina Sandstone.

Clipping to outlines

In addition to stratigraphic truncation of surfaces as described above, the extent of surfaces was also defined by stratigraphic information from wells. Outlines were defined by inspection of well data to ensure that surfaces correctly honoured well data. This process naturally relied on the lithological interpretation provided in the Well Completions Reports. Where units became very thin the interpretation can be subjective. A number of wells were analysed in detail including log re-interpretation as a form of QC and to maintain consistency of interpretation. Naturally some uncertainty remained in the exact definition of these clipping outlines.

Manual clipping

In a few locations methods above were supplemented by manual intervention to improve how well data were honoured or how surfaces terminated where surfaces were poorly constrained by wells or by other surfaces.

3.6.13 Dummy wells

Dummy wells were used to adjust surfaces to achieve the following three outcomes:

1) To separate grids to prevent grids crossing. Undesirable crossing of grids, or exceptionally thin isopachs between grids might occur where:
    - wells in close proximity with sufficiently different depth values created a ‘dipole flex’ which caused the surface to interact with one or more of the other surfaces;
    - some supplied surfaces had faults interpreted while others did not, creating ‘overshoot’ structures which in some cases caused undesirable interaction between surfaces;
    - grids extrapolated into areas with no well data might create large areas of crossing surfaces simply due to the difference in depth between the last two known well data points.
2) Improved merging of grids corresponding to the same geologic interface. Where grids from different sources had unacceptably different values, sometimes of the order of 100+m, were corrected to improve the merging of grids. Generally the grid having lower confidence would be adjusted, but if a measure of confidence could not be assigned to grids in these problematic areas both grids would be adjusted either equally or in some weighted proportion.
3) To adjust grids to more closely honour springs data. Presence of known springs required for aquifers to be present in the vicinity. While other scenarios were possible to cause surface springs, such as small, unmapped faults, it was considered more likely that the uncertainty of the surfaces – particularly when dealing with aquifer thicknesses of less than 10 m – was responsible for the observed discrepancies with surface springs.

The decision to use dummy wells was taken after careful consideration of available options and their impact on the quality and usability of the produced surfaces. Approximately 100 dummy wells were used to accomplish these adjustments.

3.6.14 Final re-tie to wells

All surfaces were re-tied to all well, dummy and outcrop data prior to clipping and export from Petrosys™.

4 LIMITATIONS

4.1 WELLS

Well location data, well names, KB elevations, deviations and formation depths, as well as all calculations were subject to extensive testing and quality assurance. Wherever errors were found they were corrected. If discrepancies could not be satisfactorily resolved such data were taken out of the respective datasets. Despite the large QC/QA effort numerous known, as well as possible unknown, errors and uncertainties remain as described below.

4.1.1 Deviated wells

Most deviated wells (inclination >10 degrees) have been removed, or depths and locations have been recalculated from the deviation survey. Where deviations are less than 10 degrees no adjustment for depth or location have been made. These differences are likely to be up to 40 m in depth and up to 475 m in location for the J surface at the deepest part of the basin. The differences would be reduced to approximately 30 m depth and 330 m in location for the C surface at the deepest part of the basin.

4.1.2 Errors (various)

Location errors were generally easy to locate and remove, however location errors less than 20 m were generally not subject to correction.

Depth differences between well data from different sources were investigated with the aim of reducing, or limiting known depth errors (differences) to 8 m. The number of wells with depth differences less than 20 m was large and the number with differences less than 8 m was very large. Due to the large number of wells with differences in the 8-20 m range the cut off for investigating sources of error was raised to 20 m. Since depths are averaged in the gridding process, 20 m depth differences at well locations are averaged. We estimate that the maximum likely surface depth error at known wells from this source is approximately 10 m.

4.1.3 Different interpretations

In some cases a depth difference was not designated as an error, but a legitimate interpretation difference. In general these interpretation differences were not greater than 20 m. Reinterpretation of logs to reconcile different interpretations was not within the scope of this work. Where interpretations were greater than 20 m the wells were removed, and where the difference was 20 m or less the wells were retained. Due to the averaging of well data during gridding the error from different interpretations was of the same order of magnitude as other differences described in the above section.

4.1.4 Final estimated well depth and location error

For the intervals of most interest located within the gross interval containing the Cadna-owie to Hutton formations, we estimate an approximate maximum depth uncertainty of the order of +/- 30 m but generally less than +/- 20 m.

The equivalent location uncertainty would be largest at uncorrected deviated wells perhaps of the order of 330 m, while for the majority of wells the location uncertainty would be less than 30 m.

4.2 SURFACES

While supplied input surfaces were assumed to be correct, numerous quality checks were performed. Obvious visible errors were identified and where possible corrected. If input surfaces could not be corrected they were excluded from the dataset as described earlier. QC of surfaces identified discrepancies between surfaces and well data, and between surfaces pertaining to the same stratigraphy. If no errors were found in the well data (and the well was retained), surfaces were corrected to tie wells. Correction surfaces were generated at various stages and retained within the project.

Absolute measures of error within each surface were difficult to estimate and to present. Work required to obtain such estimates would have required use of blind wells and a detailed analysis across the area of the study, which was not identified as a requirement.

In summary:

- all surfaces match all wells contained within the project, as well as other spatial data such as outcrops (within the capability of the gridding algorithm);
- in high well density areas the surfaces are likely to be more accurate;
- in low well density areas, and particularly where wells are absent, the surfaces will have greater error;
- using dummy wells to make manual adjustments to the grids to provide geologic integrity was expected to improve the overall accuracy of the final surfaces.

It is worth noting that in some places where geologic units were mapped as very thin, a relatively small —epth error - of a few ten— of metres - would have a substantial impact on the relative thickness of a layer. These thin areas were most likely to occur on the margins of the GAB, particularly to the west and south, and in areas where faulting, or basement highs thinned overlying units.

4.2.1 Dummy wells

Adjustments to surfaces for the purposes of grid merging and avoiding surface cross-overs, or for legitimate geological reasons, by use of dummy wells, are estimated to be mostly in the range 0 – 100 m. A small number of adjustment were greater than 100 m with one or more exceptional cases, such as near major faults, or in areas with poor well control, where dummy wells required adjustment in the 100 – 200 m range.

4.2.2 Gridding algorithm

The gridding method used within Petrosys™ was the Standard gridding operation, Minimum-Curvature Gridding algorithm with Slope type Estimation, and Bicubic Interpolation method. These parameters were recommended within the Petrosys™ suite as suitable for most standard gridding operations. More specialised gridding approaches were considered and some were examined, however the standard, recommended methods were deemed most appropriate for the specific data requirements, with minimal limitations and generally producing the most accurate results.

4.2.3 Final estimated depth error

We estimate that the depth surfaces are accurate in the most part to +/-50 m across the area of interest with errors reducing to perhaps half (~+/-25 m) in high well density areas, but increasing to perhaps the range 50 – 200 m in low well density areas.

5 RESULTS

Final mapped surfaces are displayed in figures 5 to 11 inclusive and a representative east-west cross section demonstrating facies change of aquitards on the western margins of the basin is shown in Figure 12.

