

Hydrogeological Atlas of the Great Artesian Basin



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Summary

The Great Artesian Basin (GAB) is one of Australia's most significant hydrogeological entities covering more than 1.7 million square kilometres, underlying parts of Queensland, New South Wales, South Australia and the Northern Territory. The GAB contains a vast volume of underground water (estimated at 64,900 million megalitres¹) and is the largest groundwater basin in Australia. Groundwater resources in the GAB are used to support the pastoral, agricultural, and resource sectors as well as supplying water to inland communities. Properly managing these groundwater resources, often for competing interests, requires an understanding of how the groundwater system works at a regional scale.

This atlas presents a compilation of maps documenting some of the key regional geological, hydrogeological and hydrochemical aspects of the GAB. It provides insights into the current understanding of the regional geometry and physical characteristics of the rocks and water contained within this vast groundwater basin and baseline information against which future changes can be assessed.

The atlas draws upon recent work undertaken by Geoscience Australia (GA) that has contributed to a number of projects, such as the CSIRO-led Great Artesian Basin Water Resource Assessment (GABWRA) (<http://www.ga.gov.au/scientific-topics/water/groundwater/gabwra>) project and GA's Carbon Capture and Storage project. Since these projects, new information has led to some of the concepts and interpretations being revised or refined for this atlas. Two key pieces of new work that are presented in this atlas are the up to date interpretations of the extent and thickness of the major aquifers and aquitards and the basin-wide perspective of the variation of water chemistry found within the major aquifers.

The atlas and associated datasets combine to form a valuable information resource base for water managers and communities to support informed water management decisions within the GAB. It will assist both water managers and communities to better understand the groundwater resources contained within the GAB and to evaluate the effectiveness of management activities.

Introduction

The GAB extends across parts of outback Queensland, New South Wales, South Australia and the Northern Territory. Access to groundwater from the GAB has allowed a significant portion of arid Australia to be opened up to grazing. The groundwater resources contained within the GAB are, in many cases, the only reliable domestic and stock watering supply available to the many towns and properties, across the basin. Furthermore, groundwater from the GAB is a vital resource for mining operations, hydrocarbon exploration and is in some instances used for irrigation.

Four distinct, but hydraulically-connected, geological basins; the Eromanga, Carpentaria, Surat and Clarence-Moreton basins, constitute the hydrogeological sub-basins of the GAB. Each of these sub-basins contains groundwater stored within porous and permeable sandstone formations and to a lesser extent fractures and faults. The GAB sequence reaches a thickness of approximately 3000 m in the central part of the Eromanga Basin and comprises alternating sandstone, siltstone and mudstone beds that constitute the identified aquifers and aquitards of the GAB.

The atlas is structured into three sections. Section one (Maps 1–22) presents important hydrogeological and geological aspects of the GAB, including the regional hydrostratigraphy, the outcrop and subcrop extents of the major aquifers and aquitards, the position of major faults and structural features and groundwater pressure and flow directions in the main artesian aquifer. Section two (Maps 23–32) provides details on the extent and thickness of the major aquifers and aquitards that constitute the GAB. Section 3 (Maps 33–55) shows the spatial variation in groundwater chemistry found within the major aquifers of the GAB.

The datasets and interpretations produced for the atlas draw upon data that varies in scale and accuracy. The maps presented are intended to be used for a broad, regional understanding of the basin and are not designed to be used at a local scale. Where third party data has been used, the authors have attempted to verify its accuracy before incorporating it into the maps and datasets produced for this atlas.

The data for producing this atlas is available for download via the Geoscience Australia website at www.ga.gov.au (a table listing available digital data and download instructions is provided at the back of this document). Each dataset is accompanied by a metadata statement that details the source datasets and methods used to produce the data and interpretations presented in each map.

The Great Artesian Basin—what is it, and how interconnected is it?

Understanding large-scale groundwater systems requires a clear delineation of the system extent and its geological characteristics. Where we have an incomplete knowledge of such systems (as in many parts of Australia) we are forced to use a surrogate that can be readily mapped—one or several sedimentary basins.

Thanks largely to petroleum exploration in conjunction with continued groundwater extraction, we now understand that the GAB, as a hydrogeological entity, is contained predominantly within the Jurassic-Cretaceous Eromanga, Surat and Carpentaria geological basins. Artesian water is also exploited in limited parts of the Galilee and Bowen basins, where groundwater is sourced from Triassic aquifers, and from Cenozoic aquifers in the Karumba Basin of Cape York. Historically the GAB encompassed this diversity of host basins and this definition continues in Queensland for groundwater resource management purposes (with the addition of the Laura Basin, on the northeastern portion of Cape York, and part of the Clarence-Moreton Basin, east of Toowoomba).

Today the GAB is known not to be a discrete isolated system, but to be an entity with a variably-permeable boundary, interconnected with numerous underlying and adjoining sedimentary basins as well as fractured basement. In this current state of a conceptual, but unquantified, knowledge of such variable connectivity, the challenge has been to define mappable limits to the groundwater resource we know as the GAB. Given this complex character, it was proposed by the

Great Artesian Basin Water Resource Assessment (GABWRA) that the GAB as a hydrogeological entity, be constrained to lie within the Surat, Eromanga, Carpentaria and Clarence-Moreton basins and their overlying Cenozoic basin cover.

This atlas continues with the GABWRA definition of the GAB but uses a modified hydrogeological boundary in Cape York. The revised boundary excludes the Laura Basin and is now defined by a groundwater divide at the northernmost tip of Cape York (northward of approx. 150 km northeast of Weipa). Elsewhere the hydrogeological boundary follows the geological margins of four component sub-basins—the Eromanga, Carpentaria, Surat and Clarence-Moreton sub-basins—except where the watertable delineates groundwater divides that indicate externally-draining regions. In specific areas, this drainage divide changes geographically upwards through the GAB sequence. One example is the GAB boundary within the Clarence-Moreton Basin where the broadest hydrogeological extent has been adopted as the GAB boundary.

For the purpose of this atlas, the portions of the Bowen and Galilee Basins that were historically included in the GAB, are excluded and instead are addressed through the concept of GAB basement hydroconnectivity (see Map 14). This concept qualitatively defines the hydraulic connectivity with the 27 known sedimentary basins that have contact with the base of the GAB (Figure 1).

The defined northern limit of the offshore Carpentaria Sub-basin corresponds to the international maritime boundary with Papua New Guinea. The GAB has apparent hydrogeological continuity into the southern offshore territory of Papua New Guinea in the Winton-Mackunda Aquifer and Equivalents.

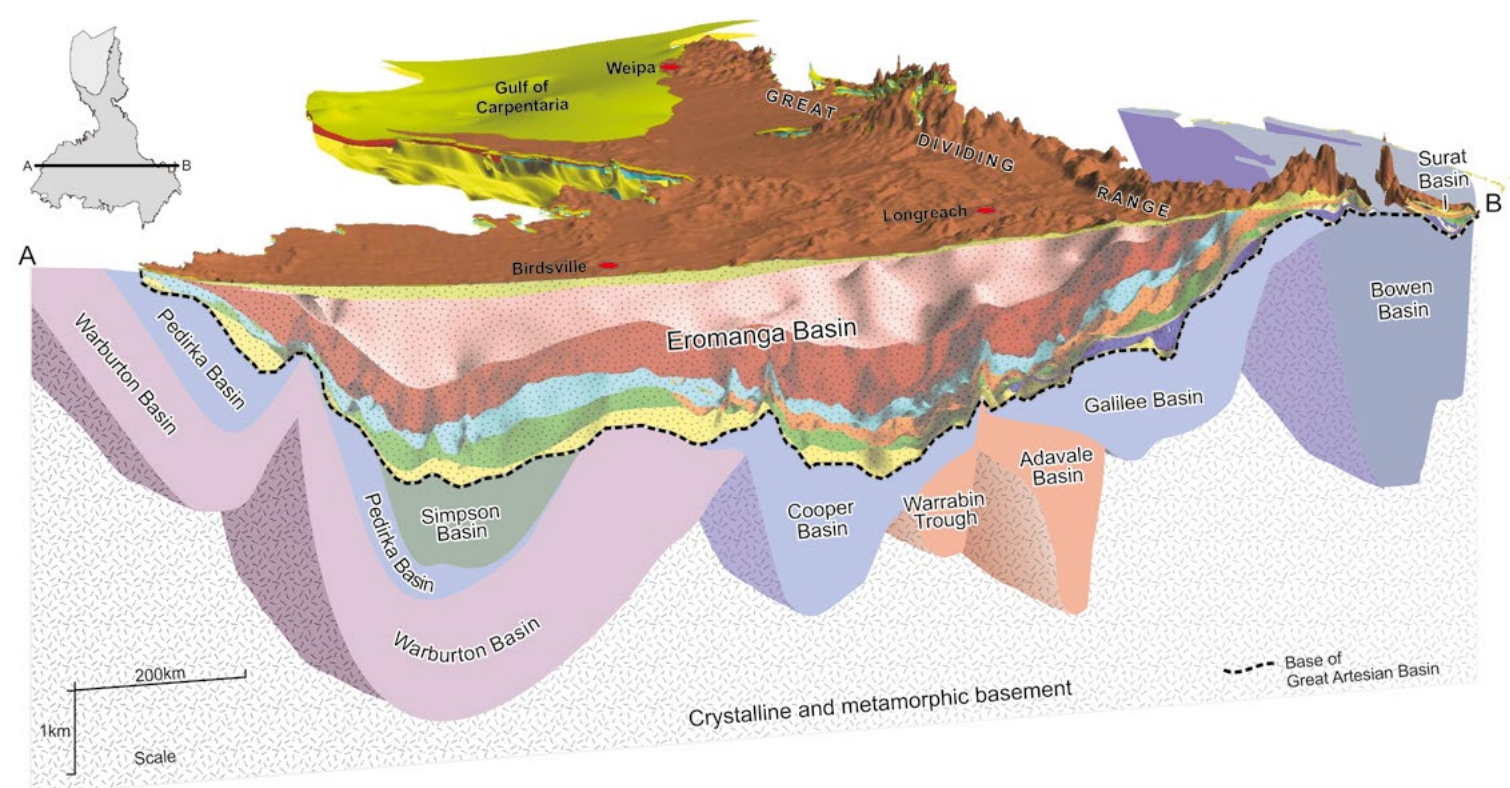


Figure 1 Three-dimensional slice through the GAB and underlying older sedimentary basins. Layers within the Eromanga Basin represent the major aquifers and aquitards of the GAB (Reproduced from work undertaken for the Great Artesian Basin Water Resource Assessment (Smerdon BD, Ransley TR, Radke BM and Kellett JR (2012)))

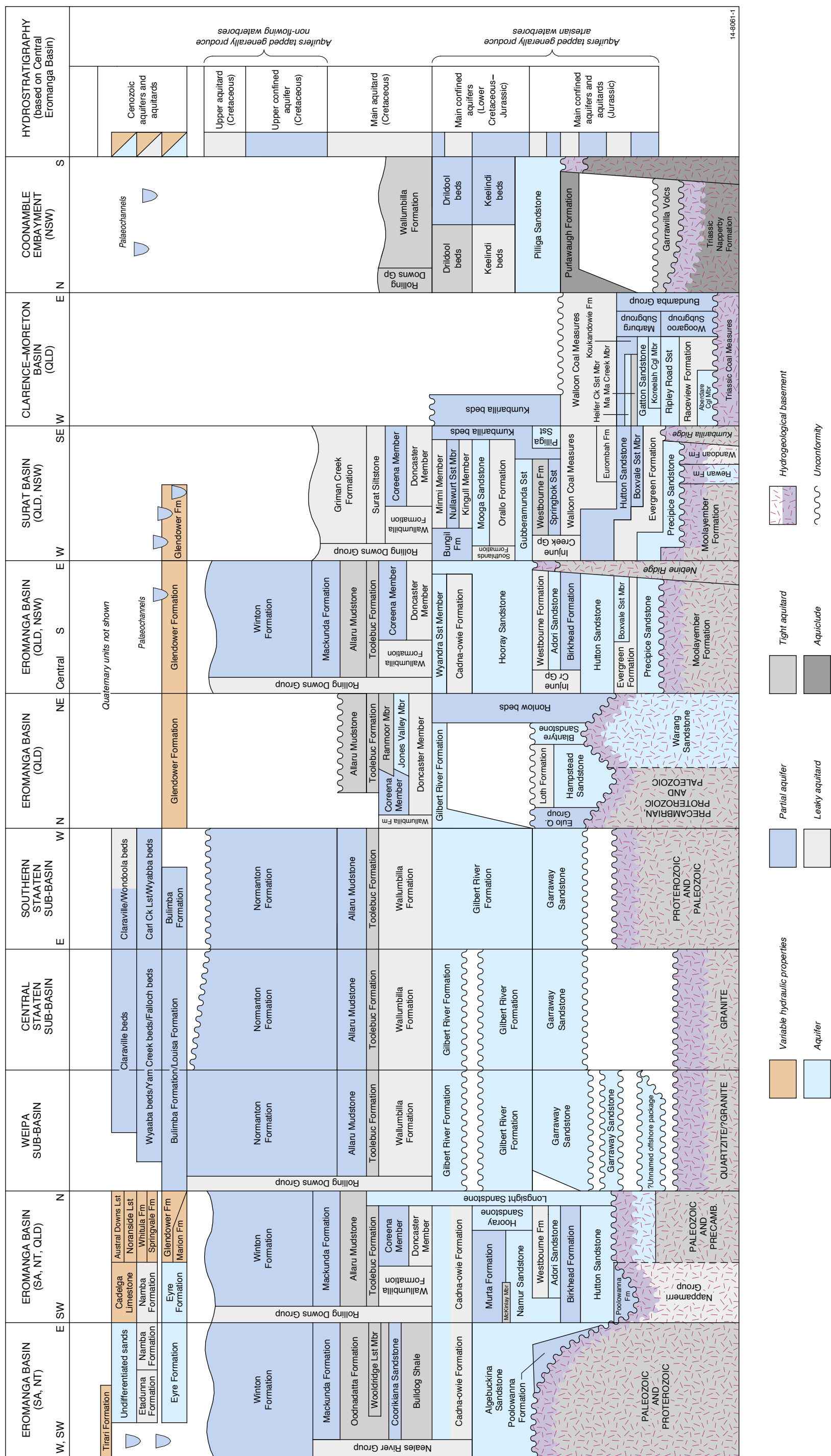
Hydrostratigraphy^{*}

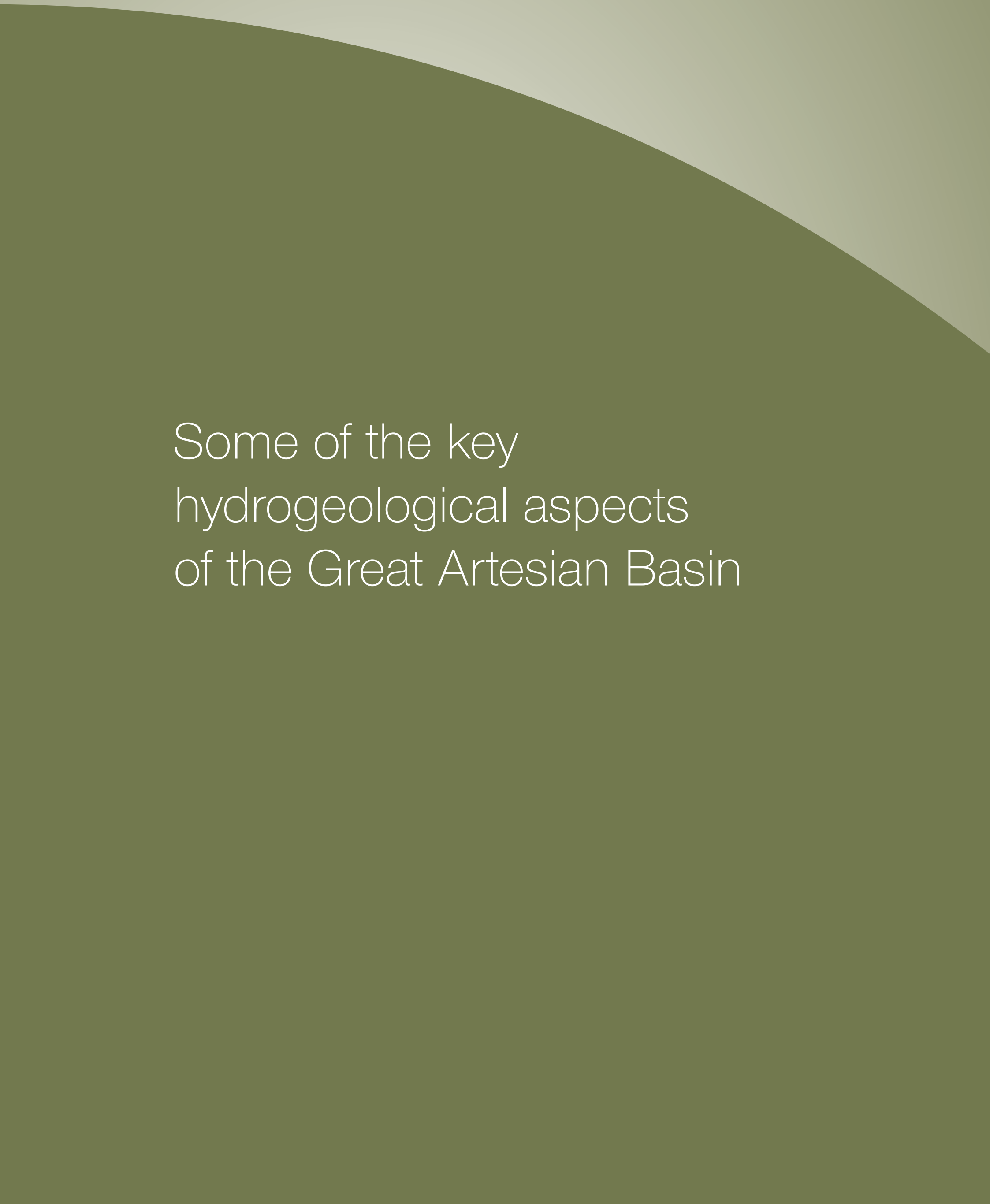
The objective of hydrostratigraphic classification is to group contiguous layers of rocks with similar hydrogeological properties. Generally this classification allows rock layers to be categorised as either aquifers or aquitards (confining units) (see glossary).

The basin-wide categorisation of aquifers and aquitards is an oversimplification of the system. There is much more variability in the character of hydrostratigraphic units so a more illustrative classification differentiates aquifers, partial aquifers, leaky aquitards, tight aquitards and aquicludes. This qualitative categorisation has been adopted for the hydrostratigraphic chart of the GAB and shows that the hydrogeological properties of a unit may vary in different regions and between the geological sub-basins that make up the GAB. This variation in properties may be due to sediment source, accommodation rates during deposition, as well as diagenetic and structural overprints.

The hydrostratigraphic chart of the GAB correlates the numerous lithostratigraphic units applied across the constituent geological basins (see Maps 1 and 4), by grouping them into regional hydrostratigraphic units. Such a classification provides a basin-wide perspective of the hydrogeological architecture of the GAB.

^{*} Modified from work undertaken for the Great Artesian Basin Water Resource Assessment (Ransley TR and Smerdon BD (2012)) using revised hydrostratigraphic classification for Hutton Sandstone and constituent sub-basins.





Some of the key
hydrogeological aspects
of the Great Artesian Basin

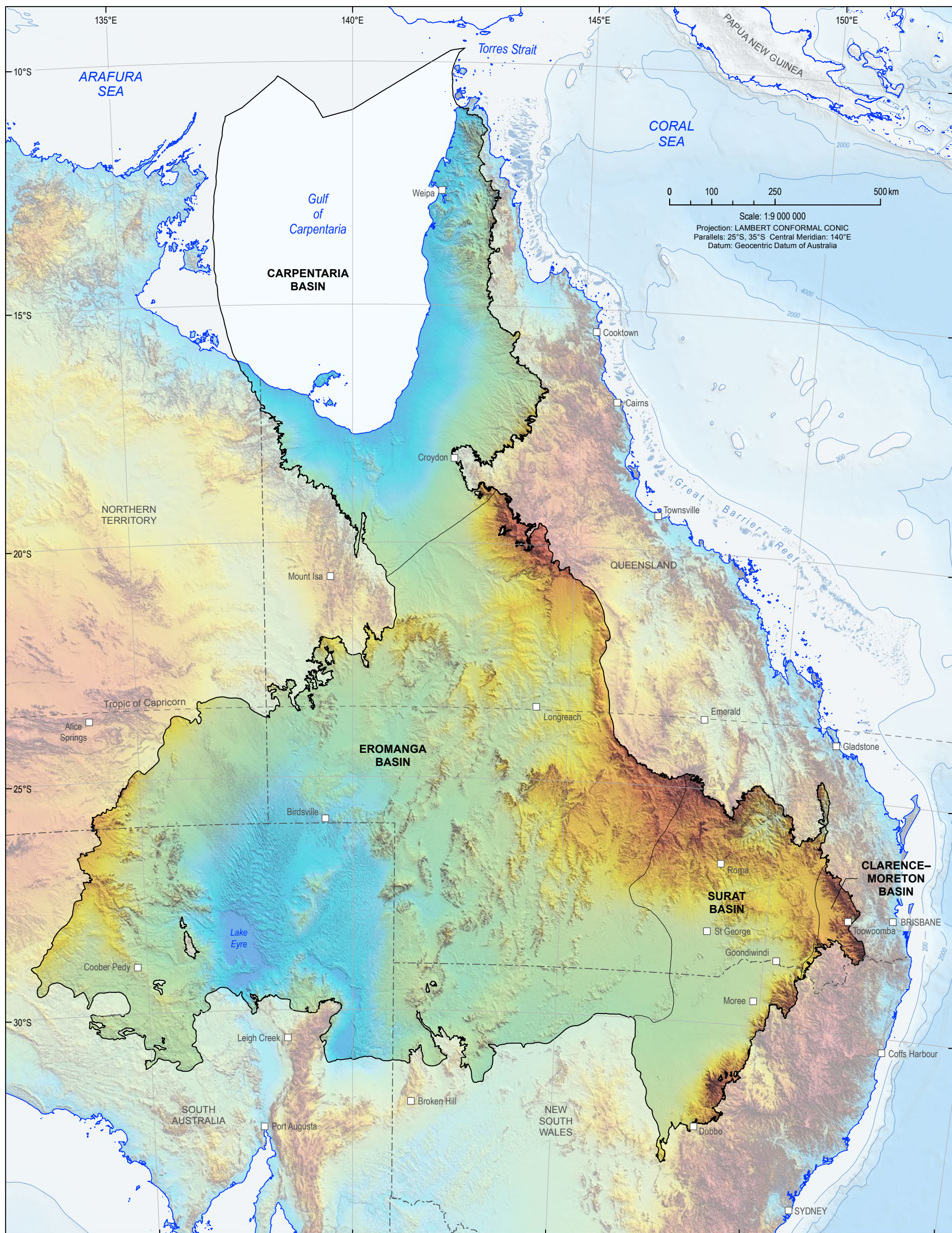
Map 1

Topography

The Great Artesian Basin comprises the Surat, Eromanga, Carpentaria and part of the Clarence-Moreton geological basins and their overlying Cenozoic cover.

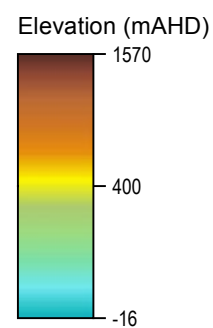
Covering around 20% of the continent, the surface of the GAB is characterised by a variety of landforms, including low-lying interior plains, the tablelands and uplands of the Great Dividing Range and dune fields of the Simpson, Tirari and Strzelecki deserts. North of latitude 21°S, surface drainage is toward the coast across terrain that slopes gently toward the Gulf

of Carpentaria. In contrast, south of latitude 21°S, ephemeral rivers draining the western slopes of the Great Dividing Range generally flow to the southwest as the ground surface slopes toward Lake Eyre. Ground elevations range from greater than 1500 m above sea level along the eastern boundary, to 15 m below sea level at Lake Eyre.



- Great Artesian Basin
- Constituent geological basin

- 200 — Bathymetry contour (depth in metres)
- - - Tropic of Capricorn
- City/town



Map 2

Hydrogeology

The GAB hydrogeological boundary follows the geological margins of its four component sub-basins—the Eromanga, Carpentaria, Surat and Clarence-Moreton sub-basins—except where the watertable indicates groundwater divides within these regions that delineate externally-draining areas. In some regions, this drainage divide changes geographically through the GAB sequence. In such areas as the GAB boundary within the Clarence-Moreton Basin, the broadest hydrogeological extent has been adopted as the GAB boundary.

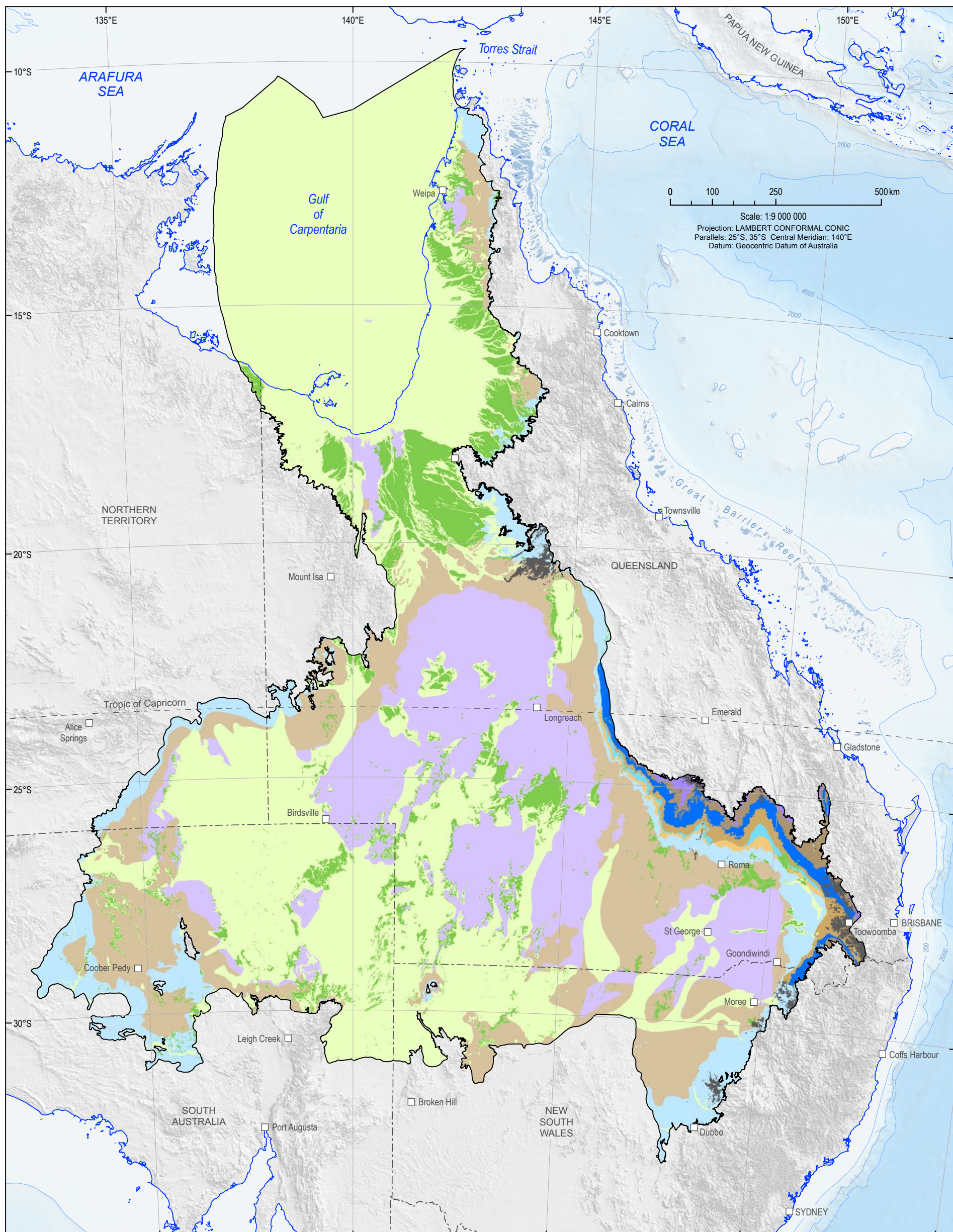
This map documents a basin-wide hydrostratigraphy of the GAB comprising five major aquifers, four intervening aquitards, and the cover of these units by Paleogene-Neogene rocks and sediments. The extensive Quaternary sediment cover has been removed to show the boundaries of the outcrop and near surface sub-crop extents of the hydrostratigraphic units of the GAB. Quaternary sediment cover is considered permeable and not an impediment to the recharge of underlying aquifers in most areas. However, the underlying Paleogene-Neogene rocks and sediments have highly variable hydrogeological character that can influence deeper connectivity. In this map individual aquifers and aquitards within the Paleogene-Neogene sequence have not been differentiated. Note that this map does not depict the full subsurface extent of these hydrostratigraphic units.

The major aquifers and aquitards of the GAB are mapped as continuous hydrostratigraphic units, which span across and between the sub-basins of the GAB. At a broad-scale it is possible to map the boundaries between the major aquifer and aquitard systems in most locations. This provides a basin-wide perspective of the regional architecture and character of this complex hydrogeological system. However, such generalisations are scale dependant and, at a local scale, the boundaries between the major aquifer and aquitards may be difficult to differentiate. Hence, this basin-wide hydrostratigraphic classification is a necessary simplification of the complex hydrogeology of the GAB.

Ten hydrogeological units are mapped within the Jurassic-Cretaceous sedimentary sub-basins and Cenozoic cover. These are an alternation of aquifers and aquitards, named after their predominant host stratigraphic units and listed in the order of their stacking, from the top down:

- ▶ Paleogene-Neogene Cover
- ▶ Winton-Mackunda Aquifer and Equivalents
- ▶ Rolling Downs Aquitard
- ▶ Cadna-owie – Hooray Aquifer and Equivalents
- ▶ Westbourne Aquitard
- ▶ Adori-Springbok Aquifer
- ▶ Birkhead-Walloon Aquitard
- ▶ Hutton Aquifer and Equivalents
- ▶ Evergreen-Poolowanna Aquitard and Equivalents
- ▶ Precipice Aquifer and Equivalents.

The outcrop, subsurface extent and thickness variations of each hydrostratigraphic unit are documented in Maps 23–32. Thickness is based solely on lithostratigraphic intercepts in drillhole data from petroleum exploration wells, water bores, and stratigraphic wells. These units are largely composites of contiguous lithostratigraphic units across the entire GAB as outlined in the hydrostratigraphic chart of the GAB (Figure 2).



Hydrostratigraphic units outcrop/subcrop extents

Paleogene-Neogene volcanics	Rolling Downs Aquitard	Birkhead-Walloon Aquitard	Great Artesian Basin
Paleogene-Neogene outcrop	Cadna-owie – Hooray Aquifer and Equivalents	Hutton Aquifer and Equivalents	Bathymetry contour (depth in metres)
Paleogene-Neogene subcrop	Westbourne Aquitard	Evergreen-Poolowanna Aquitard and Equivalents	Tropic of Capricorn
Winton-Mackunda Aquifer and Equivalents	Adori-Springbok Aquifer	Precipice Aquifer and Equivalents	City/town

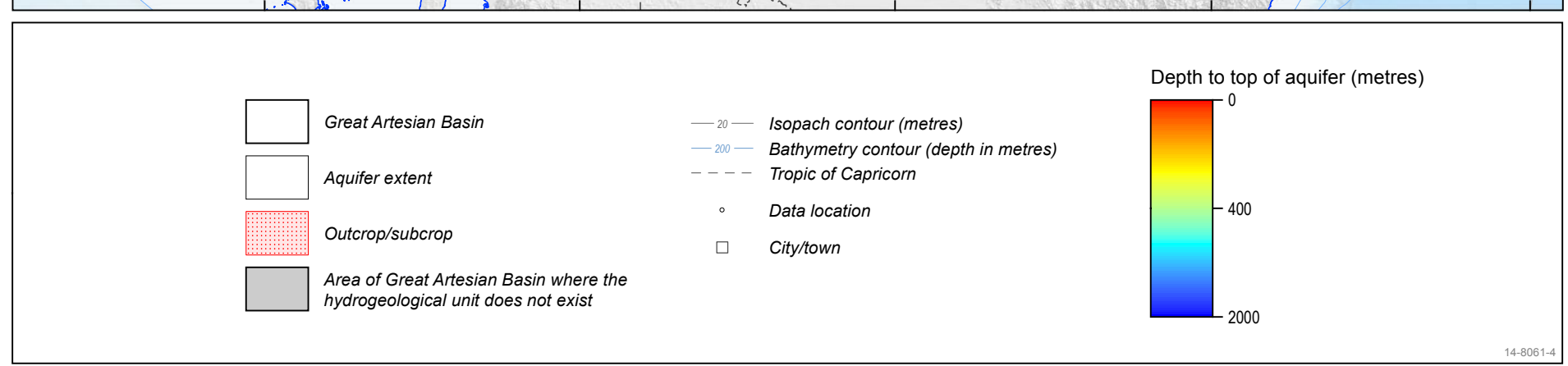
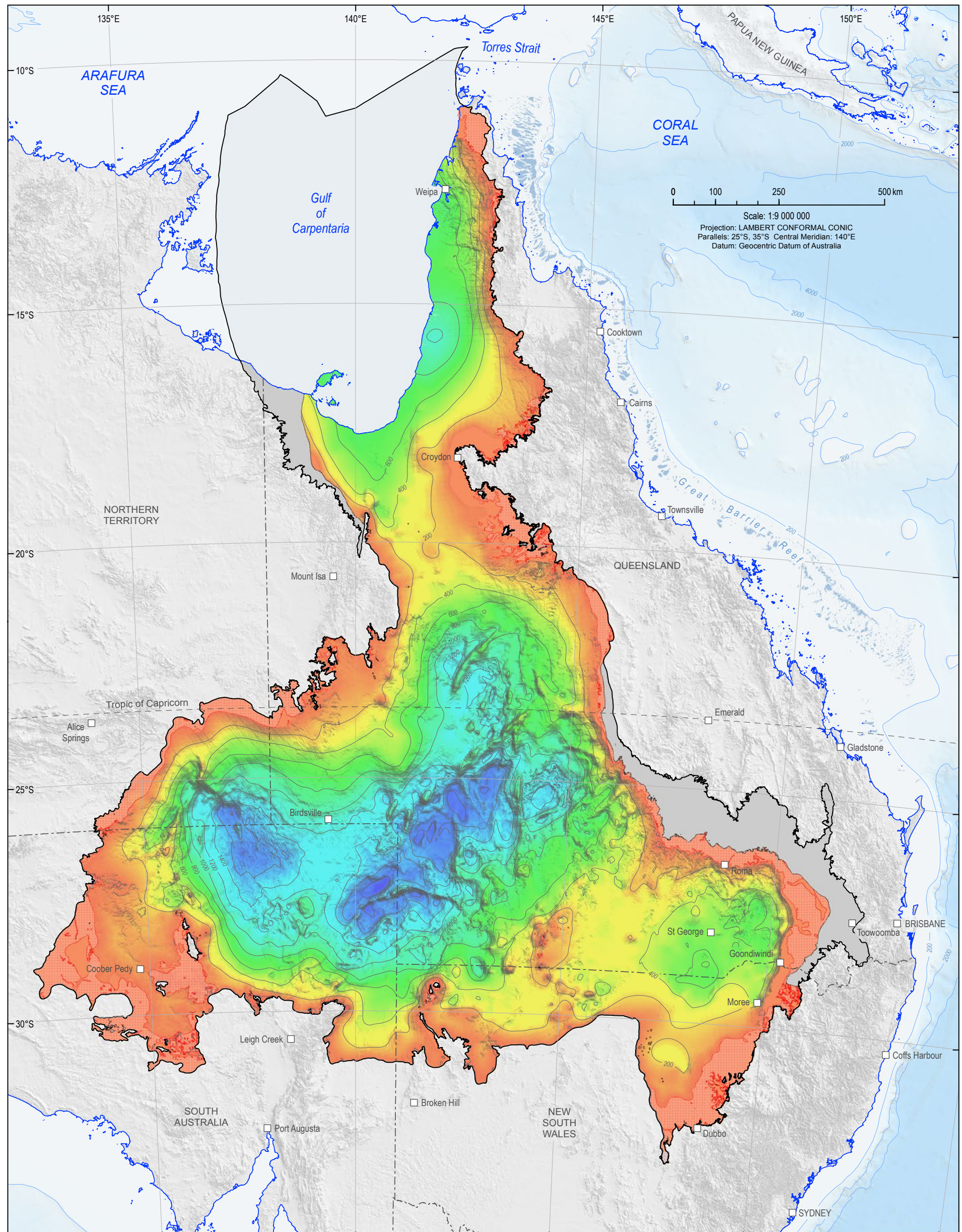
Map 3

Depth to the top of the Cadna-owie – Hooray Aquifer and Equivalents

The most widely utilised artesian aquifer within the GAB is the Cadna-owie – Hooray Aquifer and Equivalents. Lying in the early Cretaceous–Late Jurassic sequence, the aquifer is exposed at ground surface along much of the eastern and western margins of the GAB. The aquifer dips toward the central deeper parts of the basin where it is covered by up to 1900 m of overburden.

Around 3100 flowing artesian bores intersect this aquifer with the majority of them situated in the shallower areas of the basin where the top of the aquifer is closer to the ground surface. Water bore depths (artesian and non-artesian) range from around 60 m in the areas where the aquifer is exposed to some cases >1000 m. The majority of bores have groundwater temperatures of between 40–60°C, a few approach 100°C in the deeper parts of the basin.

The map opposite shows the depth below ground level to the top of the Cadna-owie – Hooray Aquifer. This map was derived by subtracting a seismically mapped elevation surface of the base of the Wallumbilla Formation² (equivalent to the top of the Cadna-owie – Hooray and Equivalents Aquifer) from a Digital Elevation Model representing ground surface elevation.



Map 4

Morphology of the base of the GAB and structural elements^{*}

There is a similar history of sediment accumulation within the component sub-basins of the GAB, closely linked to the tectonic evolution of the Eastern Plate boundary of Australia throughout the Mesozoic Era. However, each sub-basin differs slightly in timing of subsidence and deposition as a result of structural fabrics largely inherited from older underlying basins.

Eromanga Basin

The Eromanga Basin is a relatively thin (compared to underlying basins) but extensive intracratonic blanket of sediment of Jurassic to Late Cretaceous age. Its thickness and structure largely echo the structure and depocentres of underlying basins. It has a very thick sequence within a deep and heavily structured Central Eromanga Depocentre (see Maps 6 and 7). This is flanked to the northwest and southeast by a mosaic of shallower shelves of basement comprising crystalline, metamorphic or older Paleozoic rocks, which are covered by a much thinner sequence. The northeastern end of the depocentre shallows over the faulted Canaway Ridge (see Map 7).

The Central Eromanga Depocentre overlies the Cooper, Warrabin Trough and Adavale basins (Figure 1). This depocentre has the most extreme structuring within the Eromanga Basin, with a folding and superimposed faulting fabric aligned predominantly northwest to southeast. The southwestern limit of this feature is defined by the Birdsville Track Ridge.

The Birdsville Track Ridge is a broad saddle that extends in a northeast to south-southwest direction, separating the Central Eromanga Depocentre from the Poolowanna Trough to the west. The Birdsville Track Ridge, defined by surface exposures of the Winton Formation and older units, comprises a complex of related domes and ridges over Paleozoic and Proterozoic basement.

A broad complex high separates the Eromanga and Surat sub-basins (see Map 1). It comprises the anticlinal Nebine Ridge that plunges southwestward from the groundwater recharge zone (see Map 9), with an en echelon juxtaposition of the Eulo Ridge to the west-southwest.

To the north and northwest of the Lovelle Depression (see Map 5), the sequence thins and shallows steadily onto the Euroka Arch and Diamantina Shelf where there is a pronounced north-northwest–south-southeast structural fabric imposed by underlying basement features of the Mount Isa Block. These basement trends extend eastward across the Euroka Arch-Canobie Depression over the Millungera Basin, the St Elmo Structural high, and the Millungera Depression further to the east. The Diamantina Shelf extends southwestward around the margin of the Mount Isa Block, is cross-cut by the Momedah Structure and Burke River Structural Belt, onto the broader Boulia Shelf.

Two very large circular explosion features were emplaced at about 125 Ma during deposition of the Cadna-owie Formation. These are the Tookoonooka (55-60 km diameter) and Talundilly (84 km diameter) features (see Map 7). Cratering and canyon development from these events redistributed thickness of the Cadna-owie – Hooray Aquifer locally and the catastrophic event also fractured the underlying GAB sequence and basement. The current consensus is that these craters formed from bolide impacts. Previously, deep volcanic explosion events were also proposed as a possible cause.

Surat Basin

The dominant structural feature of the Surat Basin is the meridional Mimosa Syncline (Queensland)—Boomi Trough (New South Wales) that directly overlies the Taroom Trough of the Bowen Basin, and extends southward into the eastern Coonamble Embayment (see Map 7). West of this depocentre are the Roma Shelf, St George-Bollon Slope, and the Eulo and Nebine ridges that demarcate the separation with the Eromanga Basin.

The Surat Basin is bounded to the east by the Auburn Arch (to the northeast) and the New England Foldbelt (Texas High) to the southeast. Between these regions of basement, the Surat Basin is connected eastwards with the Clarence-Moreton Basin across the Kumbarilla Ridge. In the south, the Surat Basin is bounded by the Central Fold Belt, and in the north it has been eroded as a result of Cenozoic uplift.

Structure in the Surat Basin becomes more subdued upwards through the sequence than is evident in the central Eromanga Basin. At the top surface of the Evergreen Formation, the basement topography is still evident but is significantly subdued. The axis of the Mimosa Syncline follows that of the Taroom Trough but the syncline is much broader and shallower. Since the inception of subsidence of the Surat Basin, the depocentre of the Mimosa Syncline has migrated southward to near Meandarra and basement lies at about –1800 mAH, with displacement on faults seldom exceeding 200 m. Higher in the sequence, at the base of Wallumbilla Formation, the structure is very subdued compared to the same horizon in the central Eromanga Basin.

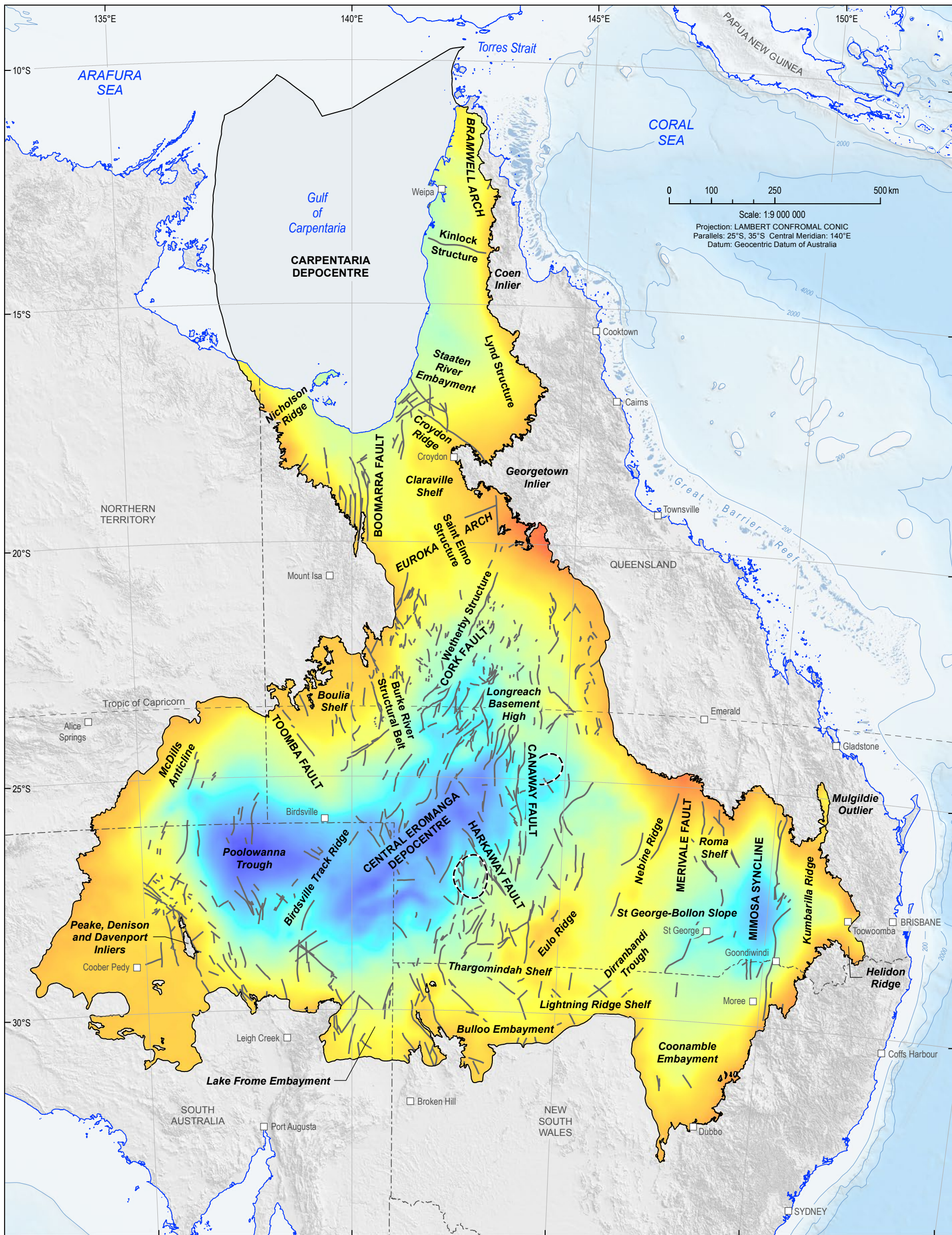
The eastern flank of the Mimosa Syncline is disrupted by the meridional Burunga-Leichhardt Fault Zone and the Moonie-Goondiwindi Fault Zone. Both thrusts are probably continuous with the Hunter-Mooki Thrust system to the south and create the general appearance of a half-graben above the underlying Taroom Trough.

Two major fault systems delimit the Roma Shelf. The north-northwest trending Hutton-Wallumbilla Fault has a westerly downthrow of up to 800 m in the north. The Merivale Fault and Abroath Fault, which form the western limit of the shelf, may be separate structures but are on the same underlying structure. The maximum westerly downthrow exceeds 1000 m on the northerly-trending Merivale Fault which is a probable thrust. The Abroath Fault has a downthrow of about 1200 m.

Carpentaria Basin

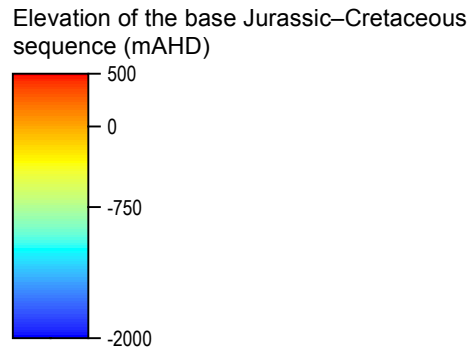
The Jurassic-Cretaceous Carpentaria Basin is a broad shallow intracratonic sag basin that underlies most of the Gulf and extends onshore onto Cape York and southwards to the Euroka Arch to connect with the Eromanga Basin (see Map 5).

^{*} Modified from work undertaken for the Great Artesian Basin Water Resource Assessment (Ransley TR and Smerdon BD (2012)) using revised GAB boundary.