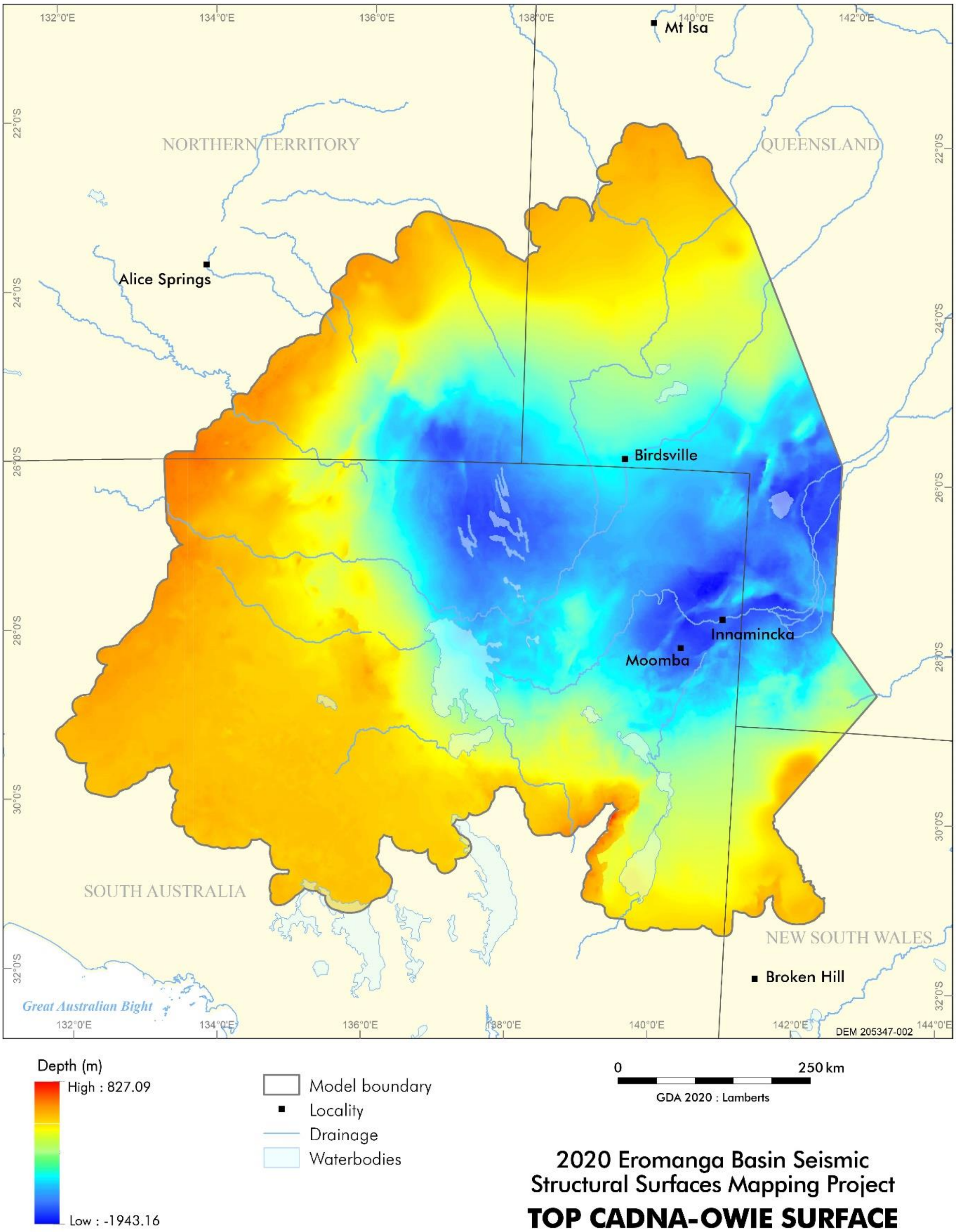

Figure 5. Top Cadna-owie Surface

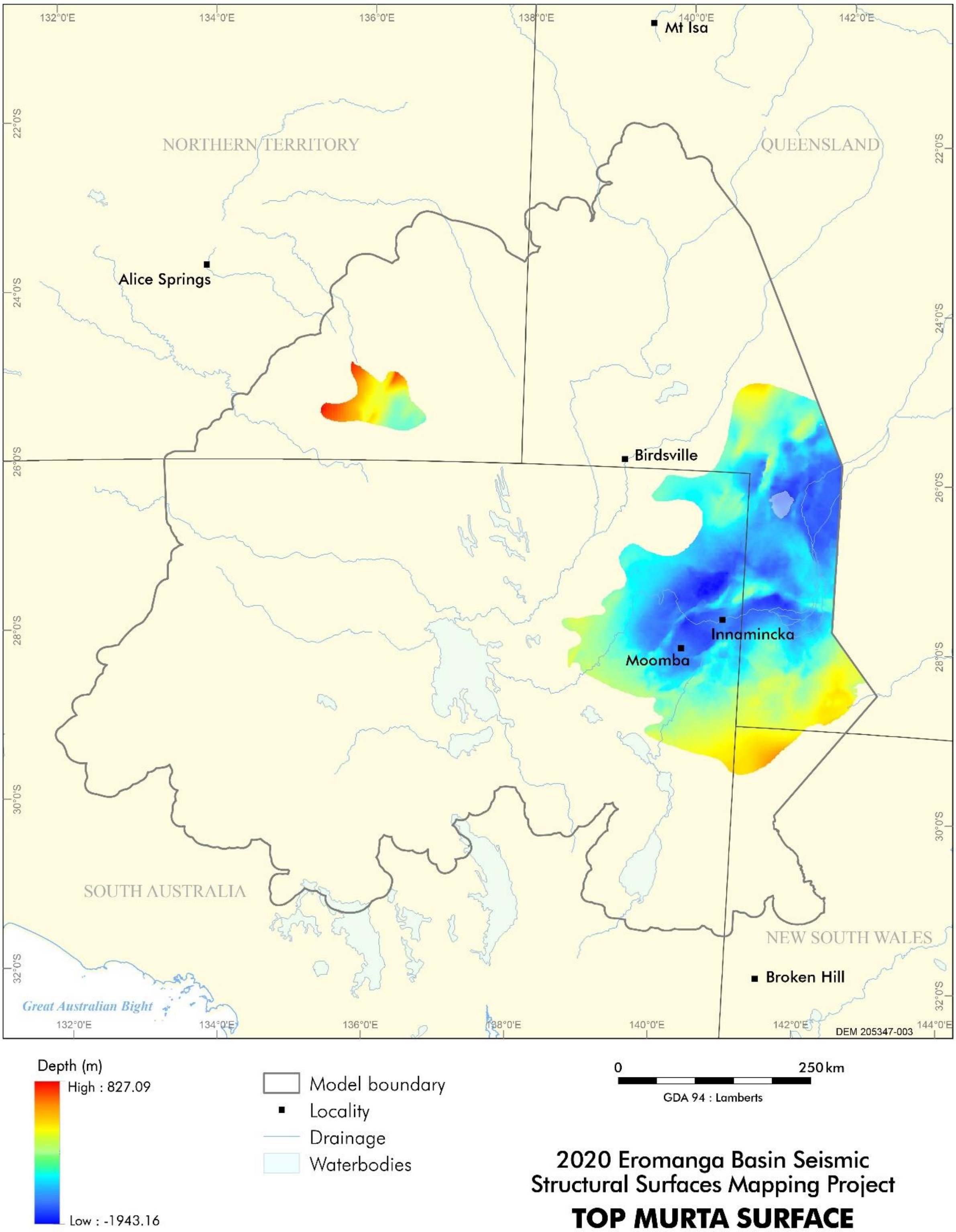

Figure 6. Top Murta Surface

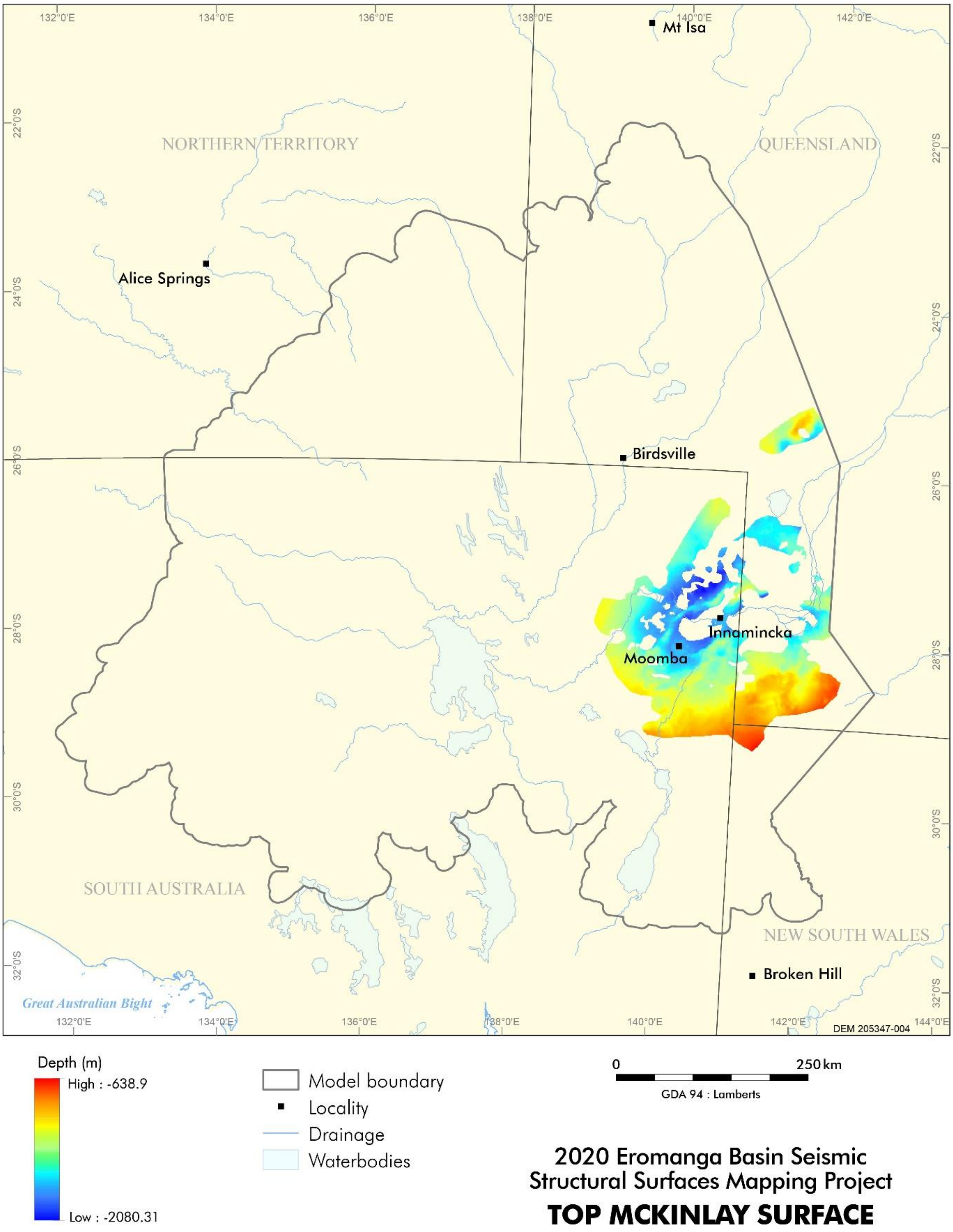

Figure 7. Top McKinlay Surface

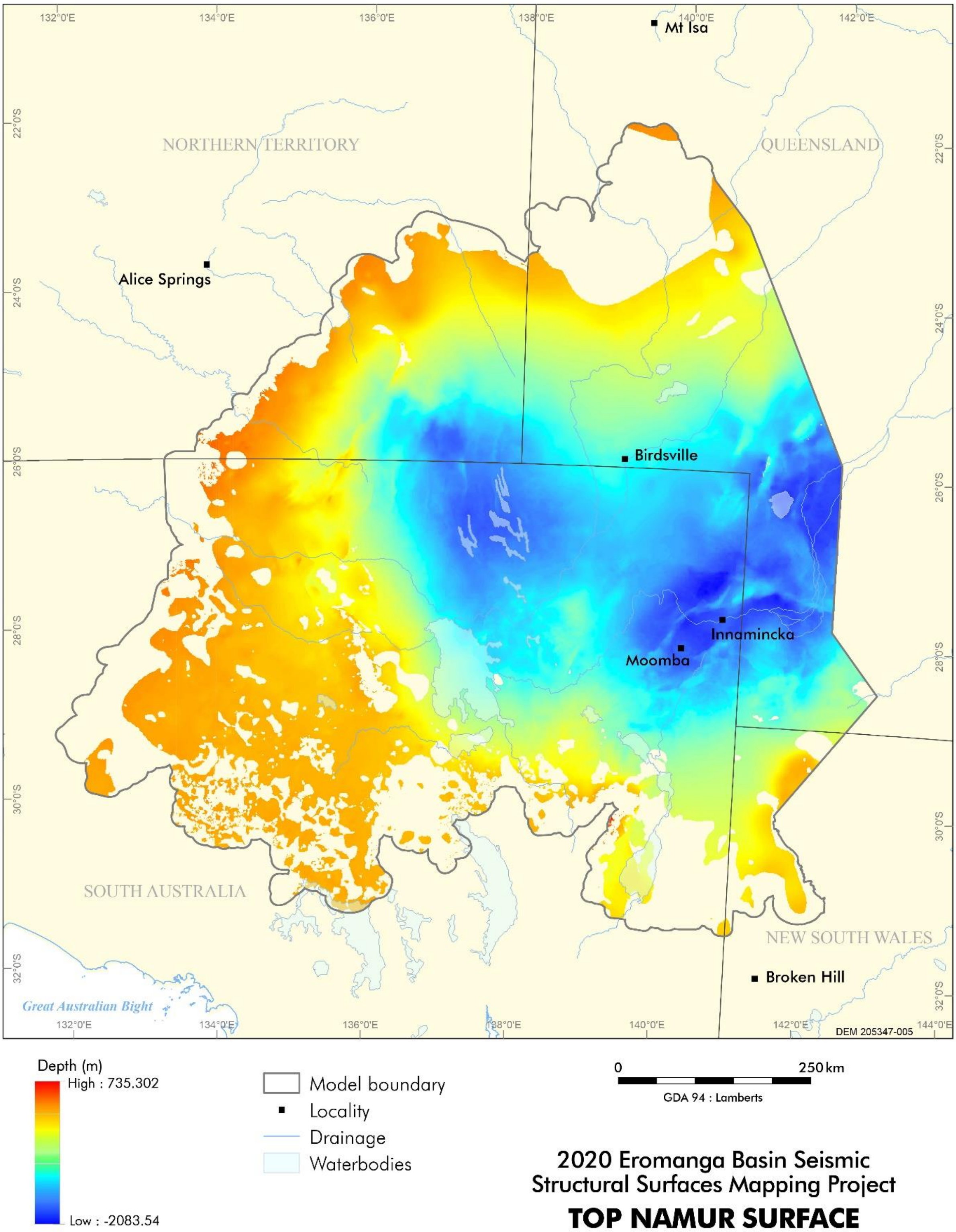

Figure 8. Top Namur Surface

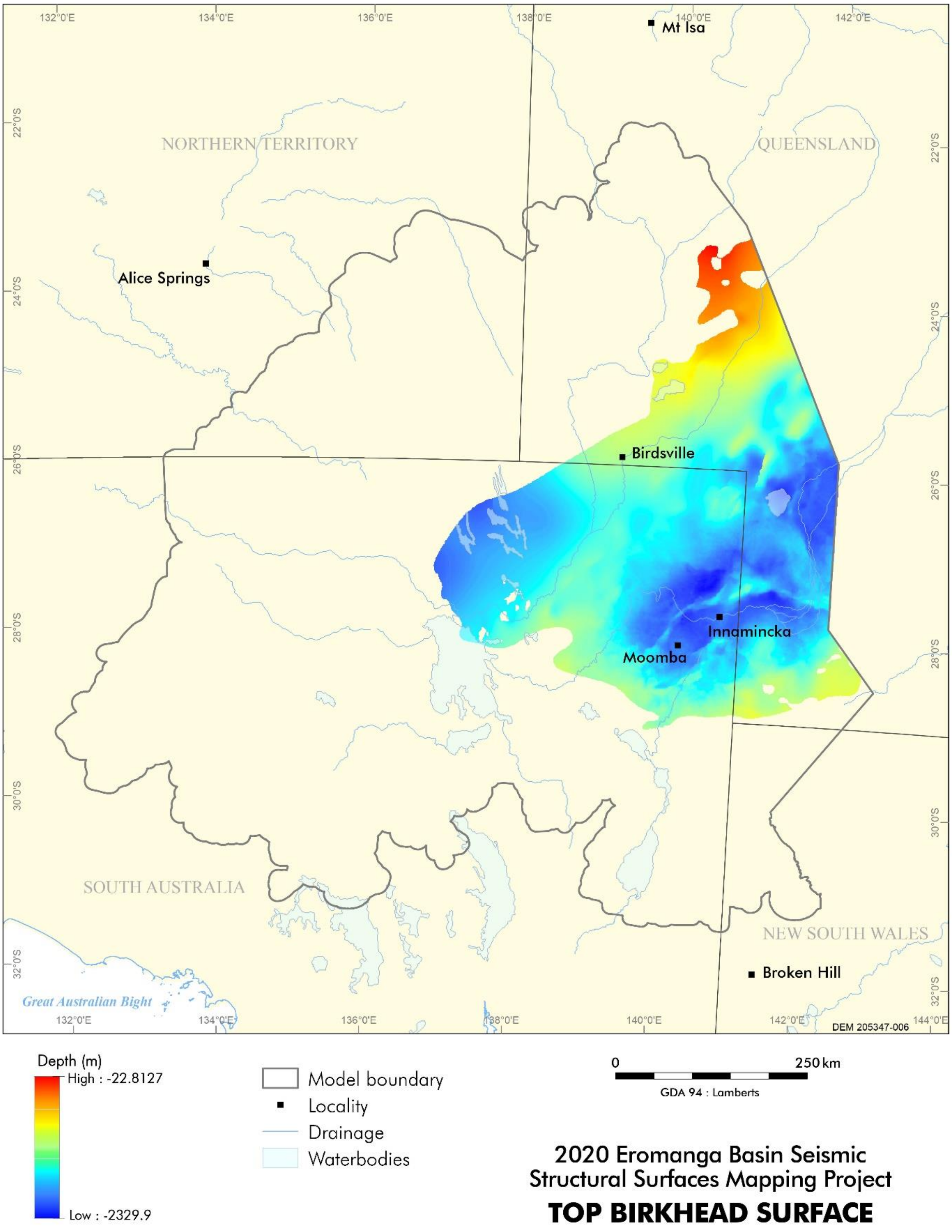

Figure 9. Top Birkhead Surface

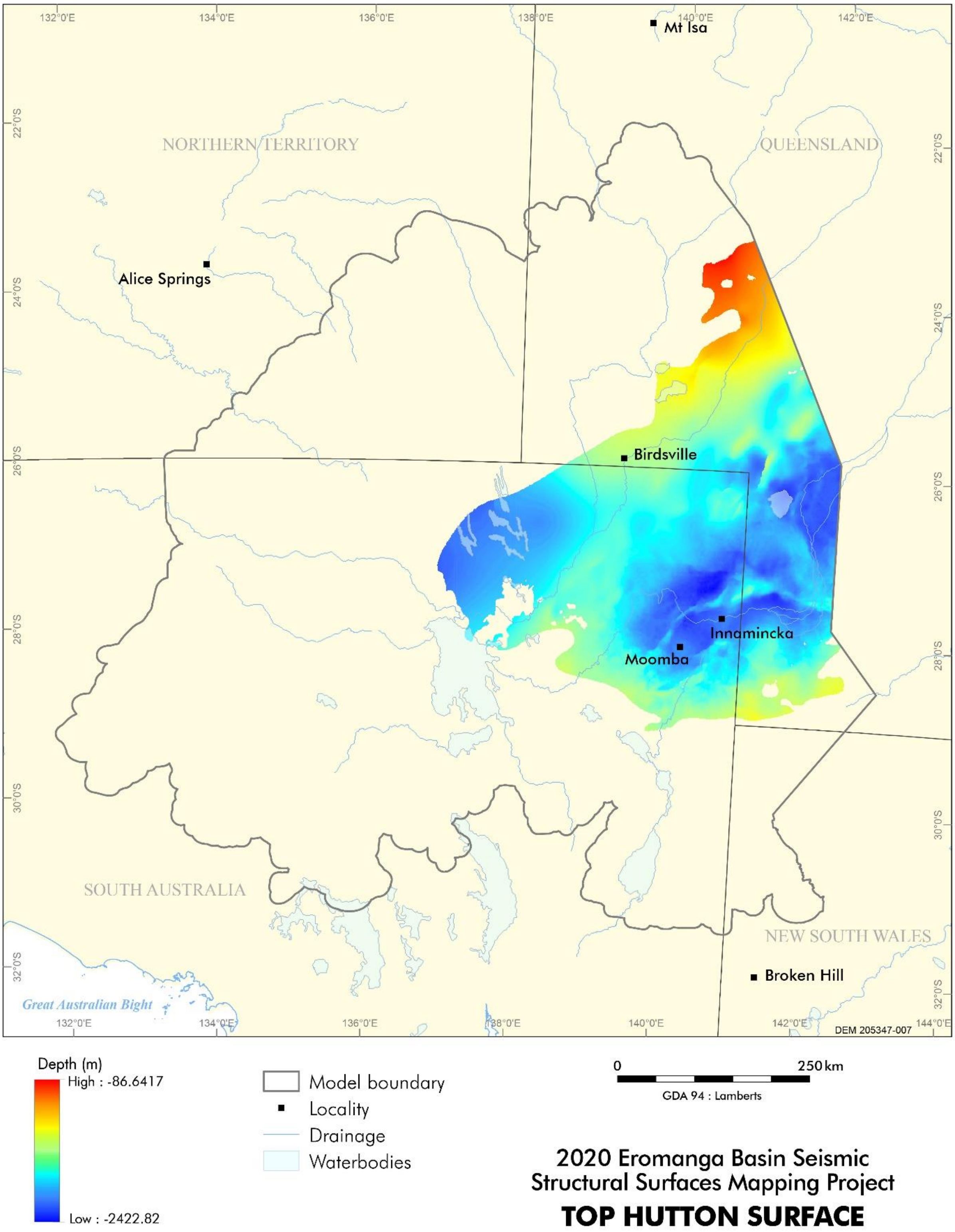

Figure 10. Top Hutton Surface

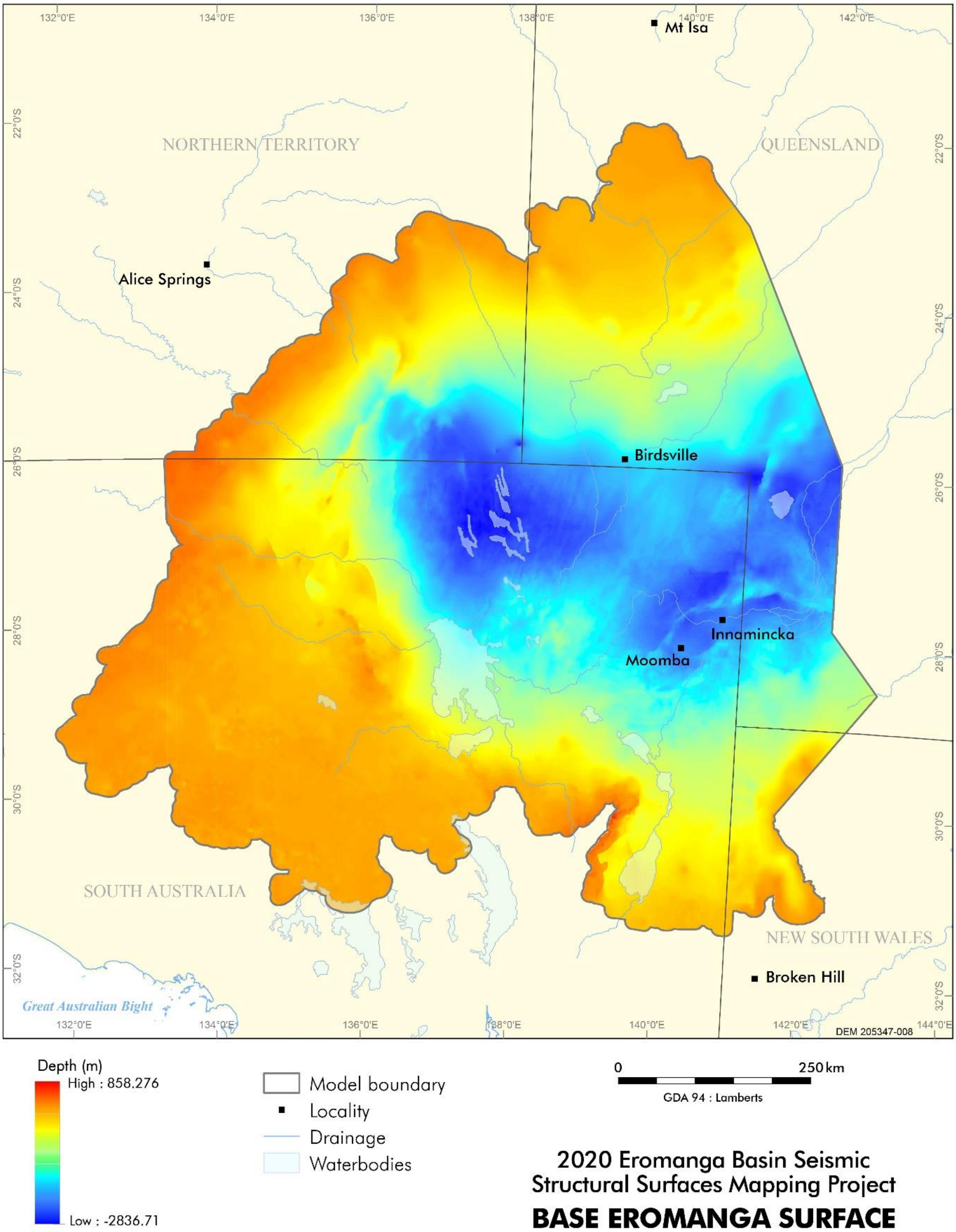

Figure 11. Base Eromanga Surface

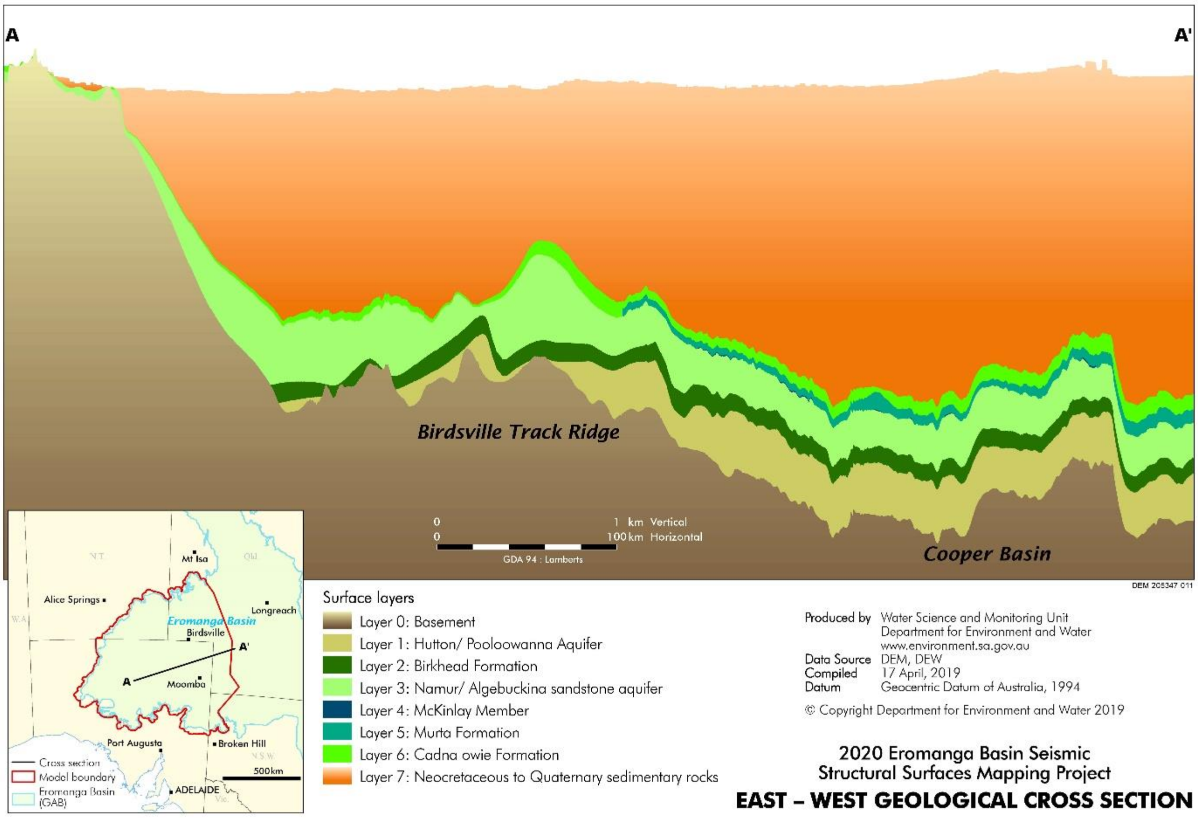

Figure 12. East – West cross section displaying facies changes on the western margins of the Eromanga Basin

6 CONCLUSIONS AND LESSONS

6.1 CONCLUSIONS

Seismic structural surfaces required for the construction of a 3-dimensional static and dynamic model were successfully created using a combination of industry and government data. In the course of this project numerous errors were corrected both in publicly-available grid and well data, and in data provided by industry. This step improved the quality of data in the public domain.

The results from this project were made available to the modelling stage of the Far North Prescribed Wells Area project, and subject to the appropriate authorities' permissions the results can be made available to the public.