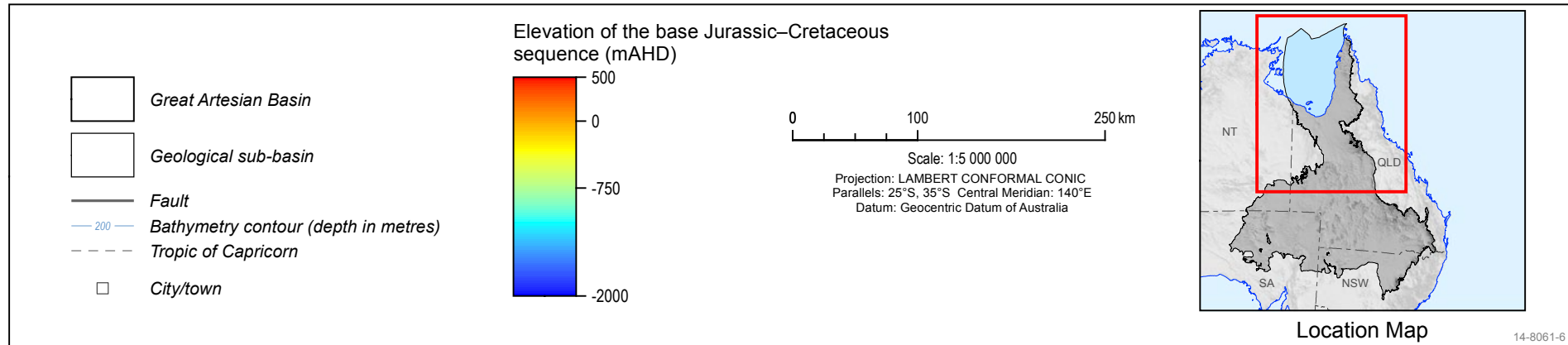
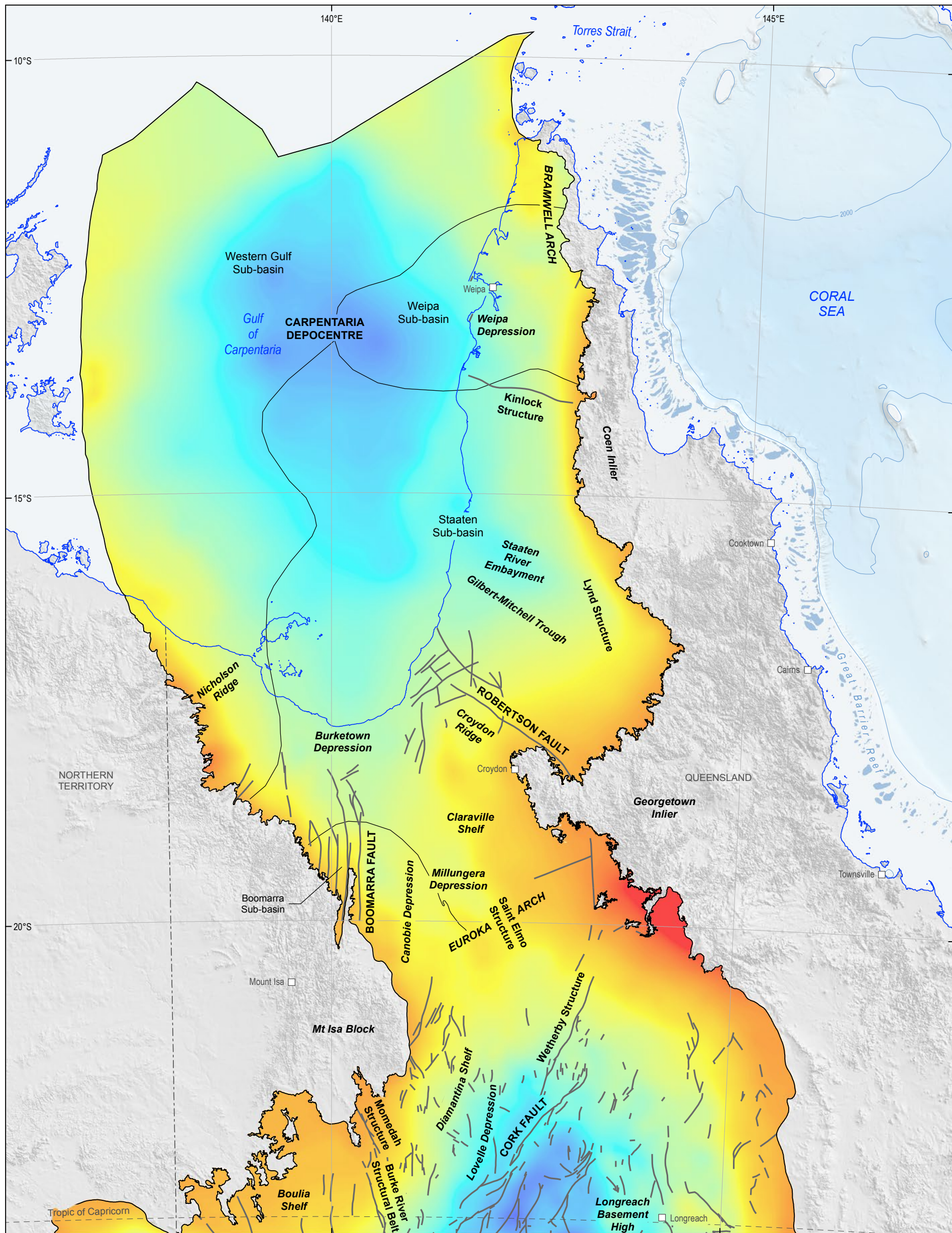
Great Artesian Basin
Explosion structure - probable bolide impact crater

Fault
Bathymetry contour (depth in metres)
Tropic of Capricorn
City/town



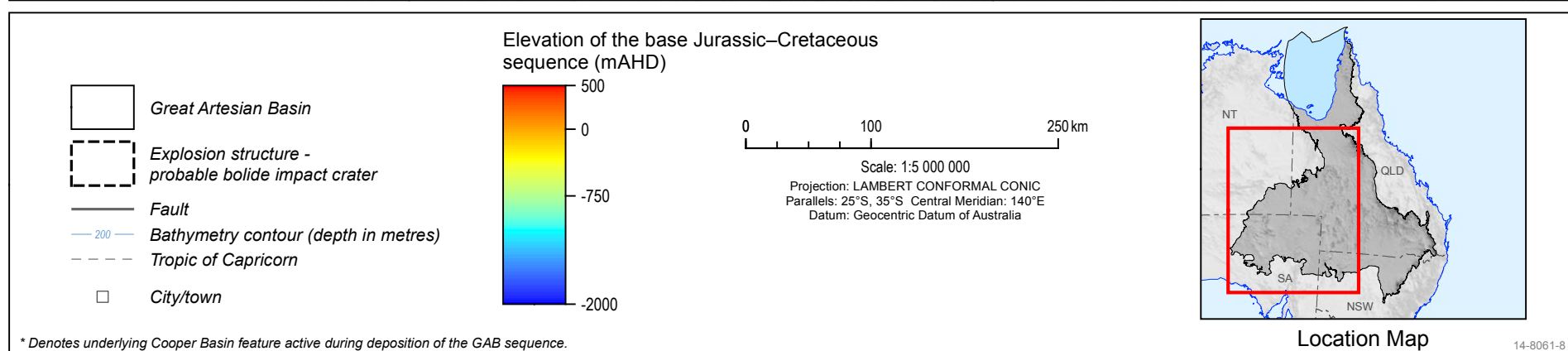
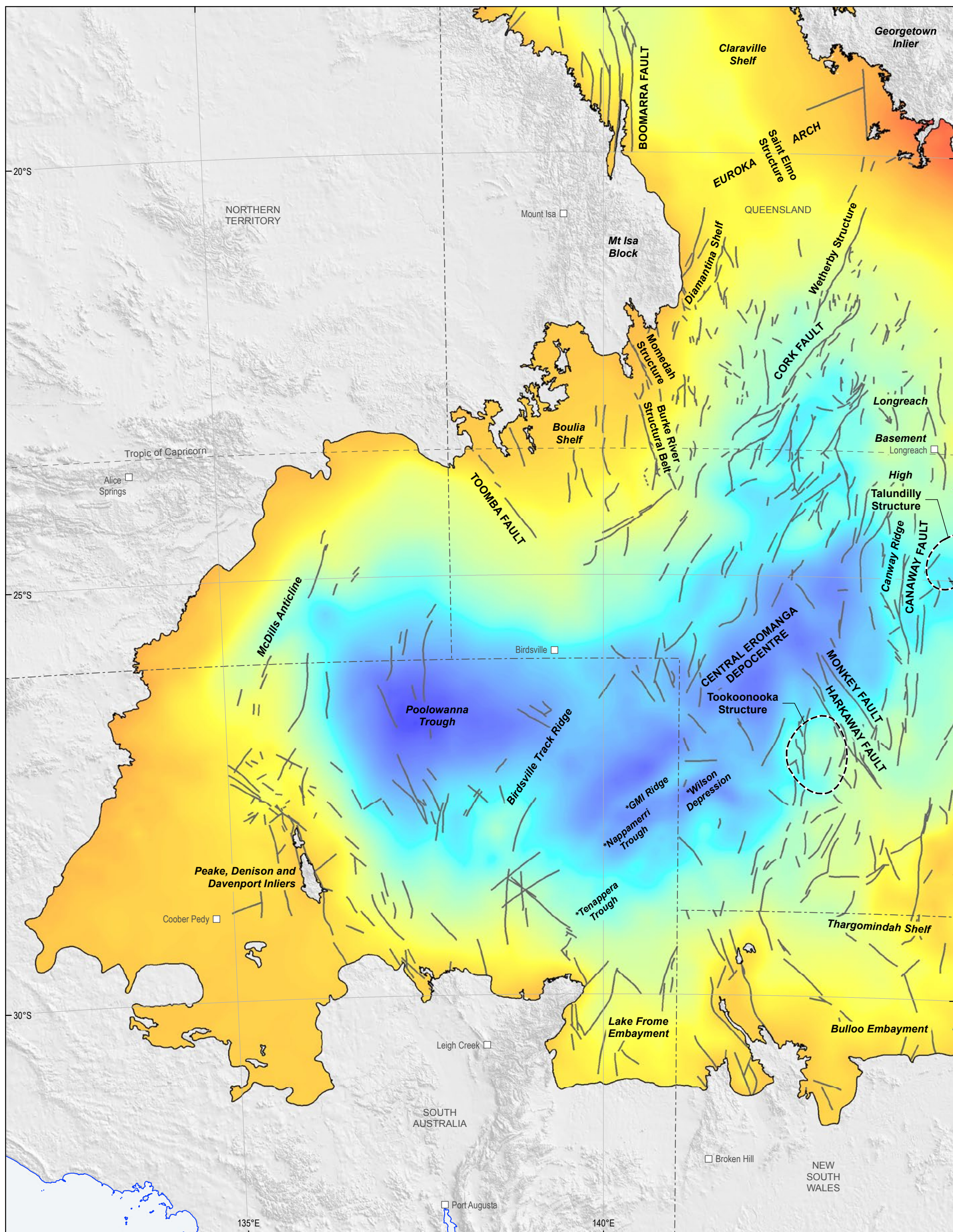
Map 5

Detailed morphology of the base of the northern GAB and structural elements



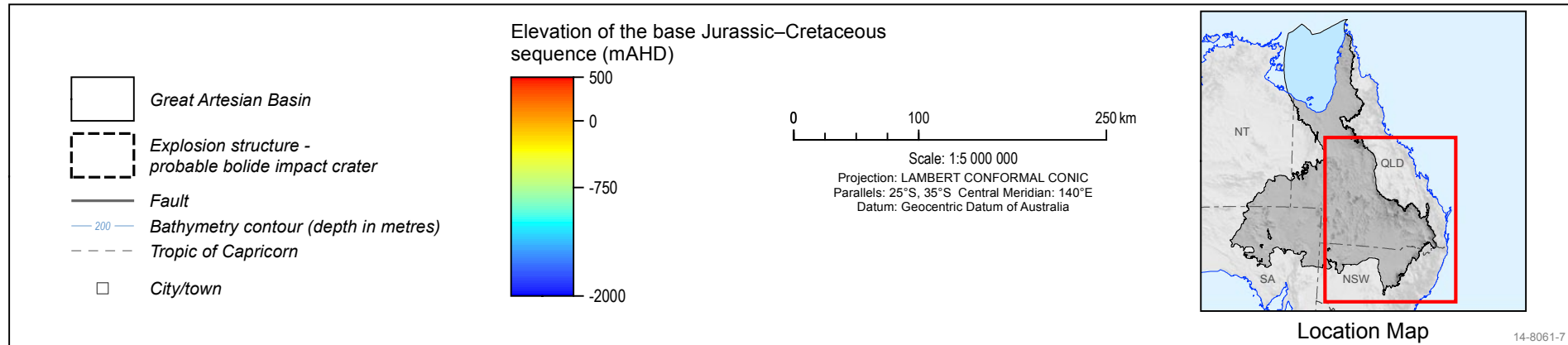
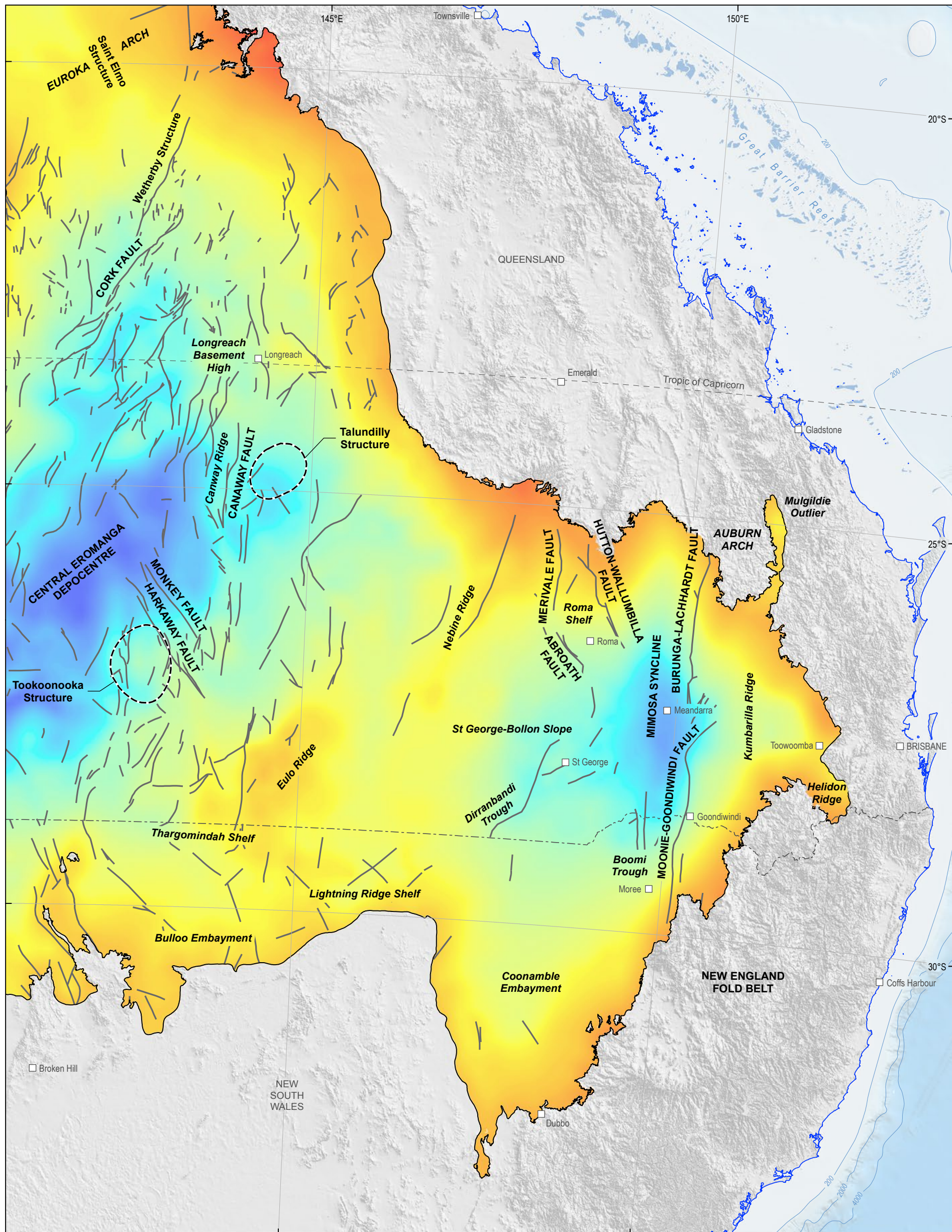
Map 6

Detailed morphology of the base of the western GAB and structural elements



Map 7

Detailed morphology of the base of the eastern GAB and structural elements



Map 8

Depth to hydrogeological basement and sedimentary basins underlying the GAB^{*}

The deepest regions of the GAB coincide with the depocentres of its three main constituent sub-basins, with maximum depths of approximately 1500 m, 2300 m and 1900 m in the Carpentaria, Eromanga and Surat basins respectively. The depth to hydrogeological basement diminishes approaching the margins of the GAB as well as across basement highs such as the Eulo-Nebine Ridge and Euroka Arch (see Map 4), where the Eromanga Sub-basin connects to the Surat and Carpentaria sub-basins.

A total of 27 sedimentary basins are known to directly underlie the GAB. The Jurassic-Cretaceous sequence in the central Eromanga, Surat and Clarence-Moreton basins thickens over underlying depocentres of several smaller, mainly nonmarine Permian-Triassic basins including the Bowen, Cooper, Galilee, Pedirka^{**}, Simpson and Arckaringa^{**} basins. Underlying crystalline basement provinces are extensive, and older sedimentary basins range in age from Precambrian to Carboniferous. These include the Drummond, Millungera, Arrowie, Barka, Warburton, Adavale, and Georgina basins.

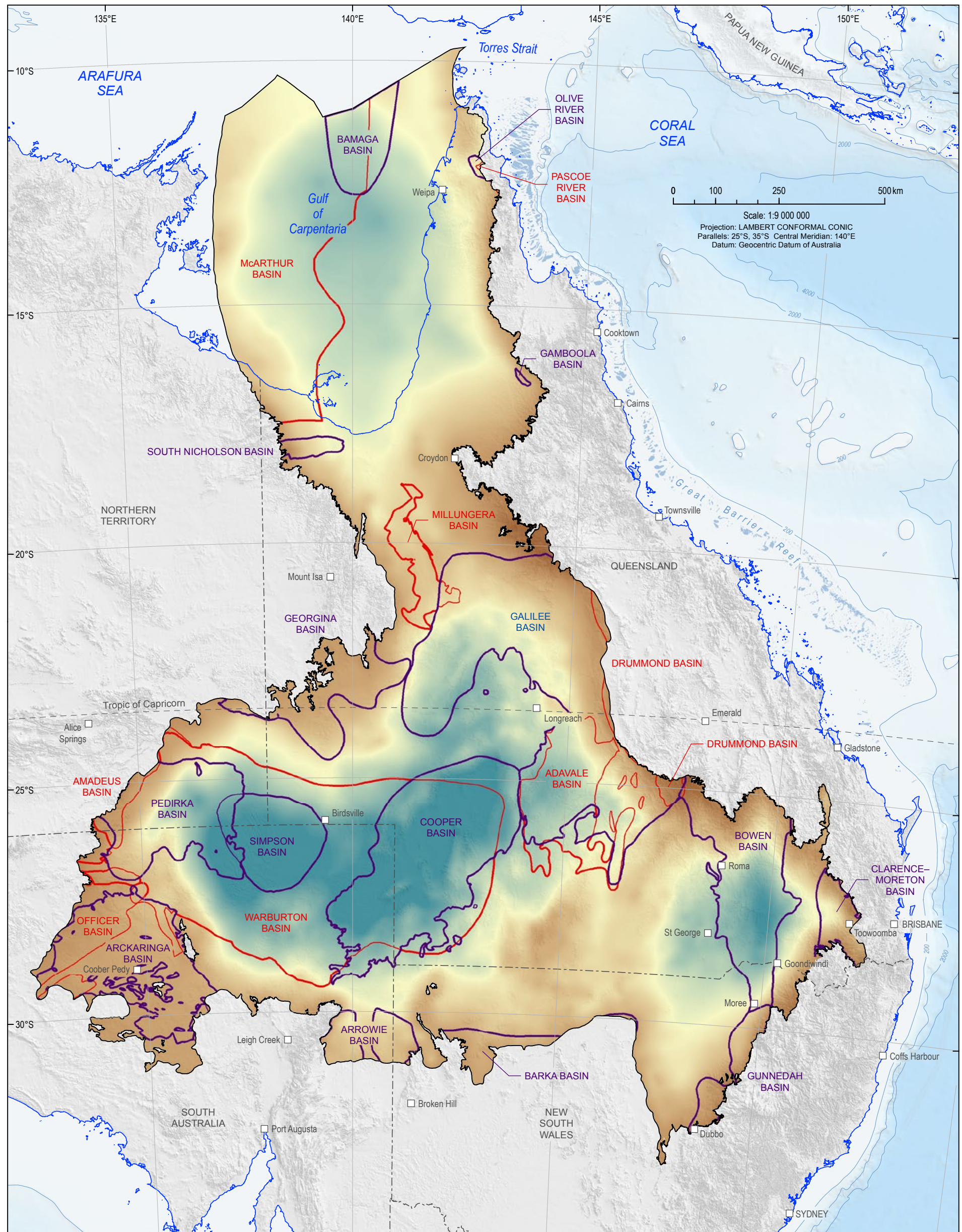
Oil fields in the Cooper region of the central Eromanga sequence are largely the result of hydrocarbon migration up from the underlying Cooper Basin, although a smaller proportion of hydrocarbons were generated within the GAB. This upward hydrocarbon migration signals the possibility of migrating groundwater as well, but the hydrochemical evidence remains equivocal whether such migration continues today, at least at a detectable rate.

The Bowen and Gunnedah sedimentary basins directly underlie the Surat Basin. The Surat Basin has many structural features inherited from basement, including those that underlie the Bowen Basin. Below the Mimosa Syncline of the Surat Basin, the Bowen Basin sequence is contained predominantly within the meridional Taroom Trough and extends southward to the Gunnedah Basin. In the north of the Taroom Trough, the Bowen Basin sequence spreads northwestward over the Nebine Ridge to the Galilee Basin.

A series of stacked sedimentary basins overlie and underlie the Carpentaria Sub-basin. Underlying these Jurassic-Cenozoic basins are several relatively small pre-Jurassic basins, some are sag basins and others are fault-defined. These include the Olive River and Pascoe River Basins in the north, the offshore Bamaga Basin³, offshore Arafura Basin (north of the northwestern limit of the GAB), and the Gamboola Basin⁴ at the southeastern end of the Staaten Sub-basin (see Map 5). All basins are separated by unconformities³ and the stacked relationship of the Carpentaria Basin and its infrabasins is analogous to the Eromanga Basin and the basins that underlie it⁵.

^{*} Modified from work undertaken for the Great Artesian Basin Water Resource Assessment (Ransley TR and Smerdon BD (2012)) using updated GAB, Pedirka and Arckaringa basin boundaries.

^{**} Updated Pedirka and Arckaringa basin boundaries supplied by D. Wohling (South Australian Department of Environment, Water and Natural Resources).



Sedimentary basins underlying Great Artesian Basin

Basin boundary in contact with base of Great Artesian Basin

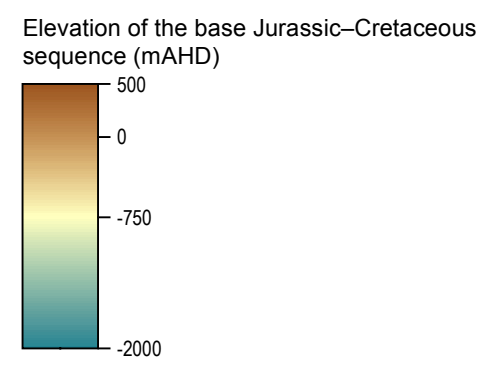
Basin boundary not in contact with base of Great Artesian Basin

Great Artesian Basin

Bathymetry contour (depth in metres)

Tropic of Capricorn

City/town



Map 9

Groundwater recharge zones

Groundwater recharge zones are those areas where water can enter the various aquifers that make up the GAB. The spatial extents of the recharge zones shown are defined by a combination of the mapped outcrop extents of the various aquifer units, and interpolation between outcrops in cases where the units are covered by a thin veneer of Cenozoic deposits.