The results, working projects, reports and adjunct data involved in this project have been saved and archived by DEW for future use. It is recommended that the DEW Far North Prescribed Wells Area Groundwater Model project (DEW, 2020) and this report are used as reference guides for future updates and extensions to the FNPWAP dataset.

6.2 LESSONS

Major projects in particular, provide opportunities for improvements of data and methods. In this project, in addition to the main purpose of improving the FNWAP transient model, there were some unexpected opportunities to improve existing data and to highlight possible improvements to methods and processes.

To ensure that input data were of the highest data quality prior to input into this project an extensive phase of well data QC of data stored in PEPS SA was carried out in the early stages of the project highlighted. This stage required more time than estimated and highlighted the need for periodic QA of the PEPS database, or for more robust methods of QA during data entry.

A program of correcting tops data in deviated wells using the well deviation survey would add value to the PEPS database and should be considered for future implementation.

A further benefit in the PEPS database would be to allow base formation depths to be extracted. An entry for base Eromanga for example would have been time-saving and extremely useful.

Our work with GABWRA surfaces downloaded from the GA website highlighted undesirable patterns contained within the publically-available data. Our work led to the removal of these patterns in the publically available grids.

Differences in exploration data in the DEW database and in the PEPS database showed how these two databases had become disconnected, and highlighted the need for the two databases to be linked, in particular for the DEW database to be dynamically updated from the PEPS database on a regular, perhaps weekly basis.

Due to the large spatial extent of the study area and the large number of grid nodes involved (up to 55.6 million in imported grids), initial computations on a small laptop were lengthy, taking up to 6 hours for more complex functions on the largest grids. Through various trials, these processes were optimised reducing the computational time to about 30 minutes. Final exported grids had 400 x 400 m cells and roughly 8.8 million nodes. With a new and more powerful computer processing times were further reduced by half.

The project was originally conceived as an extension, improvement and refinement of the previous WAP2012 grids by incorporating and interpreting seismic data. The sheer volume and, in many cases poor quality of the seismic data, prevented this approach from being implemented. Furthermore time interpretations would have required a large additiona— component - the velocity field – to translate the time grids into depth. Both steps were considered too large for the time and cost constraints of the project. Consequently, seismic data, loaded at the start of the project were used for reference and for QA of depth grids, for example confirmation of broad structural features and major faults.

A number of key staff with historical knowledge, Ieological, interpretive and general logistical skills were on hand to assist with the project. These and the excellent help from IT staff were essential in expediting the project. Additionally, personal knowledge of staff in DEM, contractors, staff in DEW and in other organisations such as GA, and operators (Santos, Senex, Beach) added value during the data collection stage of the project.

7 DATA DISBURSEMENT

The following files were delivered to DEW on 31st January 2020:

C_CadnaOwie_20200131.bil.aux.xml
C_CadnaOwie_20200131.bil.ovr
C_CadnaOwie_20200131.hdr
C_CadnaOwie_20200131.bil
C_CadnaOwie_20200131.prj
C_CadnaOwie_20200131.stx

J_BaseEromanga_20200131.bil.aux.xml

J_BaseEromanga_20200131.bil.ovr
J_BaseEromanga_20200131.hdr
J_BaseEromanga_20200131.bil
J_BaseEromanga_20200131.prj
J_BaseEromanga_20200131.stx

H_Hutton_20200131.bil.aux.xml
H_Hutton_20200131.bil.ovr
H_Hutton_20200131.hdr
H_Hutton_20200131.bil
H_Hutton_20200131.prj
H_Hutton_20200131.stx

E_Birkhead_20200131.bil.aux.xml
E_Birkhead_20200131.bil.ovr
E_Birkhead_20200131.hdr
E_Birkhead_20200131.bil
E_Birkhead_20200131.prj
E_Birkhead_20200131.stx

DM_Murta_20200131.bil.aux.xml
DM_Murta_20200131.bil.ovr
DM_Murta_20200131.hdr
DM_Murta_20200131.bil
DM_Murta_20200131.prj
DM_Murta_20200131.stx

Dn_Namur_20200131.bil.aux.xml
Dn_Namur_20200131.bil.ovr
Dn_Namur_20200131.hdr
Dn_Namur_20200131.bil
Dn_Namur_20200131.prj
Dn_Namur_20200131.stx

McK_McKinlay_20200131.bil.aux.xml
McK_McKinlay_20200131.bil.ovr
McK_McKinlay_20200131.hdr
McK_McKinlay_20200131.bil
McK_McKinlay_20200131.prj
McK_McKinlay_20200131.stx

Table 10-3. Listing of final structural surfaces ESRI BIL files

All project data, including progress reports, e-mails and images were provided to DEM on a 1TB portable USB drive for archive.

A short internal report detailing the well and surface data structures and flows within Petrosys™ was provided to DEM under the name: FNWAP 2019-2020 – Project Configuration and Use.