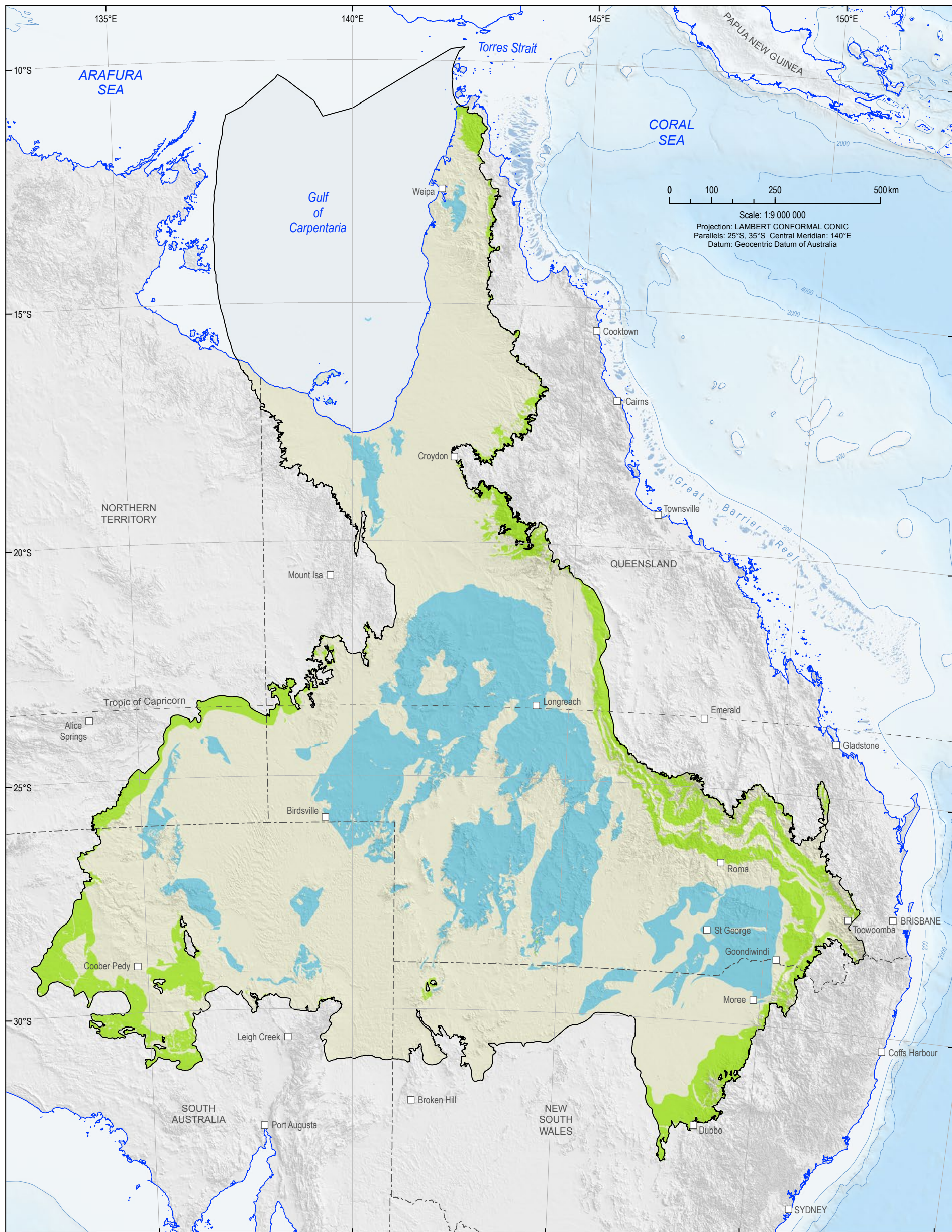
Recharge rates are a function of the aquifer capacity to store and transmit water, the amount of water available from rainfall and river leakage, and the nature of any overlying deposits. Estimation of the rates at which GAB aquifers are being recharged is essential for calculating the overall water budget for the Basin.

The mechanisms by which recharge occurs are diffuse percolation of rainfall and to a lesser extent, river bed leakage. The rates at which aquifer units are recharged has been estimated at close to zero in parts of the western recharge zones, to as much as 45 mm/year⁶ along parts of the northeastern recharge zones, south of Croydon.

In the northern GAB the volume of groundwater recharge to aquifers in the Carpentaria Sub-basin (area shown in green) has been estimated at 432 GL/year⁷.

To the south, recharge to the Eromanga Basin aquifers has been estimated at 142 GL/year⁷ for the Jurassic–Cretaceous aquifers (shown in green) and 164 GL/year⁶ to the Winton and Mackunda formations (shown in blue).

Within the Surat Basin recharge to the Jurassic–Cretaceous aquifers (shown in green) has been estimated at 237 GL/year⁷.



Groundwater recharge zones

- Great Artesian Basin
- Regionally variable local recharge with possible local upward leakage from Jurassic aquifers in some places
- Groundwater recharge area
- Area of negligible recharge to Great Artesian Basin aquifers

- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- City/town

Map 10

Potentiometric surface for the Cadna-owie – Hooray Aquifer and Equivalents, with inferred flow lines

Regional groundwater flow directions within the Cadna-owie – Hooray Aquifer and Equivalents are inferred from a potentiometric surface estimated using measurements of groundwater head.

The potentiometric surface is inferred from waterbore head measurements obtained between 2000 and 2010 that were corrected for temperature and density. Regional flow is assumed to occur down hydraulic gradient. In general, groundwater flow is basinward away from recharge areas.

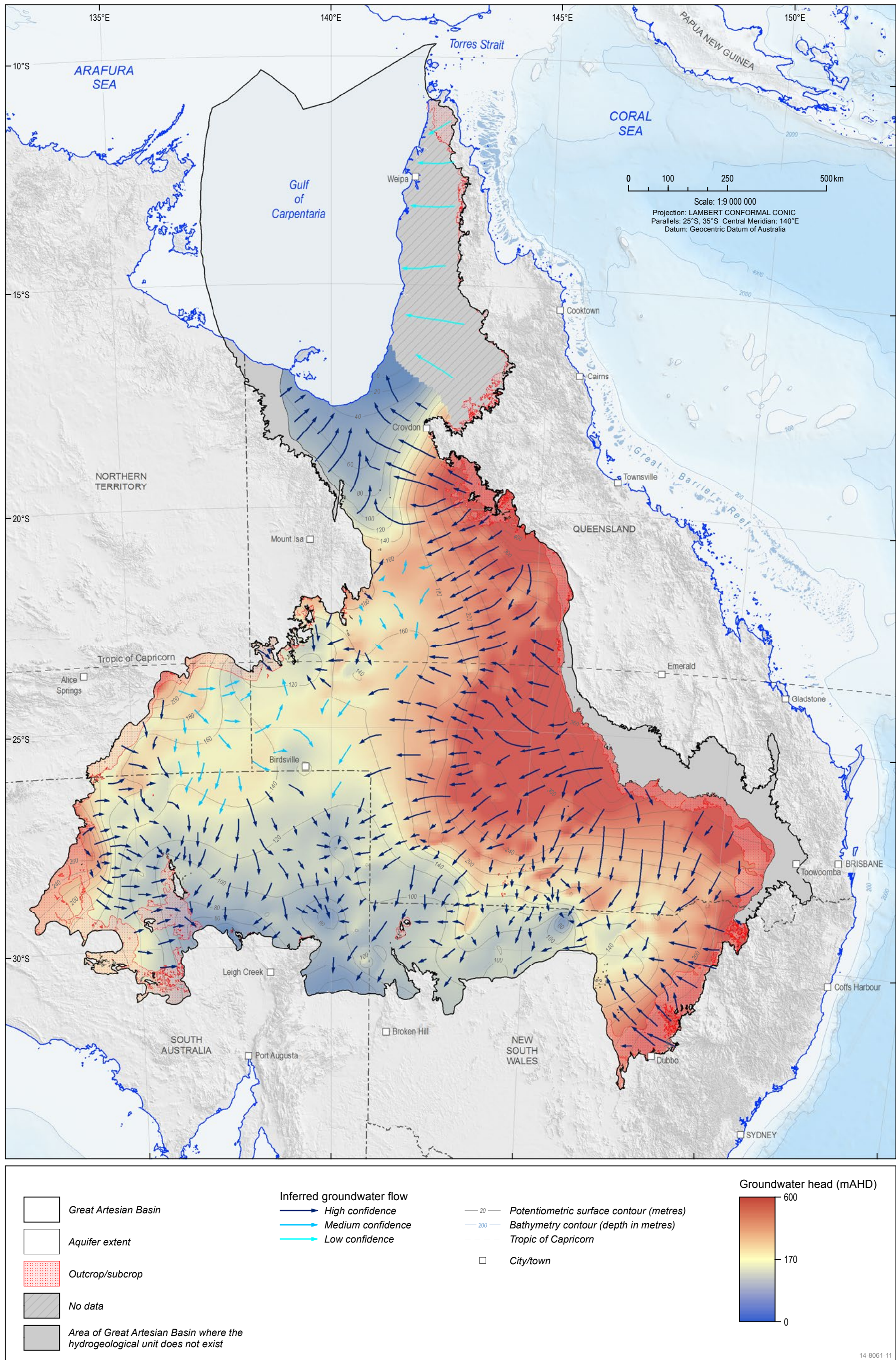
The map opposite shows a composite potentiometric surface derived from the South Australia and Northern Territory potentiometric surface—present day variable temperature assumption in Love et. al, (eds) 2013⁸ and the New South Wales and Queensland portion of the GABWRA (2012)⁶ potentiometric surface.

On the basis of inferred regional groundwater flow, three major flow systems can be delineated—a northern, eastern and western flow system. The northern flow system (north of 20°S) is characterised by groundwater flow towards the offshore depocentre of the Carpentaria Sub-basin. To the south, the extensive eastern system is associated with recharge areas located along the eastern boundary of the aquifer in Queensland and New South Wales and is characterised by

groundwater flow directions to the west and southwest, towards South Australia. The western system is characterised by easterly-directed groundwater flow emanating from the recharge areas associated with the western boundary of the aquifer in South Australia and the Northern Territory. The Eastern and Western flow systems converge at approximately 140°E where the majority of groundwater flow is diverted to the south. The zone of groundwater flow convergence is coincident with a thinning of the aquifer that occurs along the Birdsville Track Ridge (see Maps 4 and 6).

The effects of groundwater extraction can produce reductions in artesian pressure and in some cases these reductions are manifested as isolated depressions in the potentiometric surface. In some cases these depressions can be attributed to extraction from densely-clustered water bores or oil fields.

In the Carpentaria Sub-basin, there is insufficient data to generate full coverage of this surface. Cenozoic aquifers are in direct contact with GAB aquifers in this region, may be artesian, and are generally utilised in preference to deeper aquifers.



Map 11

Regional watertable^{*}

Watertable contours were constructed from shallow groundwater level data in the state databases of New South Wales and Queensland. South Australia and the Northern Territory data points were taken from a watertable surface developed at Flinders University⁸. Water levels in South Australia were corrected for density effects due to salinity. Elsewhere, density corrections for the watertable aquifer were not deemed to be an issue.

Similar to the confined aquifers, regional groundwater flow in the watertable aquifer is from the highest potentials in the intake beds on the western slopes of the Great Dividing Range (GDR) in New South Wales and Queensland. This intake zone extends northward along the western slopes of the GDR to the tip of Cape York where the pressure levels are lower than those in the southern recharge area. The watertable lies within the Jurassic formations in the intake beds but basinward it passes into the Middle Cretaceous formations (Winton (Kw) and Mackunda (Klm) Formations in the Eromanga Sub-basin, Griman Creek Formation in the Surat Sub-basin). These aquifers comprise the most areally extensive host for the watertable in the GAB. In the Lake Eyre and Karumba Basins, the watertable passes into Cenozoic sediments.

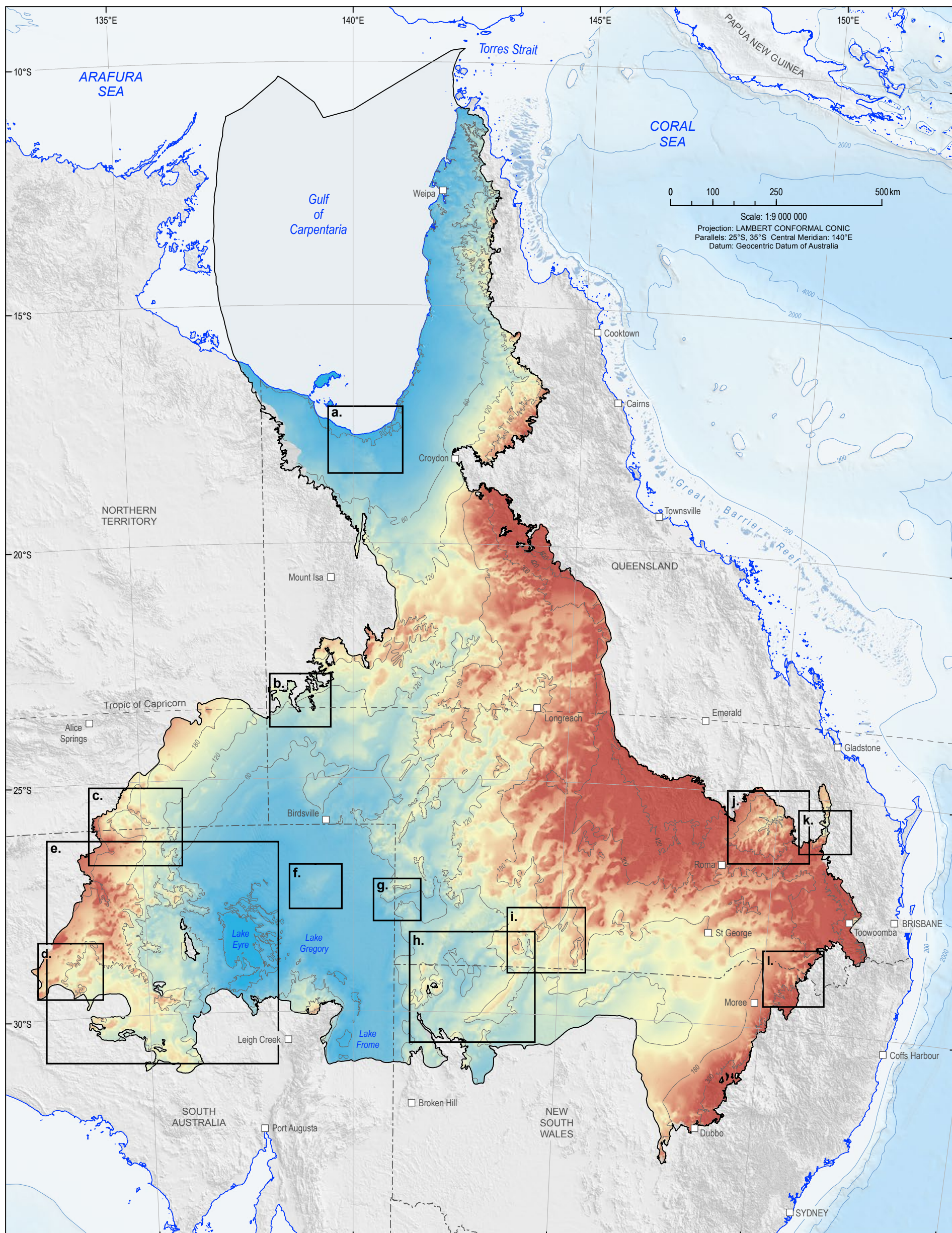
Regional discharge zones for the watertable are Lake Eyre and an eastward arcuate band of salt lakes extending from Lake Frome to Lake Gregory. Both of these regional discharge zones lie in South Australia but there is another intra-basin discharge area at the Bulloo Overflow/Caryapundy Swamp on the NSW/Queensland border (see Map 13 h). Regional discharge from the shallow aquifer in the Carpentaria/Karumba Basins is into the Gulf of Carpentaria. In the southeast, regional discharge from the shallow aquifer in the Coonamble Embayment watertable is into the Darling River alluvium (see Map 7).

Although there is a major difference in resolution between the relatively high resolution watertable surface (Map 11) and the less well constrained surface of the Cadna-owie – Hooray Aquifer (Map 10), there are subtle but significant features evident in the watertable map which distinguish it from the potentiometric surface map of the Cadna-owie – Hooray (JKh) confined aquifer:

- The watertable contours are not smooth like the JKh contours, but form local recharge mounds extending far into the basin. Some of these recharge mounds are coincident with structures like the Innamincka Dome and all of them occur in areas mapped as Winton or Mackunda formation outcrop, or in areas where the Lower Cretaceous rocks are shallowly buried by Cenozoic sediments. [In the Eromanga Sub-basin, the total intra-basin recharge into the Winton-Mackunda Aquifer is estimated to be 164 GL/year⁷ which is 21 GL/year higher than recharge to the Hooray and Hutton Sandstones on the western slopes of the GDR. Intra-basin recharge has never before been included in GAB water budgets];
- The two largest rivers in the Eromanga Basin, the Diamantina River and the Cooper Creek are prominent watertable drains. By way of contrast, there is no apparent relationship between these major streams and the potentiometry of Cadna-owie – Hooray Aquifer; and
- The watertable mounds along the Eulo Ridge (see Map 13 i) and their extension southwestwards toward the boundary of the GAB in NSW come close to forming a groundwater divide between the Surat and Eromanga sub-basins, but the line of mounds is breached in some places permitting impeded lateral throughflow. For the watertable, the Eulo Ridge acts as is an impermeable subsurface boundary but there is no apparent influence of this structure or its hydrogeological role on the potentiometry of the Cadna-owie – Hooray Aquifer.

Note. The facing map includes outlines of areas of interest shown on Maps 12 and 13.

^{*} Modified from work undertaken for the Great Artesian Basin Water Resource Assessment (Ransley TR and Smerdon BD—2012), using revised GAB boundary.



Great Artesian Basin



Bathymetry contour (depth in metres)



Watertable elevation contour (metres)

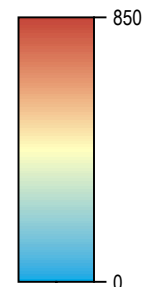


Tropic of Capricorn



City/town

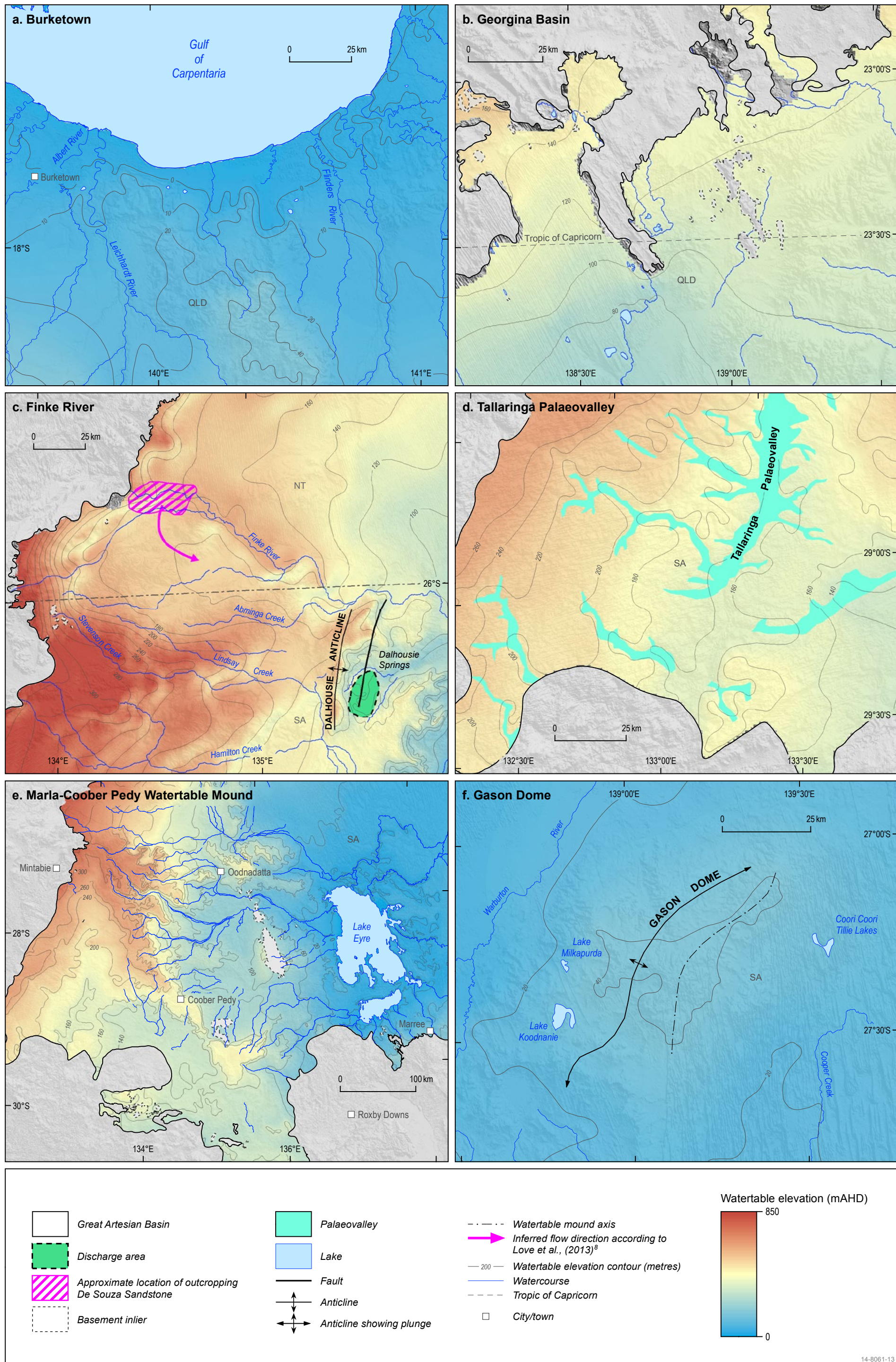
Watertable elevation (mAHd)



Map 12

Regional watertable—areas of interest

- a. Burketown:** Relative to the coastline in the southern Gulf of Carpentaria, the zero watertable contour, lies up to 30 km inland from the coast, and is not coincident with the coast as might be expected. In fact the zero contour follows the landward boundary of a Quaternary unit designated 'Qrp' on the Burketown and Normanton 1:250 000 scale geology map sheets. Simpson⁹ describes 'Qrp' as a black organic saline clay which occupies tidal flats and is inundated during the wet season and partially dries to form a thin salt crust in the dry season. According to tide gauging by the National Tidal Centre, the range from highest to lowest astronomical tide at Mornington Island is 3.793 m and at Karumba it is 4.569 m. The large high tides explain the persistence of tidal mud flats for up to 30 km inland.
- b. Georgina Basin:** Along the northwestern margin of the GAB, the basin sequence comprises outcropping porous Longsight Sandstone overlain basinward by less permeable and less porous rocks of the Wilgunya Formation (equivalent to the Wallumbilla Formation further east). The GAB sequence wedges out against Cambro-Ordovician rocks, dominantly carbonate, of the Georgina Basin. Many basement inliers protrude through the GAB sequence. The watertable contours can be interpreted as a system which is locally recharged where the Longsight Sandstone outcrops and/or is shallowly covered by sandy Cenozoic alluvium, or a system where the Georgina Basin discharges into the GAB sequence, or a system exhibiting a combination of both of these processes.
- c. Finke River:** Four, possibly hydrogeologically linked features near the northwestern boundary of the western Eromanga Basin are the Finke River, the Dalhousie Anticline and an un-named fault parallel to the Anticline and Dalhousie Springs. These springs are the highest discharging spring complex in the GAB. A pronounced groundwater mound is developed in the Finke River alluvium and this mound persists all the way downstream to the fault. It appears that the bed underflow groundwater is then transmitted southward along this fault before being discharged at Dalhousie Springs. The Finke River leakage is a significant contributor to the groundwater discharging at Dalhousie Springs. In addition, an unknown proportion of deeper circulation groundwater contributes to this spring discharge.
- d. Tallaringa Palaeovalley:** Shown is the influence exerted on the watertable contours by the Tallaringa Palaeovalley, a prominent feature in the western Eromanga Sub-basin, filled with about 70 m of carbonaceous sand of the Pidinga Formation overlain by about 30 m of silt and sand of the Garford Formation¹⁰. The Tallaringa Palaeovalley is incised into sediments of the Bulldog Shale and Cadna-owie Formation which are host to the regional watertable near the western GAB boundary. This is one of many palaeovalleys in the western Eromanga Sub-basin, and all of these palaeovalleys are prominent watertable drains. The majority of the palaeovalleys drain the watertable internally towards Lake Eyre but the Tallaringa Palaeovalley drains groundwater out of the GAB into the Officer Basin. The Kingoonya Palaeovalley to the south drains groundwater from the GAB watertable into the Eucla Basin.
- e. Marla/Coober Pedy Watertable mound:** A prominent watertable mound extends in a southeasterly direction from near Mintabie, through Coober Pedy and thence towards the south of Marree. The mound is very close to being a groundwater divide, isolating the far southwest of the GAB except at the southeastern extent of the mound. This watertable mound coincides with a topographic ridge.
- f. Gason Dome:** The Gason Dome is a major geological feature lying on the Birdsville Track Ridge, and coincides with a watertable mound. The dome is a broad structure formed in response to east-west compression and plunges to the northeast. Erosion has left a core of Winton Formation material exposed along the anticlinal axes of the dome. The watertable mound in the vicinity of the Gason Dome is unlikely to be a recharge mound, rather a groundwater discharge feature resulting from upward leakage, probably from the underlying Algebuckina/Hutton Sandstone



Map 13

Regional watertable—areas of interest

g. Innamincka: A watertable mound overlies the Innamincka Dome. The Innamincka Dome is an elongate feature with closure (broad anticline) which formed in response to east-west compression and plunges to the northeast. This erosion has left a core of Winton Formation material exposed along the anticlinal axes of the dome. The favoured interpretation of this watertable mound is that it is in all probability a local recharge mound. Extension fractures formed from the folding would provide an enhanced infiltration capacity of the exposed Winton Formation if they have remained open.

h. Bullo Overflow: The watertable contours are derived from pressures in the Winton Formation on the Milparinka 1:250 000 Sheet and from sub-artesian bores in undifferentiated Rolling Downs Group. The most prominent feature is a groundwater sink defined by the closures of the 60 mAH and 80 mAH watertable contours. The sink defined by the 60 m closed contour overlies the terminus of the Bulloo River, the Bulloo River Overflow, and Caryapundy Swamp. The average elevation of these swampy areas is 78 mAH.

The sink appears to have been created by an impedance to westerly throughflow of groundwater afforded by Cenozoic (probably Pliocene) uplift along a pre-existing north-northwest trending fault, parallel and close to the Mt Poole, New Bendigo and Warratta Faults. The uplift was probably only of the order of about 20 m (there is a 20 m jump-up in the digital elevation model), but this appears to have been sufficient to defeat surface drainage in an almost flat landscape and to impede groundwater throughflow.

The sink constitutes a local groundwater discharge zone but the only surface expression of groundwater discharge is a salt lake of 45 km² surface area in the southern lobe of the 80 m closed contour. It would be expected that the sink would gradually fill over time and that discharge features such as salt lakes would become prevalent, but this has not eventuated. It could be that the excess groundwater is being transpired at the watertable by deep rooted vegetation, but this appears not to be the case since the dominant wetland vegetation is cane grass and lignum, not high transpiring species. Alternatively, the lack of a significant brine pool could indicate that the structural uplift and groundwater impedance occurred more recently than the Pliocene. Thus the sink appears to be something of a mystery that cannot be explained at this stage. It is not known whether the sink will gradually fill up and develop salinisation at ground surface.

i. Eulo Ridge: Shown is the potentiometric surface of the uppermost Lower Cretaceous aquifers and leaky aquitards over the Eulo Ridge. The Eulo Ridge is the basement high separating the Surat and Eromanga hydrogeological sub-basins and is also a site of many springs, most of which have ceased to flow. The axis of the Eulo Ridge is coincident with the watertable highs and passes through granite basement inliers.

Both local groundwater recharge and discharge features are expressed in the watertable aquifer. Although the watertable is considered to be regional in nature, on the Eulo Ridge it exhibits some characteristics of a local groundwater flow system. With this interpretation, there are local recharge mounds along the Eulo Ridge and there are two mounds straddling the Paroo River and a small granite intrusive (too small to see in the figure). Bores in these mounds intersect the Doncaster Member of the Wallumbilla Formation and are flowing artesian wells.

An alternative (and more likely) explanation is that there is regional leakage upward from the Cadna-owie – Hooray Aquifer into the Doncaster Member. As well as diffuse leakage upwards along the axis of the Eulo Ridge, leakage up local faults may contribute to the small but linear artesian mounds observed on either side of the Paroo River. In almost this entire region, the potentiometric heads in the Cadna-owie – Hooray Aquifer exceed those of the watertable.

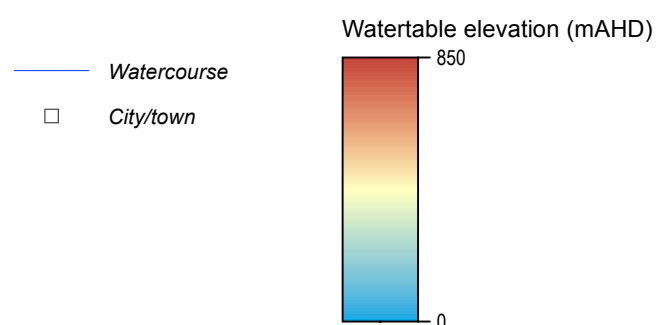
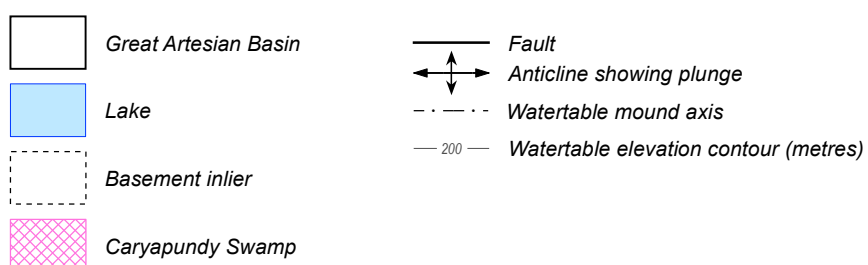
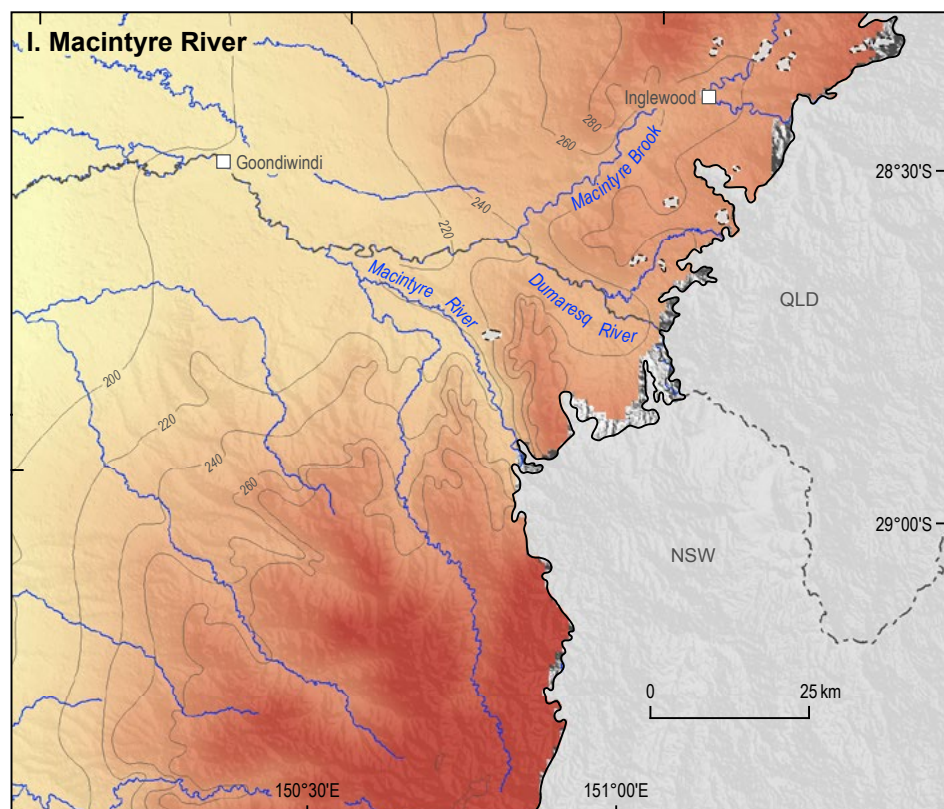
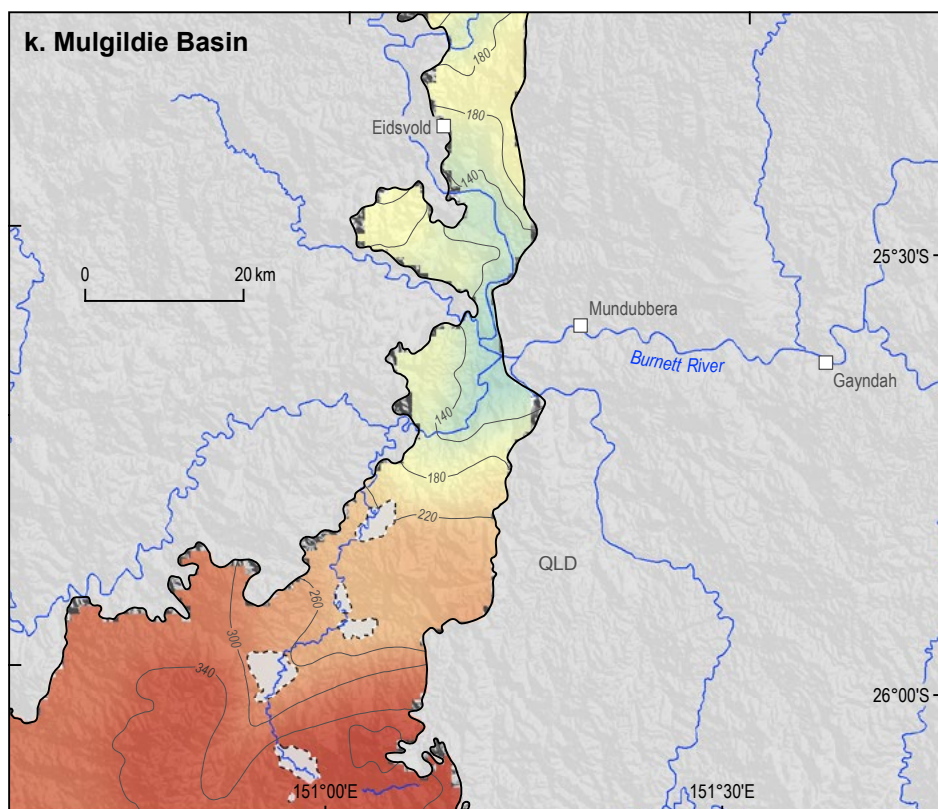
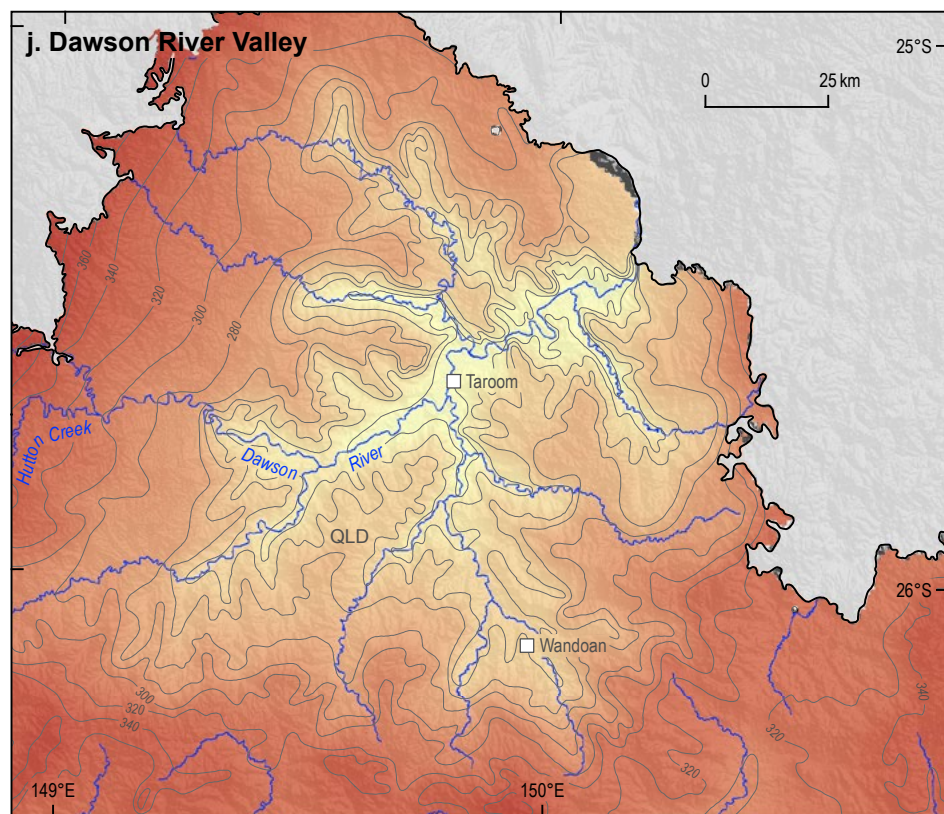
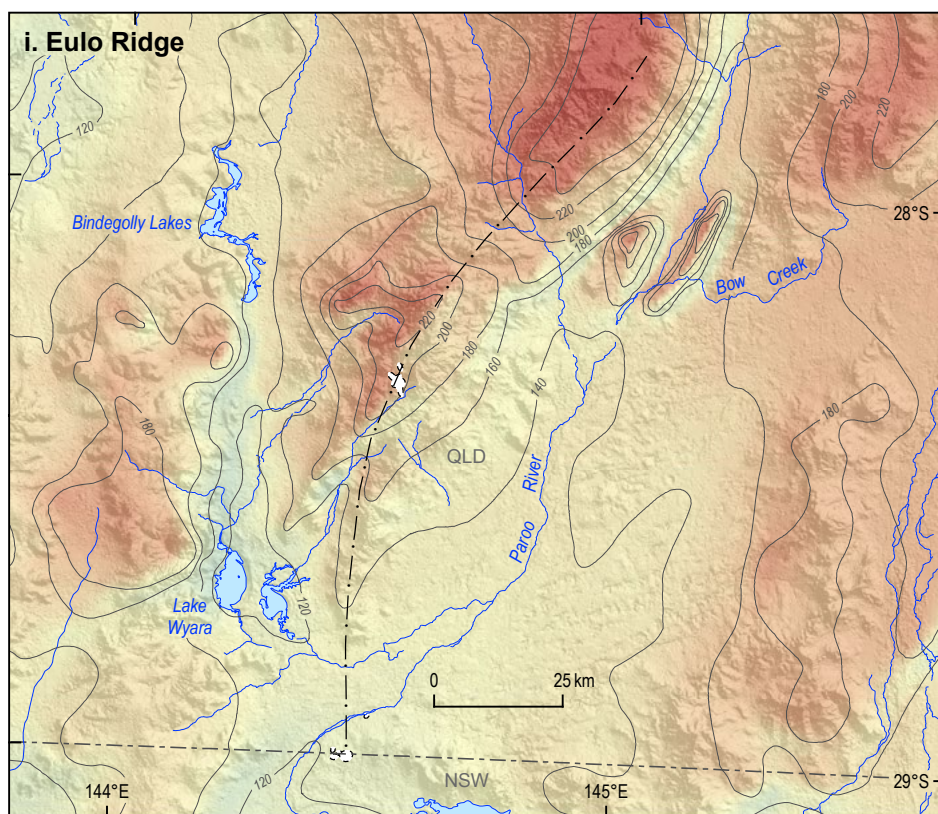
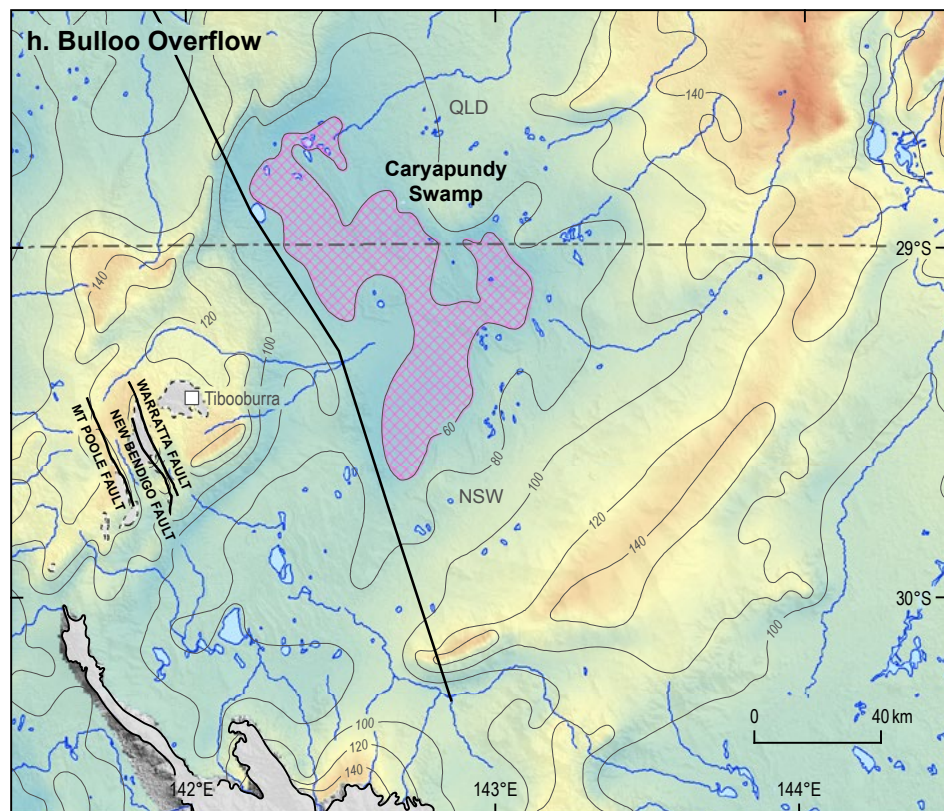
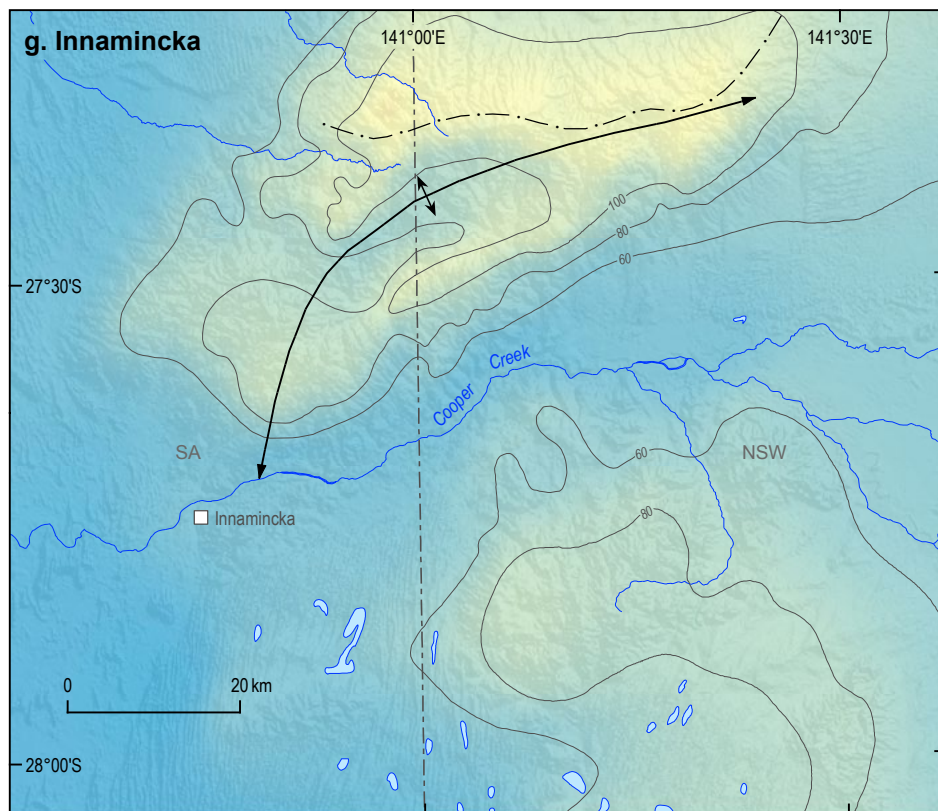
A local groundwater discharge zone is indicated by the closed 120 m watertable contour around Lake Wyara.

j. Dawson River Valley: The Dawson River joins the Fitzroy River west of Rockhampton and this drainage flows into the Pacific Ocean. Headward erosion of the Dawson River has produced a deeply-dissected valley. The effect of this dissection on the regional watertable is expressed as flow from the watertable aquifer towards the Dawson River and its tributaries, notably Hutton Creek—a line sink with many baseflow springs. The watertable converges to a choke in the Dawson River 45 km northeast of Taroom where it leaves the Great Divide. Thus the Dawson River valley is an area of flow loss from the GAB estimated to be in the order of 8500 ML/year⁵.

k. Mulgildie Basin: The elongated lobe 10 km west of the town of Mundubbera is known informally as the Mulgildie Basin or outlier, and is intersected at its narrowest point by the Burnett River which flows eastward towards Bundaberg and the Pacific Ocean. The watertable map clearly shows the neck of the Mulgildie Basin drains groundwater from the north and from the south—from GAB aquifers, the Precipice and Hutton Sandstones. The groundwater leaves the system as baseflow into the Burnett River. Therefore, like the Dawson River valley, the Mulgildie Basin is an area of groundwater loss from the GAB.

Estimated groundwater flow loss northward from the GAB intake beds to the Mulgildie Basin and Burnett River is 3900 ML/year⁸. Most of this flow loss is likely to be from the Precipice Sandstone and to a lesser extent from the Hutton Sandstone.

l. Macintyre River: The watertable is remarkable here because of the influence of the rivers on its configuration. East of Goondiwindi, the watertable aquifers are the Hutton Sandstone and sandstones of the Marburg Subgroup intake beds, which grade northward to the Kumbarella beds. On the New South Wales side the watertable aquifer is the Pilliga Sandstone in the intake beds, grading westwards to undifferentiated Rolling Downs Group (probably Griman Creek Formation equivalent). The flow directions in the watertable are noteworthy. In Queensland, groundwater flow is towards the southwest and in New South Wales it is to the northwest. The flow lines converge around the Macintyre River. This is a rare example of a state boundary coinciding with a hydrogeological one. East of Goondiwindi, the watertable is depressed about the Macintyre Brook, Dumaresq River and Macintyre River indicating that these may be gaining streams. However, the watertable shows a groundwater mound 10 km west of Goondiwindi, possibly indicating the Macintyre River here is a losing stream recharging the Griman Creek Formation partial aquifer. The groundwater mound may in part be generated by hydraulic loading from the Goondiwindi Weir which lies 5 km downstream of the centre of the town.



Map 14

Hydraulic connectivity across the base of the Great Artesian Basin^{*}

This map categorises the hydraulic nature of the basal surface of the GAB through the properties of rocks in direct contact below and above the base, on a regional scale. The map indicates areas of potential connectivity between aquifers in older basins and the basal aquifers in the GAB sequence.