8 APPENDICES

8.1 ABBREVIATIONS

AOI: Area of Interest
C: Cadna-owie
CRS: Coordinate Reference System
DEW: Department for Environment and Water
DM: Murta
Dn: Namur
E: Birkhead
FNPWA Far North Prescribed Wells Area
FNWAP: Far North Water Allocation Plan
H: Hutton
GA: Geoscience Australia
GAB: Great Artesian Basin
GABWRA: Great Artesian Basin Water Resource Assessment
J: Base Eromanga
McK: McKinlay
MSL: Mean Sea Level
m: metres
PEPS: Petroleum Exploration and Production System
QC/QA: Quality Control/Quality Assurance
QPED: Queensland Petroleum Exploration Data
TB: Terra byte
WAP/WAP2012: Water Allocation Plan (2012)

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11 Units of measurement

11.1 Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

11.2 Shortened forms

bgs	below ground surface
EC	electrical conductivity (µS/cm)
pH	acidity
pMC	percent of modern carbon
Ma	Million years

12 Glossary

Act (the) — In this document, refers to the *Natural Resources Management (SA) Act 2004,* which supersedes the *Water Resources (SA) Act 1997*

Ambient — The background level of an environmental parameter (for example, a measure of water quality such as salinity)

Ambient water monitoring — All forms of monitoring conducted beyond the immediate influence of a discharge pipe or injection well, and may include sampling of sediments and living resources

Ambient water quality — The overall quality of water when all the effects that may impact upon the water quality are taken into consideration

Anastomosing river — A river with a channel pattern composed of splitting and rejoining channels that enclose variously shaped and sized islands of remnant floodplain or non-alluvial landforms

Aquiclude — In hydrologic terms, a formation that contains water but cannot transmit it rapidly enough to furnish a significant supply to a well or spring

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining unit') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resources available for development from the well

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them

ArcGIS — Specialised GIS software for mapping and analysis developed by ESRI

Arid lands — In South Australia, arid lands are usually considered to be areas with an average annual rainfall of less than 250 mm and support pastoral activities instead of broadacre cropping

Artesian — An aquifer in which the water surface is bounded by an impervious rock formation; the water surface is at greater than atmospheric pressure, and hence rises in any well, which penetrates the overlying confining aquifer

Artificial recharge — The process of artificially diverting water from the surface to an aquifer; artificial recharge can reduce evaporation losses and increase aquifer yield; see also 'natural recharge', 'aquifer'

Basin — The area drained by a major river and its tributaries

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

Buffer zone — A neutral area that separates and minimises interactions between zones whose management objectives are significantly different or in conflict (for example, a vegetated riparian zone can act as a buffer to protect the water quality and streams from adjacent land uses)

^{14}C — Carbon-14 isotope (percent modern Carbon; pMC)

Catchment — That area of land determined by topographic features within which rainfall will contribute to runoff at a particular point

CFC — Chlorofluorocarbon; measured in parts per trillion (ppt)

Climate change — The balance of incoming and outgoing solar radiation which regulates our climate. Changes to the composition of the atmosphere, such as the addition of carbon dioxide through human activities, have the potential to alter the radiation balance and to effect changes to the climate. Scientists suggest that changes would include global warming, a rise in sea level and shifts in rainfall patterns.

CMB — Chloride mass balance

Cone of depression — An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction that exceeds the rate of recharge; continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality

Confining unit — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

CSG — coal seam gas

CSIRO — Commonwealth Scientific and Industrial Research Organisation

δD — Hydrogen isotope composition, measured in parts per thousand (**°/₀₀**)

Dams, off-stream dam — A dam, wall or other structure that is not constructed across a watercourse or drainage path and is designed to hold water diverted or pumped from a watercourse, a drainage path, an aquifer or from another source; may capture a limited volume of surface water from the catchment above the dam

Dams, on-stream dam — A dam, wall or other structure placed or constructed on, in or across a watercourse or drainage path for the purpose of holding and storing the natural flow of that watercourse or the surface water

Dams, turkey nest dam — An off-stream dam that does not capture any surface water from the catchment above the dam

DEW — Department for Environment and Water

DEWNR — Department of Environment, Water and Natural Resources (Government of South Australia)

DfW — former Department for Water (Government of South Australia)

dGPS — differential Global Positioning System

DO — Dissolved Oxygen

DOC — Dissolved Organic Carbon

Domestic purpose — The taking of water for ordinary household purposes; includes the watering of land in conjunction with a dwelling not exceeding 0.4 hectares

Dryland salinity — The process whereby salts stored below the surface of the ground are brought close to the surface by the rising watertable. The accumulation of salt degrades the upper soil profile, with impacts on agriculture, infrastructure and the environment.

DSS — Dissolved suspended solids

DWLBC — former Department of Water, Land and Biodiversity Conservation (Government of South Australia)

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

Ecology — The study of the relationships between living organisms and their environment

Ecological processes — All biological. physical or chemical processes that maintain an ecosystem

Ecological values — The habitats, natural ecological processes and biodiversity of ecosystems

Ecosystem — Any system in which there is an interdependence upon, and interaction between, living organisms and their immediate physical, chemical and biological environment

Endemic — A plant or animal restricted to a certain locality or region

Environmental values — The uses of the environment that are recognised as being of value to the community. This concept is used in setting water quality objectives under the Environment Protection (Water Quality) Policy, which recognises five environmental values — protection of aquatic ecosystems, recreational water use and aesthetics, potable (drinking water) use, agricultural and aquaculture use, and industrial use. It is not the same as ecological values, which are about the elements and functions of ecosystems.

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral.

Erosion — Natural breakdown and movement of soil and rock by water, wind or ice; the process may be accelerated by human activities

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

Fresh — A short duration, small volume pulse of streamflow generated by a rainfall event that temporarily, but noticeably, increases stream discharge above ambient levels

Fully-penetrating well — In theory this is a well-hole that is screened throughout the full thickness of the target aquifer; in practice, any screen that is open to at least the mid 80% of a confined aquifer is regarded as fully-penetrating.

GAB — Great Artesian Basin

GDE — Groundwater dependent ecosystem

Geological features — Include geological monuments, landscape amenity and the substrate of land systems and ecosystems

Geomorphic — Related to the physical properties of the rock, soil and water in and around a stream

Geomorphology — The scientific study of the landforms on the Earth's surface and of the processes that have fashioned them

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Groundwater Data — Interactive map and search tool for viewing information about South Australia's wells with access to well details including, graphs showing water salinity and water level. It provides a variety of search methods, including filtering the results. [*waterconnect.sa.gov.au/Systems/GD/]*

Head (hydraulic) — Sum of datum level, elevation head and pressure head. The altitude to which water will rise in a properly constructed well. In unconfined aquifers it is the groundwater elevation, and in confined aquifers it is the potentiometric head.

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Hydrography — The discipline related to the measurement and recording of parameters associated with the hydrological cycle, both historic and real time

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

Infrastructure — Artificial lakes; dams or reservoirs; embankments, walls, channels or other works; buildings or structures; or pipes, machinery or other equipment

Injection well — An artificial recharge well through which water is pumped or gravity-fed into the ground

Irrigation — Watering land by any means for the purpose of growing plants

Kati Thanda–Lake Eyre — Lake Eyre was co-named with the name used by the Arabana people in December 2012

Kati Thanda–Lake Eyre National Park — was proclaimed in November 2013 to recognise the significance of Lake Eyre to the Arabana people and co-name the lake Kati Thanda–Lake Eyre.

Lake — A natural lake, pond, lagoon, wetland or spring (whether modified or not) that includes part of a lake and a body of water declared by regulation to be a lake. A reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

Land — Whether under water or not, and includes an interest in land and any building or structure fixed to the land

Licence — A licence to take water in accordance with the Act; see also 'water licence'

Licensee — A person who holds a water licence

LMWL — Local meteoric water line

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

MAR — Managed aquifer recharge (MAR) is a process where water is intentionally placed and stored in an aquifer for later human use, or to benefit the environment.