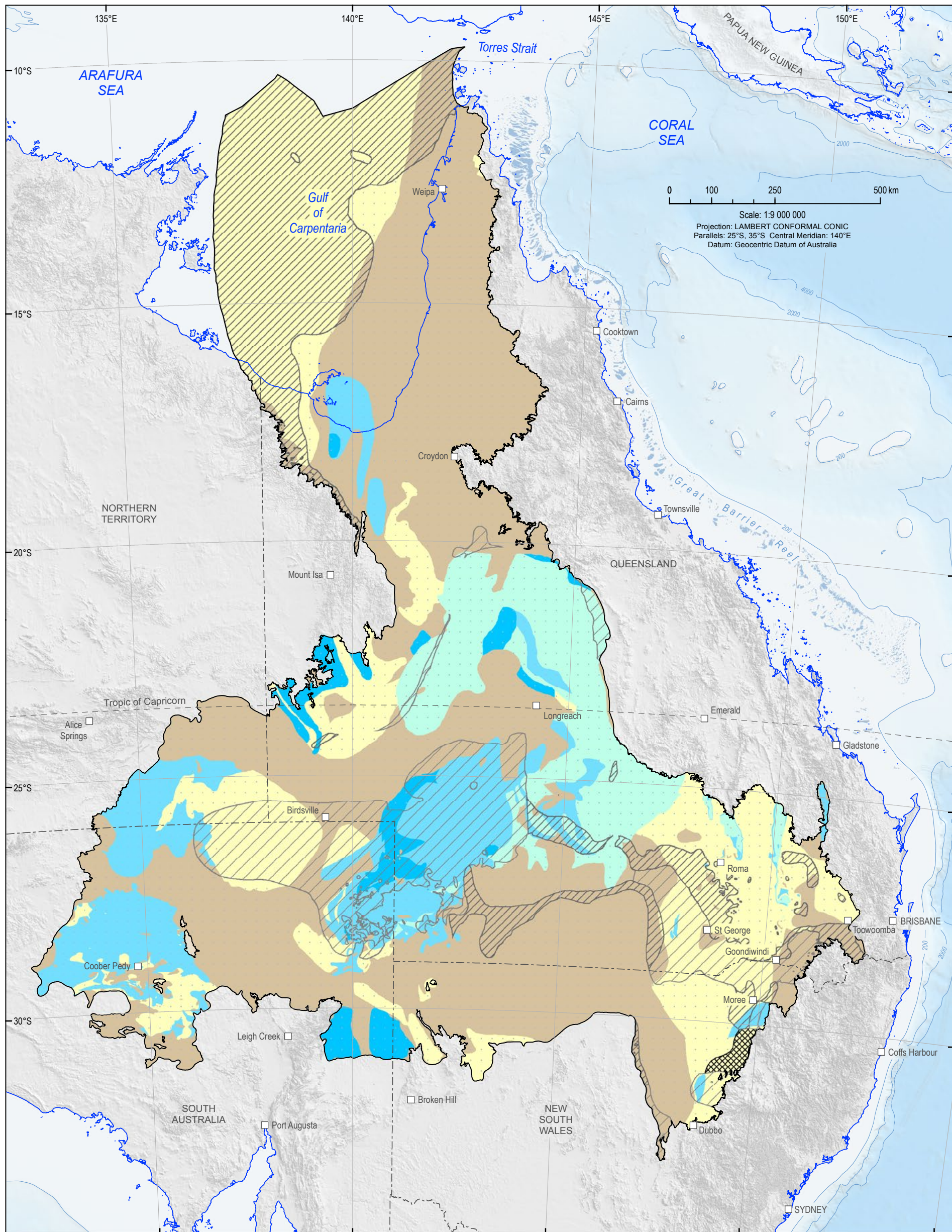
Approximately twenty seven sedimentary basins are currently known to underlie and be in direct contact with the base of the GAB.

The basal hydroconnectivity is illustrated in the map by means of two superimposed coverages of hydraulic character, both with qualitative categories: from Aquiclude, through Tight Aquitard, Leaky Aquitard, to Partial Aquifer and Aquifer. The hydraulic character of underlying units in older sedimentary

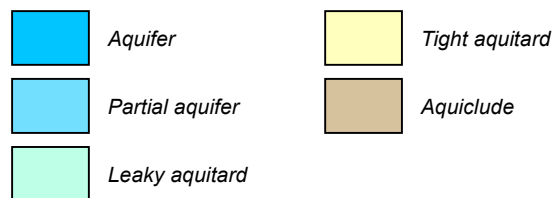
basins is classified by colour. The hydraulic character of GAB rock units sitting directly on the GAB basement is classified by monotone patterns.

The monotone scheme ranges from a dark cross hatch (aquiclude) diminishing through to a light stipple (aquifer) such that the more clearly the underlying colours can be discerned, the better the hydraulic connectivity across the base of the GAB.

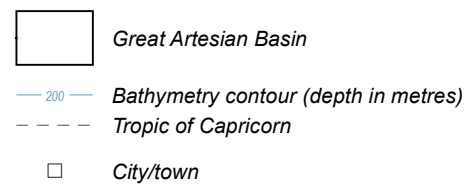
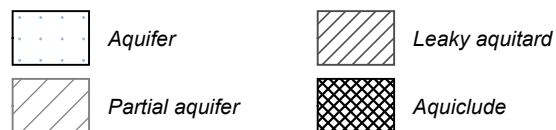
^{*} Modified from work undertaken for the Great Artesian Basin Water Resource Assessment (Ransley TR and Smerdon BD (2012)) using updated boundaries for GAB units directly overlying basement and revised Arckaringa and Pedirka basin mapping supplied by D. Wohling (South Australian Department of Environment, Water and Natural Resources).



Basement units in contact with
base of Great Artesian Basin



Great Artesian Basin units
directly overlying basement



Map 15

Hydraulic connection between Quaternary alluvium and GAB aquifers in the Surat Sub-basin

Contours of recent water level measurements in the Quaternary alluvial aquifer in the Surat Sub-basin demarcate areas where water levels in the Quaternary alluvium are higher than the regional watertable in the uppermost GAB aquifer, and areas where the GAB regional watertable is equal to or higher than the water levels in the alluvium.

A higher water level in the alluvium than that in the GAB aquifer is a necessary but not sufficient condition for downward leakage and recharge from the alluvium to the GAB formations. A second condition which must be satisfied is that a pathway exists for inter-formational groundwater flow. During the Late Cretaceous to Early Paleogene, the exposed GAB rocks were subjected to prolonged and intense weathering which produced a basin-wide thick layer of saprolite. The lower part of the saprolite is clay rich and of very low permeability. It is this layer that generally prohibits vertical fluid flow.

Airborne electromagnetic surveys, calibrated by drilling programs, have been flown in the Lower Balonne and Lower Macquarie River valleys of the Surat Basin. These surveys have shown the lower impermeable saprolite forms a continuous blanket over the GAB rocks, and prevents hydraulic connection between the Quaternary alluvium and the GAB sequence. However, in places where the saprolite has been removed by erosion, hydraulic connection is possible and highly likely. Such areas occur beneath Neogene palaeochannels where erosion during their formation was sufficient to strip the saprolite to expose unaltered rock. There are many of these palaeochannels in the Surat Basin and they either underlie modern stream channels (eg. Warrego and Castlereagh Rivers) or are buried adjacent to them (eg. Namoi and Dirranbandi Palaeovalleys).

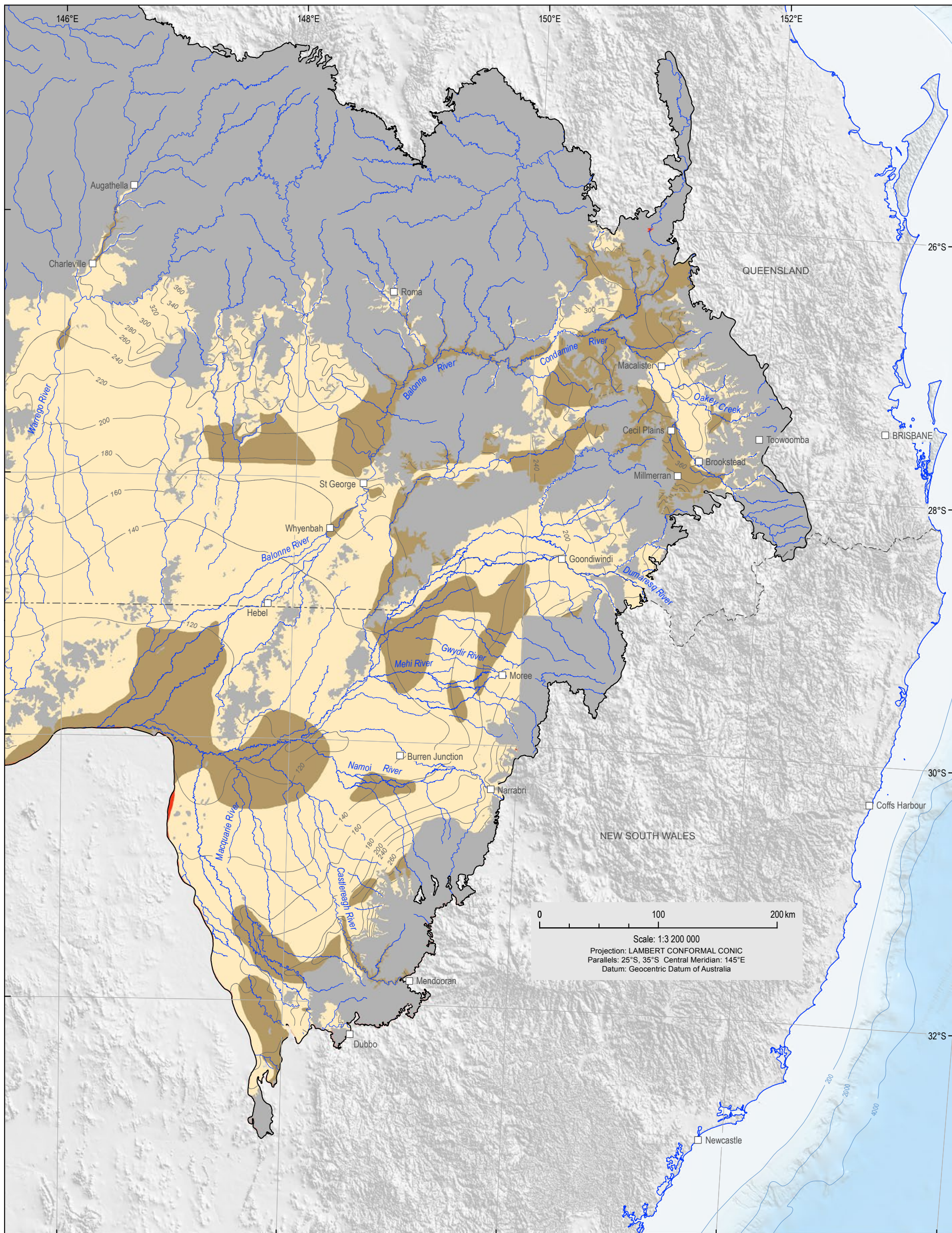
Thus the majority of the olive-coloured areas on the map of groundwater heads are those where the water levels in the Quaternary sediments are perched slightly above the regional GAB watertable as there is no hydraulic connection due to the saprolite seal. Some of these areas have been generated by irrigation loading in the alluvium, such as in the Lower Macquarie and St George irrigation areas. However, olive coloured areas on the map coincident with the modern rivers and their paleochannels represent zones where it is highly likely that the GAB formations are recharged by downward leakage from the Quaternary alluvial aquifer which in many cases is fed by stream water (losing streams).

Areas where it is highly likely that leakage from the Quaternary aquifer recharges the GAB formations are:

- ▶ Warrego River—Augathella to Charleville and Dillalah to Quilberry.
- ▶ Castlereagh River—Mendooran to Curban.
- ▶ Macquarie River—Buddah kink (20 km north of Narromine).
- ▶ Condamine-Balonne River—Macalister to Beardmore Dam (including the northern third of the Dirrandandi Palaeovalley)
- ▶ Condamine River (South Branch)—Millmerran to Cecil Plains.
- ▶ Balonne River—Blue Lagoon to Whyenbah.

Conversely, areas where it is highly likely that there is vertical upward leakage from the GAB formations into the alluvium are:

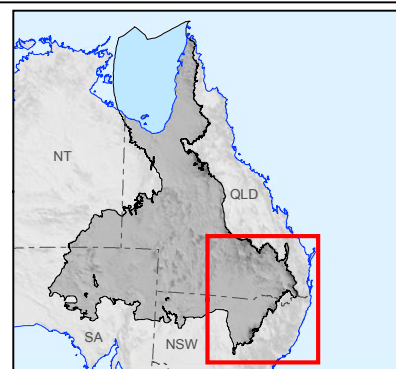
- ▶ Border Rivers (Macintyre and Dumaresq Rivers and Macintyre Brook)—upstream of Goondiwindi.
- ▶ Gwydir River—upstream of Mehi River Anabranh.
- ▶ Namoi River, Pian Creek Anabranh and Namoi Palaeochannel—Narrabri to Burren Junction (leakage is into Neogene Gunnedah and Cubbaroo formations).
- ▶ Dirranbandi Palaeovalley—St George to Hebel.
- ▶ Condamine River (North Branch)/Oakey Creek—Brookstead to Macalister.



Alluvial aquifer water level

- Quaternary alluvial aquifer absent or unsaturated
- Head in Quaternary alluvial aquifer higher than Great Artesian Basin watertable
- Head in Quaternary alluvial aquifer lower than Great Artesian Basin watertable
- Unknown

- Great Artesian Basin
- Bathymetry contour (depth in metres)
- Alluvium watertable elevation contour (metres)
- Watercourse
- City/town



Location Map

14-8061-16

Map 16

Polygonal and normal faulting in the Great Artesian Basin

Groundwater loss from the GAB system through upward leakage in areas away from outcropping aquifers is indicated by several lines of indirect evidence.

Indirect evidence of groundwater loss includes:

- ▶ the anomalous imbalance in the groundwater budget for the GAB system⁷; and
- ▶ anomalous evapotranspiration rates from riparian vegetation within these drainage systems (see Map 17).

The conceptual model below (Figure 3), illustrates the effect of fault displacement of aquifers, and possible conduits for upward leakage through a combination of faults and polygonal faulting into Cenozoic sediments and then to the ground surface. It should be noted that faults can act as impermeable barriers to groundwater flow as well as act as permeable conduits.

The regional understanding of fault displacements and fault-zone characteristics within the GAB sequence is basic, but major faults are known to have a range of vertical displacements from 200 m up to 780 m in the Jurassic-Cretaceous sequence, displacement which can completely disrupt aquifer continuity.

Additionally, the Rolling Downs Group has extensive to almost ubiquitous intraformational faulting—also known as polygonal faulting. Although little is known of the permeability of this faulting style in rocks of this age, the pervasive extent and multiple orientations of faulting, make a proportion of faults in each polygonal cell susceptible to dilation by any anisotropy in crustal stresses.

Polygonal overprints are generally manifested from the top of the Cadna-owie – Hooray Aquifer and Equivalents upwards, penetrating through both the Rolling Downs Aquitard and the Winton-Mackunda Aquifer and Equivalents.

Polygonal faulting is not known to generally penetrate Paleogene-Neogene cover but in some areas of Cenozoic duricrusted surfaces, circular to irregular patterns of comparable size to those of underlying polygonal cells appear to have been influenced during their formation by the underlying polygonal fault fabrics. Such features suggest upward groundwater leakage in such areas at the time of duricrust formation.

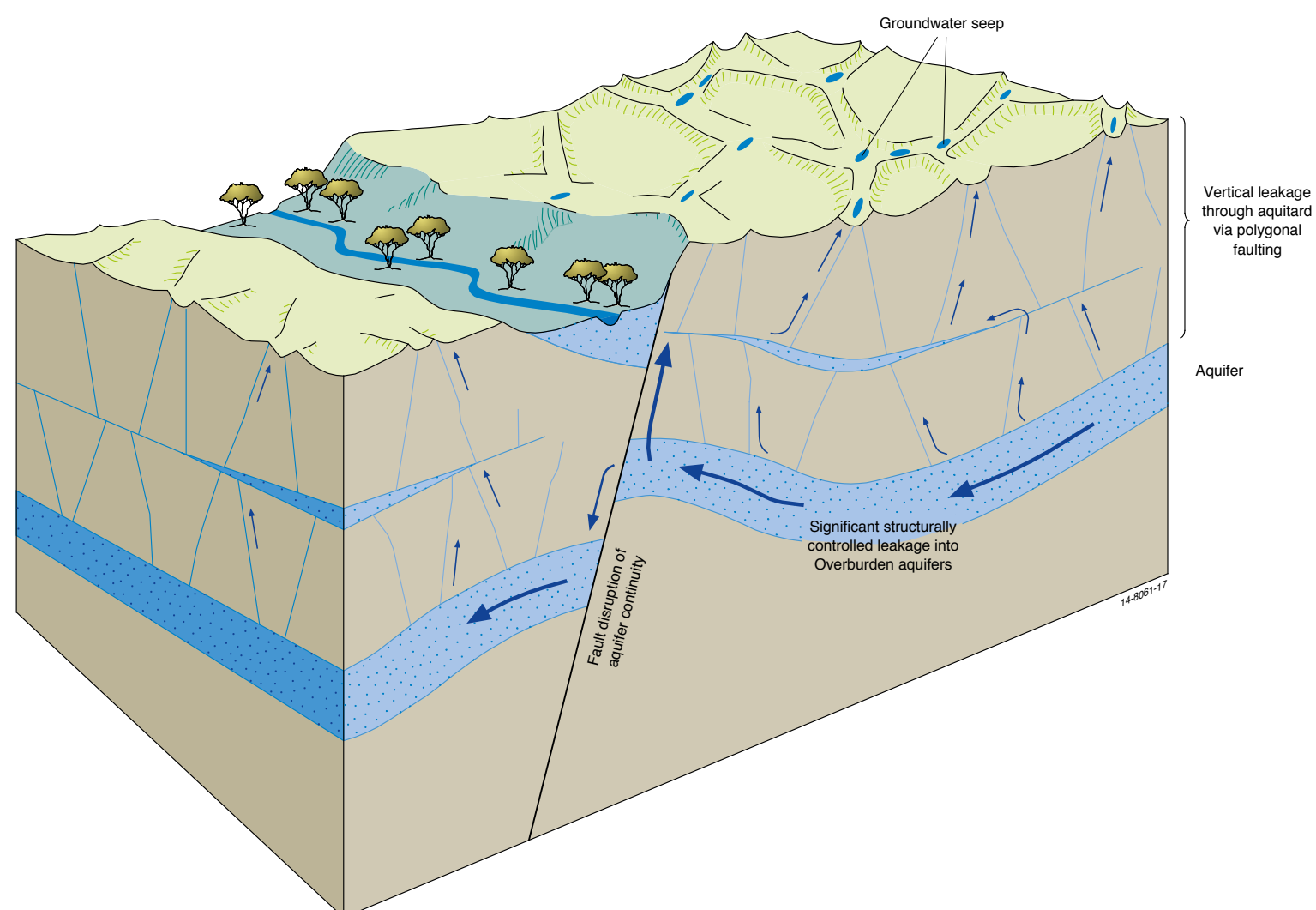
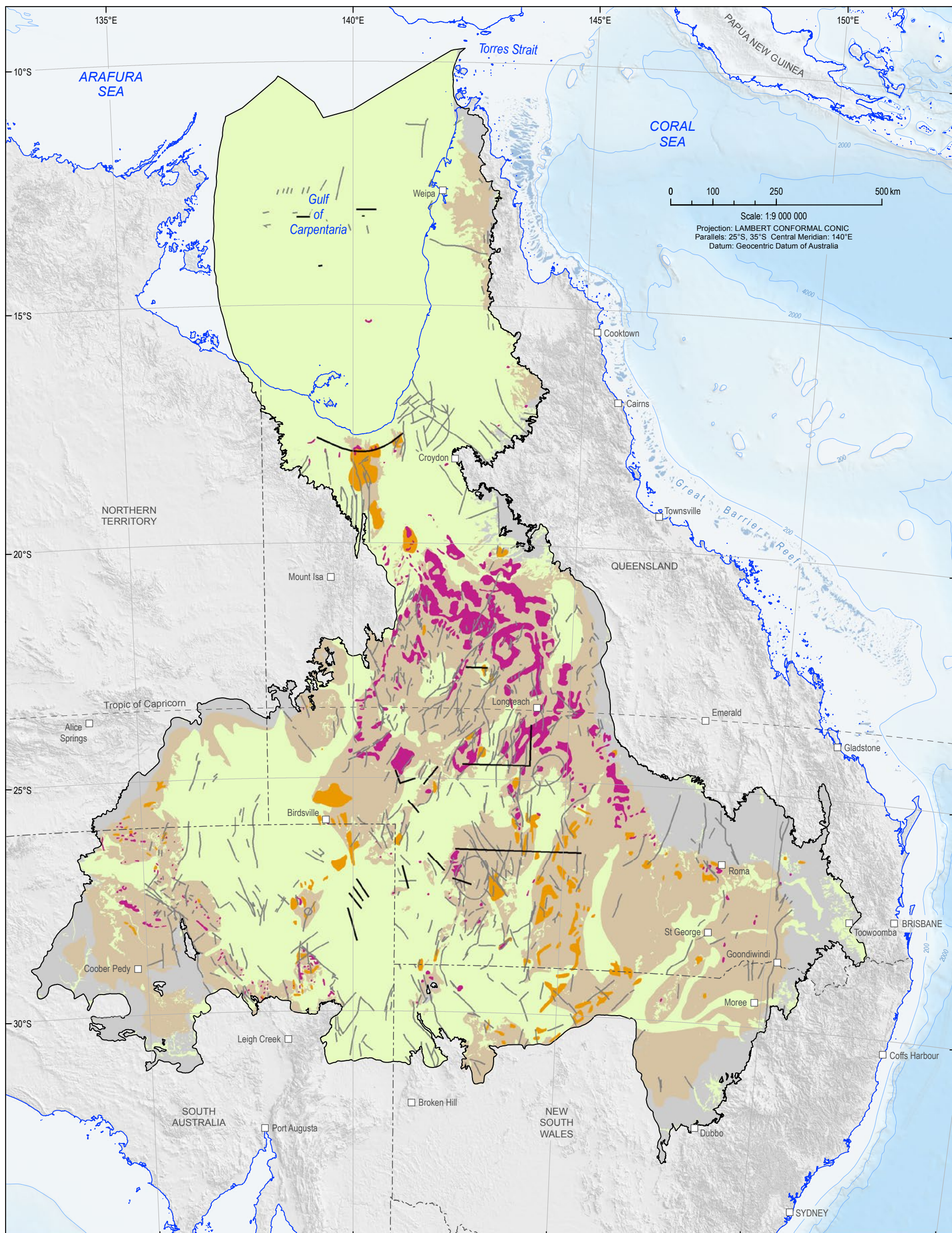


Figure 3 Vertical leakage of groundwater through a regional tectonic fault and polygonal faults



Polygonal faulting

- Cenozoic duricrust with folding/doming
- Surface expression of polygonal faulting and/or related folding in Cretaceous Rolling Downs Group
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Paleogene-Neogene Cover
- Rolling Downs Aquitard

- Great Artesian Basin
- Seismic transects indicating polygonal faulting
- Fault
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- City/town

Map 17

River tracts with inferred groundwater leakage from anomalous evapotranspiration

Water loss through evapotranspiration is an important factor for consideration in water-balance calculations in the GAB. To estimate water loss through evapotranspiration, the use of remote-sensing information allowed for the rapid, broad-scale identification of healthy, vigorous vegetation that was accessing shallow groundwater sources.

Changes in the health and vigour of vegetation are observable in satellite imagery through the application of vegetation index calculations such as the NDVI (Normalised Difference Vegetation Index). By comparing the spectral response and reflection from green plants in imagery acquired at separate dates, these calculations highlight changes in vegetation health and vigour over time.

Pre-existing time series imagery from the MODIS platform was assessed. The dataset covers the period from 2000 to 2008, consisting of 186 readings for each pixel of data. The Enhanced Vegetation Index (EVI) is applied to the MODIS data as the method is more responsive to canopy structural variations, including leaf area index (LAI), canopy type, plant physiognomy, and canopy architecture ¹¹.

The assessment of the EVI data proved effective for detecting riparian vegetation that maintained health and vigour during the period 2000 to 2008 despite the severe drought across the GAB for this period. During drought conditions, vegetation with access to groundwater retains a higher EVI response relative to nearby vegetation with no access to groundwater.

The data used was The National Dynamic Land Cover Dataset ¹². For each pixel, a set of 12 EVI coefficients have been calculated from the 186 time-series values at each pixel location. Coefficients included the mean, standard deviation, flatness, maximum, minimum, as well as a variety of rates-of-change coefficients.