Metadata — Information that describes the content, quality, condition, and other characteristics of data, maintained by the Federal Geographic Data Committee

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change

MODFLOW — A three-dimensional., finite difference code developed by the USGS to simulate groundwater flow

Molar (M) — A term describing the concentration of chemical solutions in moles per litre (mol/L)

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals, and other living things

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Natural resources — Soil, water resources, geological features and landscapes, native vegetation, native animals and other native organisms, ecosystems

NRM — Natural Resources Management; all activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively

NWC — National Water Commission

$\delta^{18}O$ — Oxygen isotope composition, measured in parts per thousand (‰)

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

ORP — Oxidation Reduction Potential

Owner of land — In relation to land alienated from the Crown by grant in fee simple — the holder of the fee simple; in relation to dedicated land within the meaning of the *Crown Lands Act 1929* that has not been granted in fee simple but which is under the care, control and management of a Minister, body or other person — the Minister, body or other person; in relation to land held under Crown lease or licence — the lessee or licensee; in relation to land held under an agreement to purchase from the Crown — the person entitled to the benefit of the agreement; in relation to any other land — the Minister who is responsible for the care, control and management of the land or, if no Minister is responsible for the land, the Minister for Sustainability, Environment and Conservation.

Paleochannels — Ancient buried river channels in arid areas of the state. Aquifers in paleochannels can yield useful quantities of groundwater or be suitable for ASR

PEPS SA — Petroleum Exploration and Production System — South Australia. PEPS SA is a web-based system containing a wide range of technical data relevant to the petroleum and geothermal industries. The web based system is maintained by the South Australian Government, Department for Energy and Mining.

Percentile — A way of describing sets of data by ranking the dataset and establishing the value for each percentage of the total number of data records. The 90th percentile of the distribution is the value such that 90% of the observations fall at or below it.

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m/d

Piezometer — A narrow tube, pipe or well; used for measuring moisture in soil, water levels in an aquifer, or pressure head in a tank, pipeline, etc.

PIRSA — Primary Industries and Regions South Australia (Government of South Australia)

Population — (1) For the purposes of natural resources planning, the set of individuals of the same species that occurs within the natural resource of interest. (2) An aggregate of interbreeding individuals of a biological species within a specified location

Porosity — The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment (Middlemis, 2000).

Porosity, effective — The volume of the inter-connected void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.

Porosity, Primary — The porosity that represents the original pore openings when a rock or sediment formed (Middlemis, 2000).

Porosity, Secondary — The porosity that has been caused by fractures or weathering in a rock or sediment after it has been formed (Middlemis, 2000).

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

Prescribed water resource — A water resource declared by the Governor to be prescribed under the Act, and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

Prescribed well — A well declared to be a prescribed well under the Act

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

Protolith — The original, unmetamorphosed or undeformed rock from which a given metamorphic or structurally deformed rock is formed.

PWA — Prescribed Wells Area

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

RSWL —Reduced Standing Water Level measured in metres AHD (Australian Height Datum). The elevation of the water level is calculated by subtracting the Depth to Water (DTW) from the reference elevation. A negative value indicates that the water level is below mean sea level.

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access through the offices of PIRSA. Custodianship of data related to minerals and petroleum, and groundwater, is vested in PIRSA and DEW, respectively. DEW should be contacted for database extracts related to groundwater

Salinity — The concentration of dissolved salts in water or soil, expressed in terms of concentration (mg/L) or electrical conductivity (EC)

SARIG — South Australian Resource Information Gateway. SARIG is a mapping portal that delivers a diverse range of open geoscience data, information and products for the mining, petroleum, and exploration community. The portal is maintained by the South Australian Government, Department for Energy and Mining.

SDE — South Australian government dataset containing all other spatially explicit data not housed by SA GEODATA, HYDSTRA, or BDBSA

Seasonal— Pertaining to a phenomena or event that occurs on a on a seasonal basis

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; measured in m^{-1}

Specific yield (S_y) — The volume ratio of water that drains by gravity to that of total volume of the porous medium. It is dimensionless

Stock use — The taking of water to provide drinking water for stock other than stock subject to intensive farming (as defined by the Act)

Storativity (S) — Storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is the product of specific storage Ss and saturated aquifer thickness (dimensionless)

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Sustainability — The ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time

SWL — Standing Water Level (metres) recorded for the water well. This is the distance from the ground surface to the water surface. A negative value indicates that the water level is above ground level.

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago). Also known as the Paleogene to Neogene period.

Threatened species — Any species that is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow), measured in m^2/d

Tributary — A river or creek that flows into a larger river

Turbidity — The cloudiness or haziness of water (or other fluid) caused by individual particles that are too small to be seen without magnification, thus being much like smoke in air; measured in Nephelometric Turbidity Units (NTU)

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

USGS — United States Geological Survey

Volumetric allocation — An allocation of water expressed on a water licence as a volume (for example, kilolitres) to be used over a specified period of time, usually per water use year (as distinct from any other sort of allocation)

Water allocation — (1) In respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence. (2) In respect of water taken pursuant to an authorisation under s.11 means the maximum quantity of water that can be taken and used pursuant to the authorisation

WAP — Water Allocation Plan; a plan prepared by a water resources planning committee and adopted by the Minister in accordance with the Act

Water body — Includes watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers

Water column — a section of water extending from the surface of a body of water to its bottom. In the sea or ocean, it is referred to as 'pelagic zone'

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Water dependent ecosystems — Those parts of the environment, the species composition and natural ecological processes, that are determined by the permanent or temporary presence of flowing or standing water, above or below ground; the in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water dependent ecosystems

Water licence — A licence granted under the Act entitling the holder to take water from a prescribed watercourse, lake or well or to take surface water from a surface water prescribed area; this grants the licensee a right to take an allocation of water specified on the licence, which may also include conditions on the taking and use of that water; a water licence confers a property right on the holder of the licence and this right is separate from land title

Water plans — The State Water Plan, water allocation plans and local water management plans prepared under Part 7 of the Act

Water quality data — Chemical, biological, and physical measurements or observations of the characteristics of surface and groundwaters, atmospheric deposition, potable water, treated effluents, and wastewater, and of the immediate environment in which the water exists

Water quality information — Derived through analysis, interpretation, and presentation of water quality and ancillary data

Water quality monitoring — An integrated activity for evaluating the physical, chemical, and biological character of water in relation to human health, ecological conditions, and designated water uses

Water resource monitoring — An integrated activity for evaluating the physical., chemical., and biological character of water resources, including (1) surface waters, groundwaters, estuaries, and near-coastal waters; and (2) associated aquatic communities and physical habitats, which include wetlands

Water resource quality — (1) The condition of water or some water-related resource as measured by biological surveys, habitat-quality assessments, chemical-specific analyses of pollutants in water bodies, and toxicity tests. (2) The condition of water or some water-related resource as measured by habitat quality, energy dynamics, chemical quality, hydrological regime, and biotic factors

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

Wetlands — Defined by the Act as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial., permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.

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