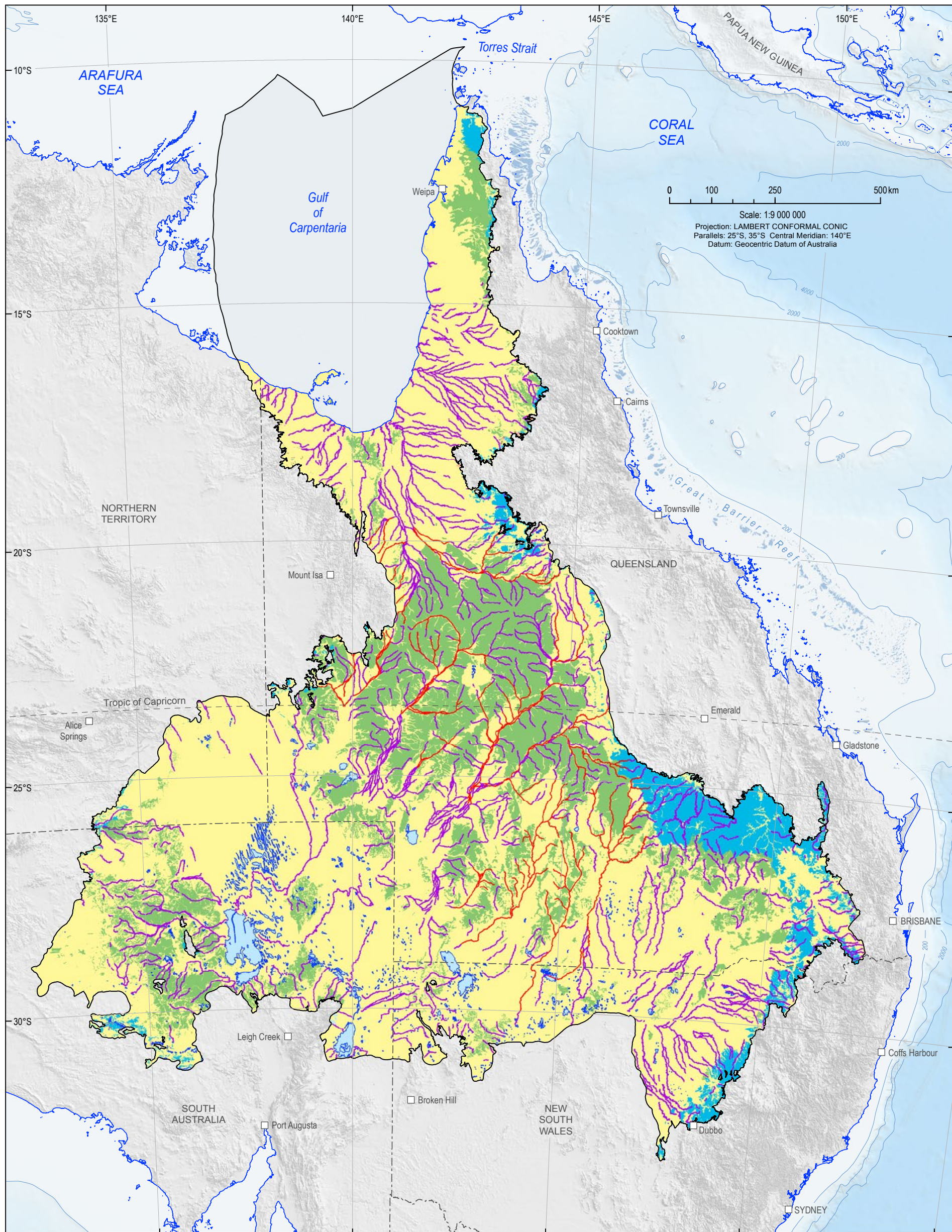
Key coefficients to the outcomes of this approach are the mean, standard deviation, and flatness and were displayed as an RGB colour image for interpretation. The major rivers of the GAB

were classified according to the adjacent riparian vegetation and corresponding consistency in high EVI values during 2000 to 2008, an extended drought.

This was extended to an evapotranspiration (ET) loss estimate by assessing tree density along the riparian zones of the major rivers. The National Dynamic Land Cover Dataset is a vegetation map for all Australia, with tree density broken into four classes (Closed, Open, Sparse, Scattered). Where riparian vegetation maintained a high EVI, the total numbers of trees were estimated from tree density. This allowed for the estimate of ET losses by applying typical transpiration values associated with major tree species as derived from previous studies ¹³. This approach allowed for the calculation of water-use along several major river systems in inland Queensland. These calculations were only undertaken on river systems that were unregulated and therefore not under the influence of irrigation or managed flow conditions.

The following list of potential ET losses from riparian vegetation from stream systems in the GAB in mega litres per year (ML/yr):

Stream system	Mega Litres per year (ML/yr)
Flinders River	21 674
Warrego River	21 060
Barcoo River	15 275
Thomson River	6 446
Diamantina River	124
Bulloo River	123
Paroo River	110
Georgina River	64
Farrars Creek	3
Wilson River	3
Total	64 882



Surface geology (1:1 000 000)

- Quaternary
- Cretaceous
- Jurassic

Riparian vegetation vigour and health 2000–2008

- High
- Low

- Great Artesian Basin
- Lake
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- City/town

Map 18

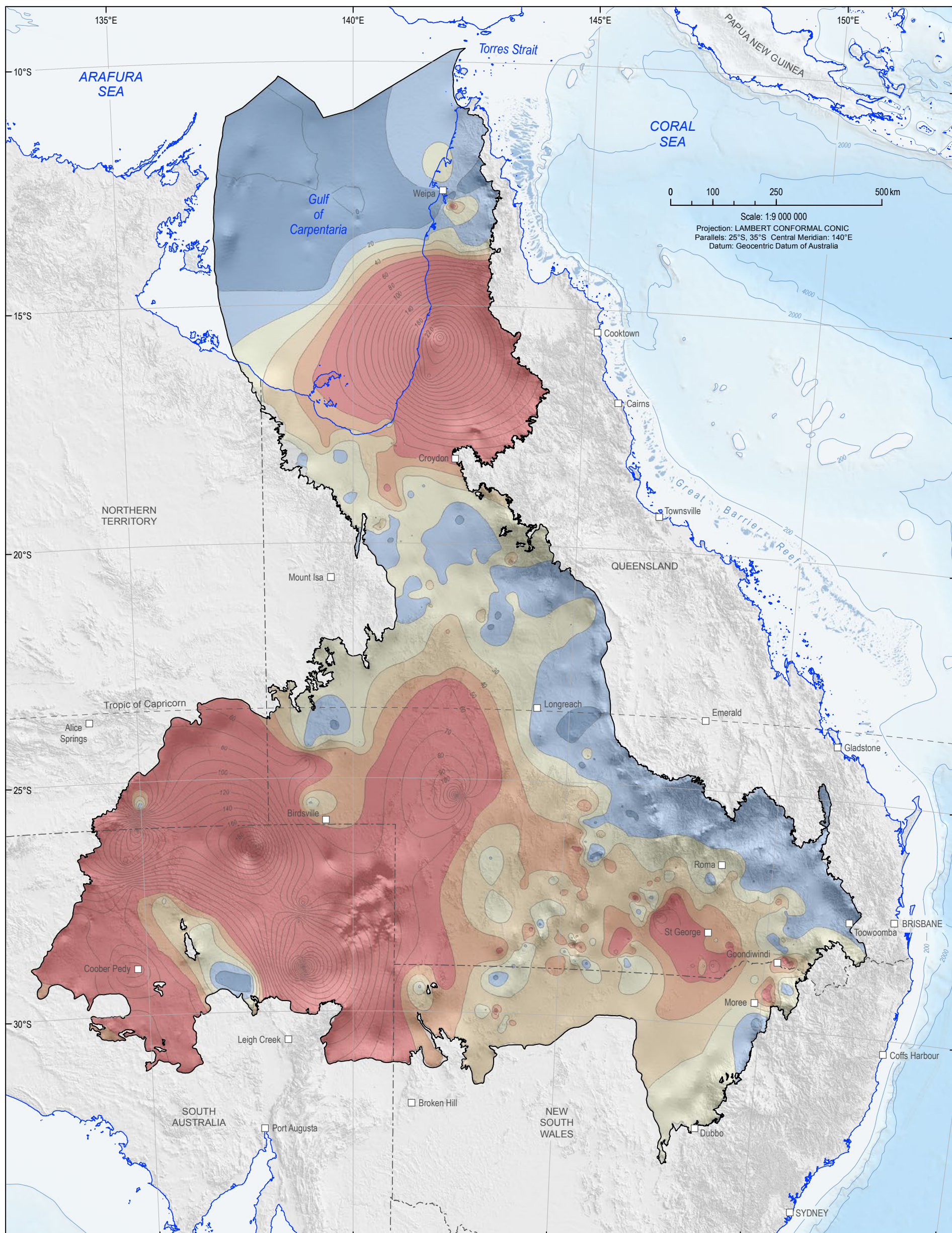
Thickness of Cenozoic weathering^{*}

Although weathering of rocks is ongoing through time, several periods of extremely intense weathering resulted from high temperatures, precipitation and atmospheric CO₂ at the close of the Cretaceous and subsequently culminating in the Paleocene-Eocene Thermal Maximum event (PETM at 56 Ma).

These and subsequent events have left distinct profiles and duricrusted surfaces on both exposed Mesozoic rocks and on older Paleogene-Neogene cover. The thickness of weathering is highly variable. Greatest weathering thickness is within and below the Cenozoic basin accumulations of Lake Eyre Basin and Karumba Basin. In contrast to these Cenozoic depocentres with thicker well-preserved weathering profiles, regional uplift along the Great Dividing Range and from the Flinders Ranges northward towards the Peake-Denison-Davenport Inliers

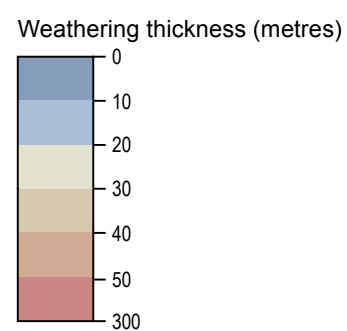
(see Maps 4 and 7) has caused erosion, which significantly reduced the thickness of the saprolite. Uplift of the eastern ranges, in conjunction with subsidence in basin depocentres, has tilted the Surat and Eromanga sub-basins, steepening southwestward drainage to enable deep incision of channels that have commonly incised through the less-permeable saprolite. This has enhanced connectivity between GAB aquifers and the alluvial aquifers in many of the resultant deep leads.

^{*} Modified from work undertaken for the Great Artesian Basin Water Resource Assessment (Ransley TR and Smerdon BD (2012)), using revised GAB boundary.



Great Artesian Basin
 20 Weathering thickness contour (metres)

200 Bathymetry contour (depth in metres)
 Tropic of Capricorn
 City/town



Map 19

Geomorphology

The geomorphology map of the GAB classifies the various landforms present across the basin. The landforms presented were interpreted using the SRTM-derived 3 second Digital Elevation Model version 1.0 in association with the 1:250 000 geological map series of Australia.

The geomorphology of the GAB, as with the thickness of weathering (see Map 18) and the Paleogene-Neogene cover (see Map 23), is the cumulative result of the distinctive climatic events and tectonism experienced throughout the Cenozoic. Intense climatic events created widespread thick weathering profiles topped by duricrusted surfaces around the Lake Eyre Basin.

Ongoing and subsequent uplift of the Great Dividing Range along the entire eastern margin, in conjunction with subsidence in the Callabonna and Tirari depocentres of the Lake Eyre Basin, has created a regional southwestern tilt in the Eromanga and Surat sub-basins. Initially intense erosion created the outwash gravels of the Glendower Formation which have subsequently become resistant silicified cappings to terrain.

The regional southwestward tilt controlled drainage from active denudation/erosional regions in the east (Rolling Downs) where the saprolite thickness was significantly thinned or entirely removed by erosion, and fluvial incision created deep leads at the headwaters of many (if not all) riverine plains that extended southwest, following parallel fracture systems that controlled fluvial and colluvial exhumation below the widespread duricrusted tablelands. These riverine systems have transported sediment from the Surat Sub-basin into the Darling River system of the Murray Basin, as well as from the eastern Eromanga Sub-basin into the Callabonna and Tirari depocentres of the Lake Eyre Basin. Today the southern margins of these depocentres continue to be the lowest areas in elevation within the basin, and are the groundwater sinks for the regional watertable (see Map 11), creating a belt of playa salt lakes along the southern margin of the GAB, that flanks the recently-uplifted Flinders-Willouran Ranges.

Fluvial sediments transported into these lake systems (Lakes Frome, Callabonna, Blanche, Gregory, Eyre South and Eyre North), have been partially redistributed by aeolian processes into the vast dune fields surrounding and downwind of these sinks and deflation areas. Pleistocene interglacial highstands of these much-expanded lakes have left a distinctive signature of modified seif dune topography in both the Simpson Desert and Strzelecki deserts, where inter-dune ephemeral lakes superimposed a pattern of lunette and shoreline dune ridges on the seif dune fabric, but seif dune development has subsequently re-established to partially overprint these palaeoshoreline features and the numerous adjoining claypans.

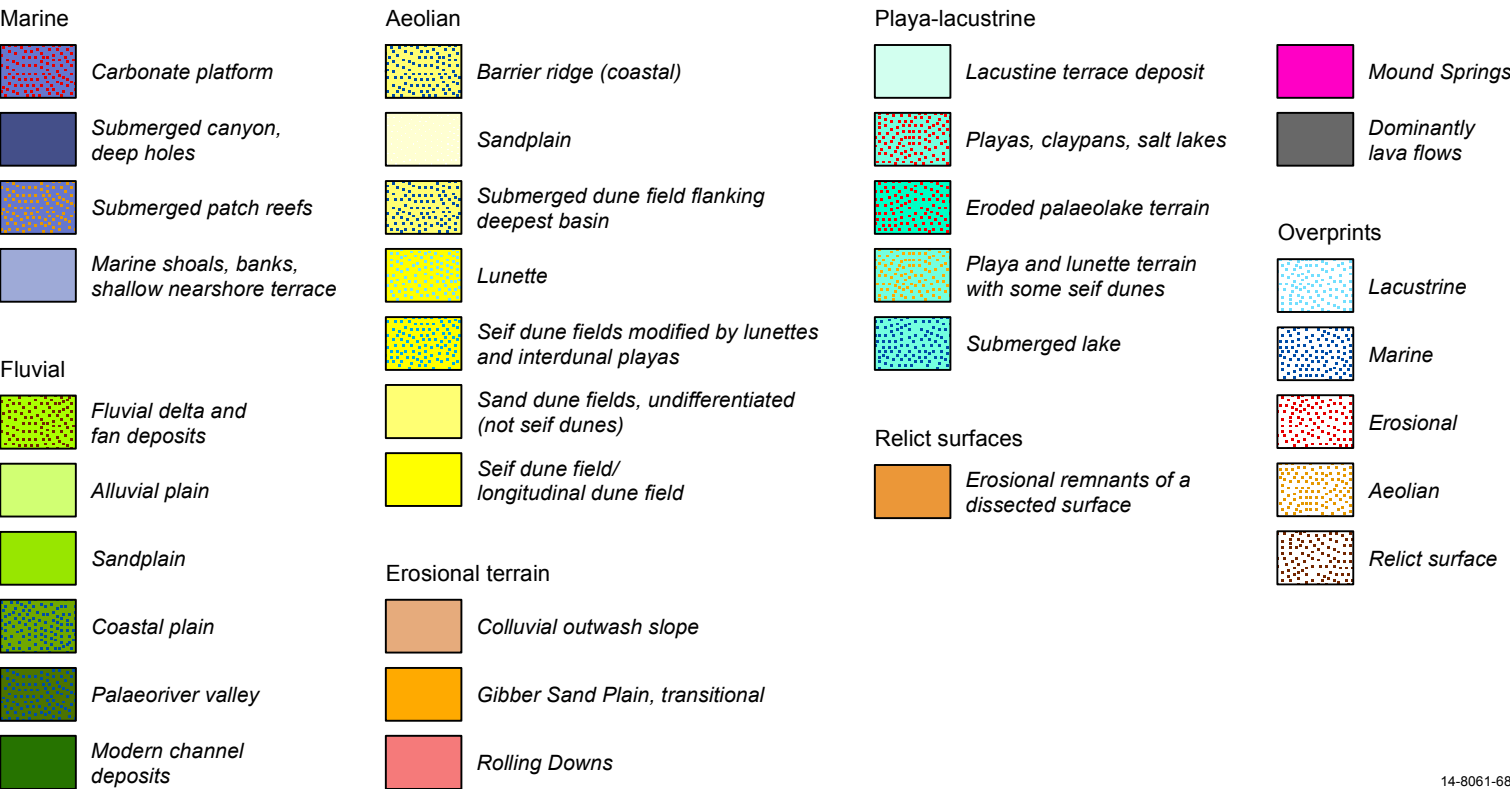
Southwest of these Cenozoic depocentres of the Lake Eyre Basin, the GAB sequence is thin, basement is shallow and relatively stable, and the terrain consists of predominantly dissected residual surfaces with scattered palaeolakes and palaeodrainage systems. Here the eastern extremities of the Great Victoria Desert offer only partial dune cover over a dissected and intensely weathered terrain.

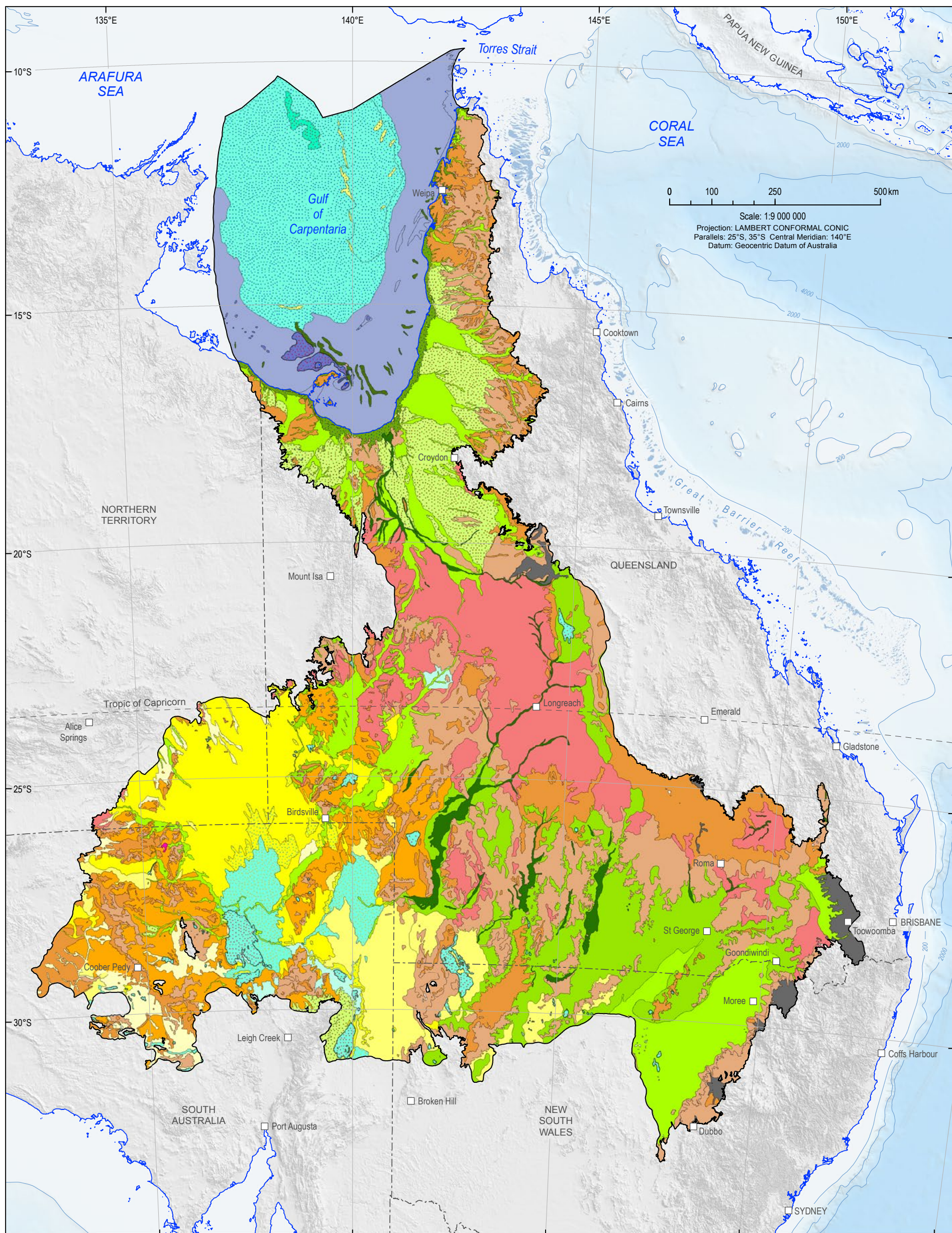
Northwards across the Euroka Arch (see Maps 4 and 5) into the Karumba Basin (overlying the Carpentaria Sub-basin) fluvial landforms are predominant—as riverine plains northward-directed towards the Gulf, and as multi-phased fluvial fans off the eastern dividing range. Fan sediment was derived from mass wasting and erosion of duricrusted surfaces that developed during the three major depositional-weathering cycles of the Karumba Basin. During Pleistocene low stands of sea level, these fluvial features extended into the Carpentaria palaeolake. This became an isolated body of water when sea level dropped 53 m below current sea level and a sill to the northwest, outside of the GAB in Australian Territory, separated it from the Arafura Sea. Remnants of relict drainage valleys are evident in bathymetry surrounding the eastern margin of the palaeolake, but their connection with onshore drainage systems has been masked by the recent accumulation of a sediment wedge nearshore and on the coastal plain. A low stand event of this Carpentaria palaeolake is evident in bathymetry approaching 70 m below sea level (see Map 20). This low stand feature parallels the cape offshore from Cape Keeweer to the Torres Strait and lies on the eastern side of the palaeolake. It is rimmed on its eastern margin by en-echelon sand shoals, and on its western margin by apparent barrier/beach ridges.

Coral reefs, as plateaux and patches, developed prior to and during Pleistocene marine incursions in the southern tectonically uplifted region of the Gulf. These reefs and karstified plateaux are now sufficiently submerged to virtually suppress modern reef growth.

Cenozoic volcanic terrain exists as scattered foci along the eastern margin of the GAB—from the Coonamble Embayment in the south, northwards through the Darling Downs of the eastern Surat Sub-basin, to the Springsure and Hughenden basaltic flows of the eastern Eromanga Sub-basin. Basaltic flows have had variable influence on terrain in these regions.

Geomorphology





Great Artesian Basin



200 Bathymetry contour (depth in metres)



Tropic of Capricorn



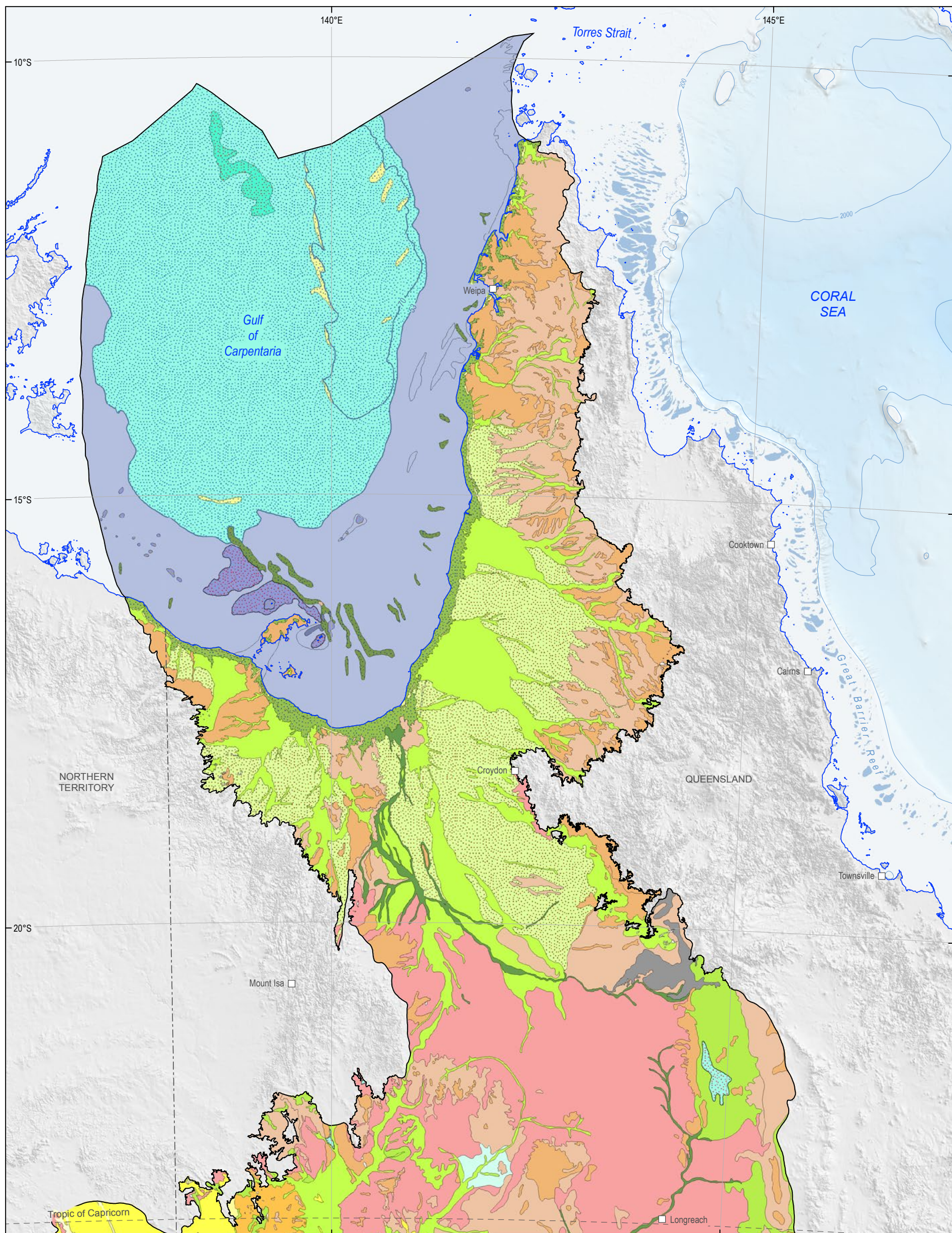
City/town

Map 20

Geomorphology—northern GAB



14-8061-69

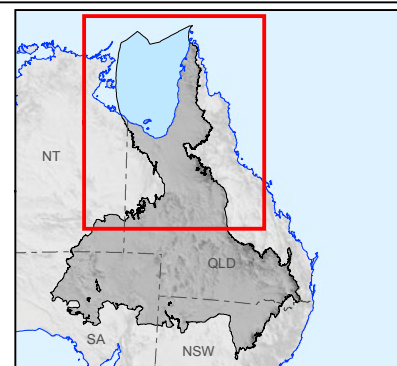


- Great Artesian Basin
- 200 — Bathymetry contour (depth in metres)
- - - Tropic of Capricorn
- City/town

0 100 250 km

Scale: 1:5 000 000

Projection: LAMBERT CONFORMAL CONIC
Parallels: 25°S, 35°S Central Meridian: 140°E
Datum: Geocentric Datum of Australia

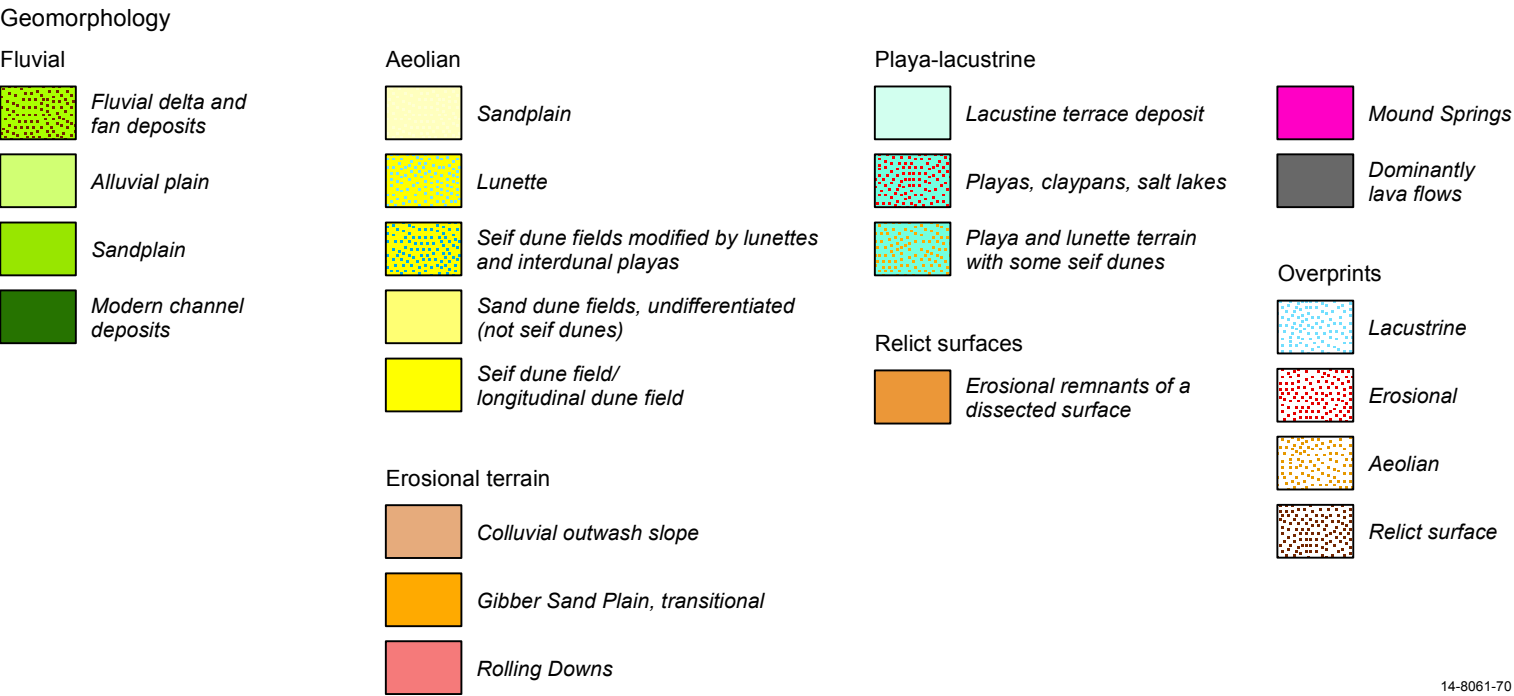


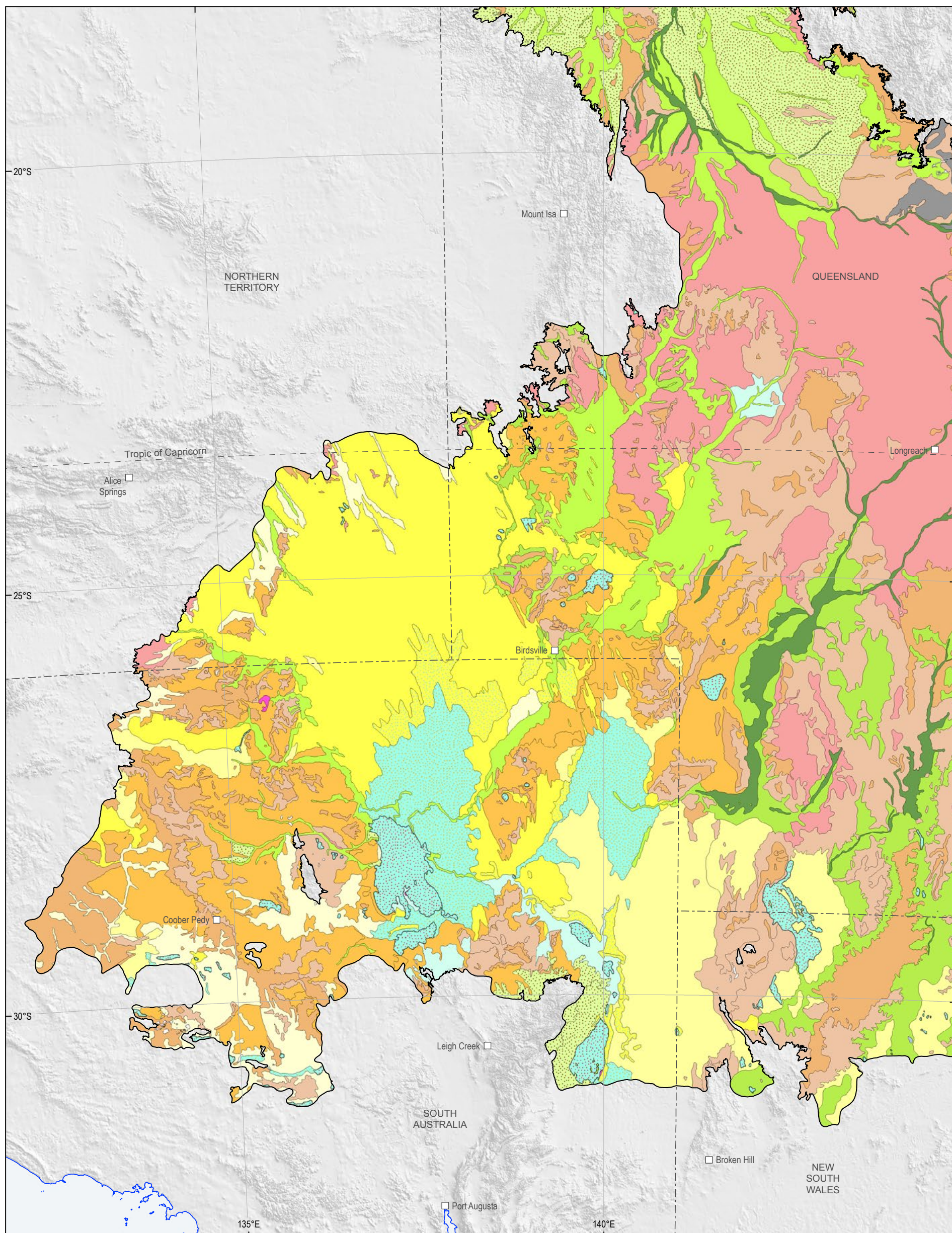
Location Map

14-8061-22

Map 21

Geomorphology—western GAB



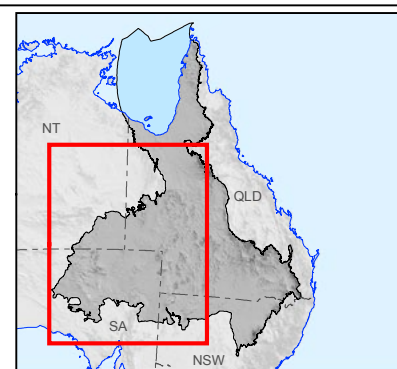


- Great Artesian Basin
- Tropic of Capricorn
- City/town

0 100 250 km

Scale: 1:5 000 000

Projection: LAMBERT CONFORMAL CONIC
Parallels: 25°S, 35°S Central Meridian: 140°E
Datum: Geocentric Datum of Australia

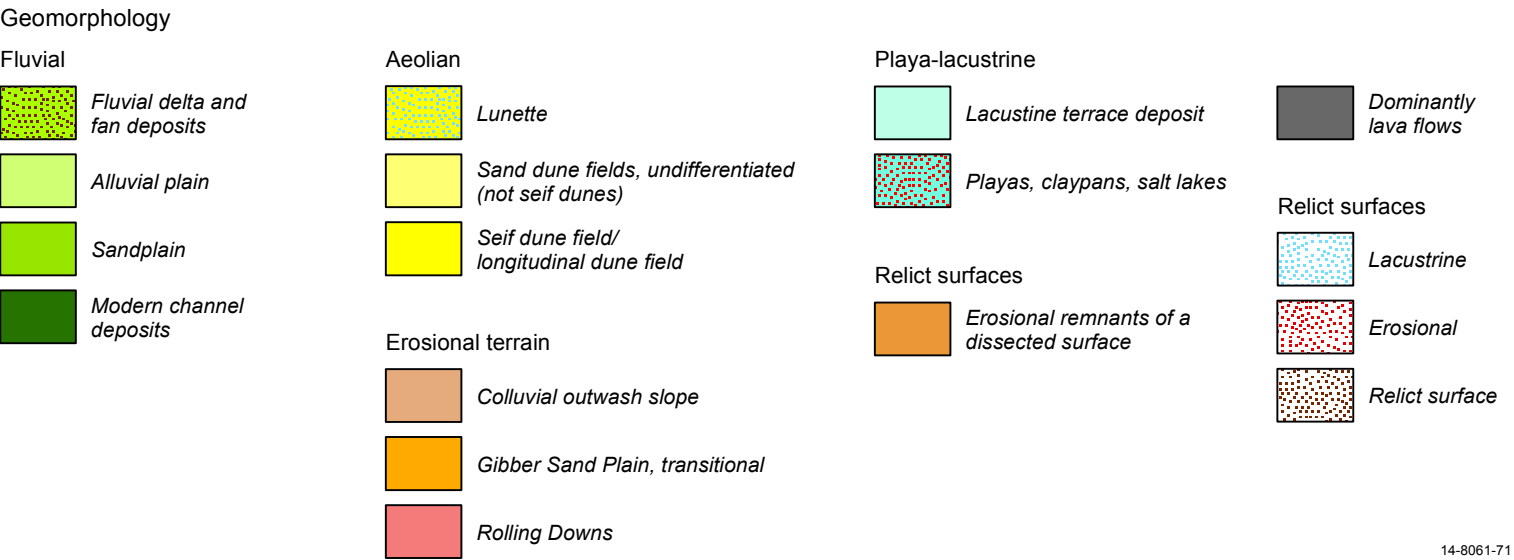


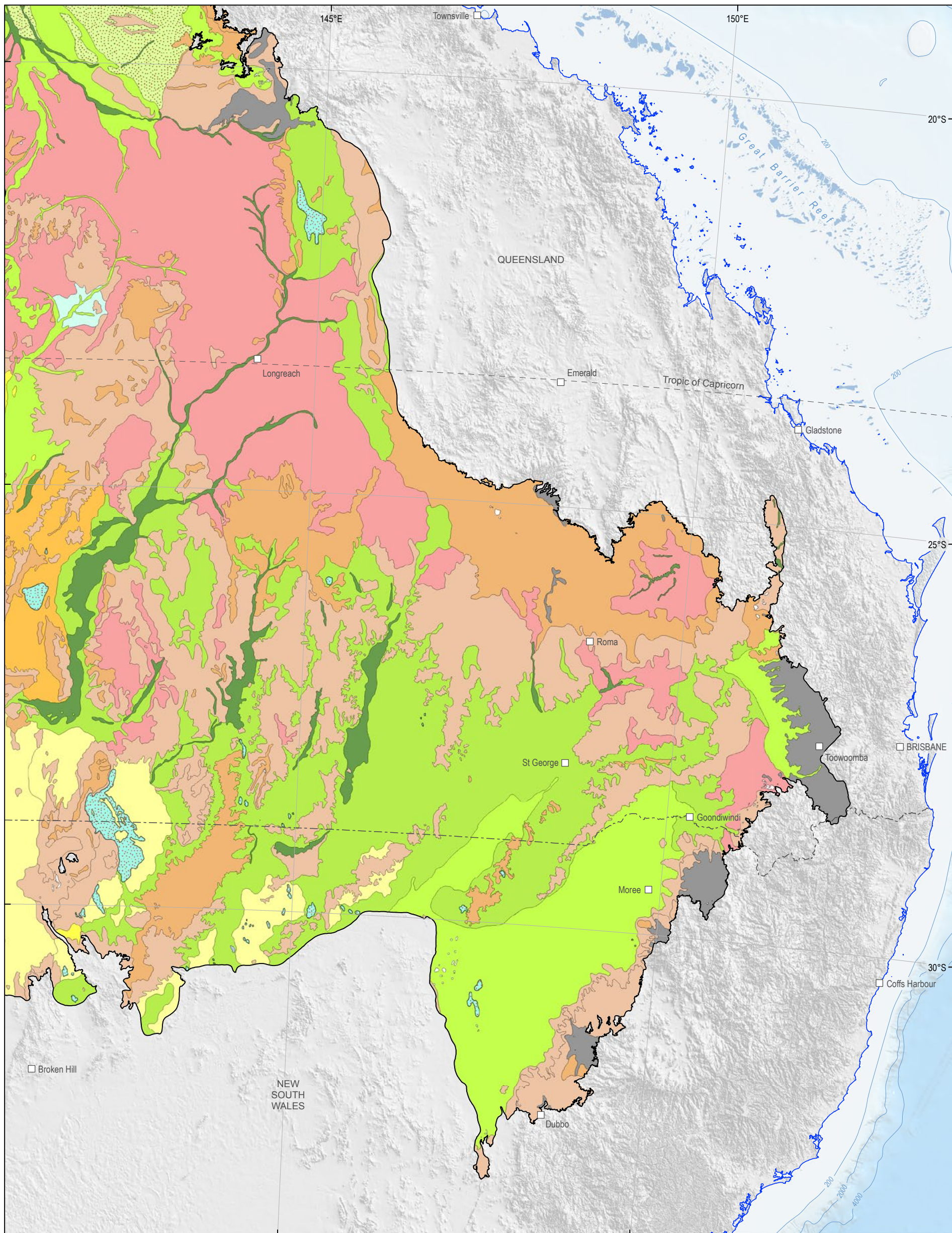
Location Map

14-8061-23

Map 22

Geomorphology—eastern GAB



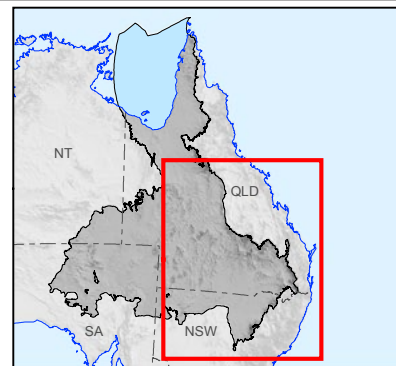


- Great Artesian Basin
- 200 — Bathymetry contour (depth in metres)
- - - - Tropic of Capricorn
- City/town

0 100 250 km

Scale: 1:5 000 000

Projection: LAMBERT CONFORMAL CONIC
Parallels: 25°S, 35°S Central Meridian: 140°E
Datum: Geocentric Datum of Australia



Location Map

14-8061-24

Hydrostratigraphic units— outcrop, extent and thickness

The following maps have been derived from the lithostratigraphic intercepts in drillhole data from petroleum exploration wells, water bores, and stratigraphic wells. The maps presented are a regional interpretation produced at the scale of 1: 1 000 000. Outcrop extents were modified from Habermehl, M.A. & Lau, J.E. (1997) Hydrogeology of the Great Artesian Basin (Map at scale 1: 2 500 000). Canberra, Australian Geological Survey Organisation.

Map 23

Paleogene-Neogene cover

The Cenozoic cover over the GAB comprises surficial Quaternary sediment overlying Paleogene and Neogene sediments and rocks. The Quaternary cover consists predominantly of sands of alluvial, colluvial and aeolian origin, which are relatively permeable, and allow direct recharge to the underlying rocks. In contrast, the Paleogene and Neogene sequence has more variable hydrogeological properties.

Paleogene and Neogene accumulations over the GAB lie predominantly in two depocentres—the Karumba and Lake Eyre basins.

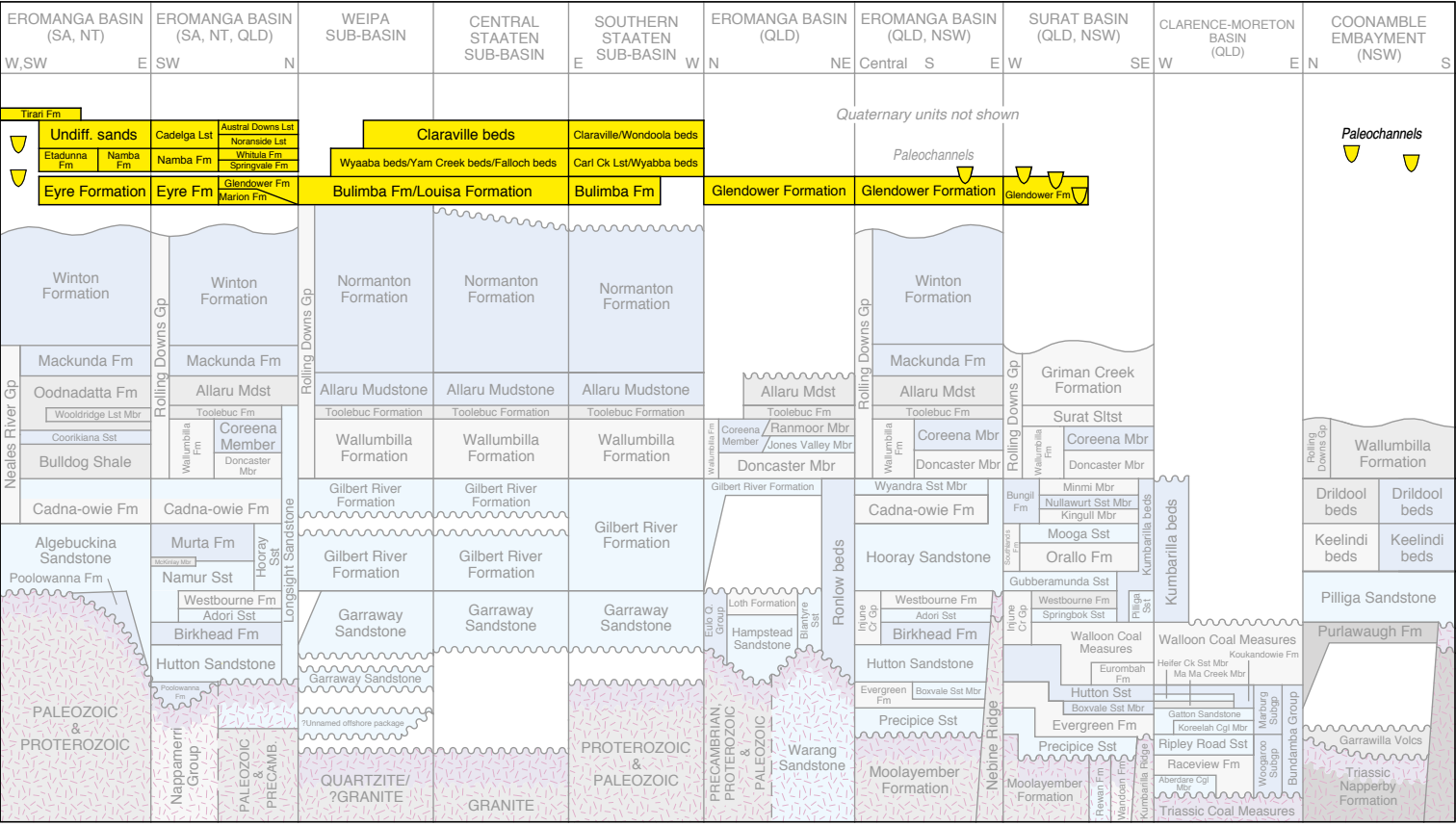
The Karumba Basin overlies but is more extensive than the Carpentaria Sub-basin except for the uplifted and eroded eastern margin. Within this basin, two depocentres are evident: offshore where the sequence reaches 450 m thickness, slightly offset to the northwest of the Cretaceous Carpentaria Depression (see Maps 4 and 5), and another within the Gilbert-Mitchell Trough (>200 m). These depocentres are separated by a northeast-southwest trending ridge, an extension of the Nicholson Ridge, which is foundation to a line of patch reefs.

Over the southwestern Eromanga Sub-basin, Paleogene-Neogene thickness is greatest in the Lake Eyre Basin which is partitioned by the Birdsville Track Ridge into the thicker Tirari Sub-basin (up to 450 m) to the west over the Poolowanna Trough, and the Callabonna Sub-basin (up to 200 m thickness) over the Central Eromanga Depocentre and Lake Frome Embayment. Sediments in the Lake Eyre Basin are predominantly fluvial sands and are good aquifers. Northeastwards towards the eastern GAB margin, this cover becomes progressively eroded and more discontinuous in isolated basins or along palaeodrainage channels. Remnant pediments of duricrusted and indurated sheetwash deposits of

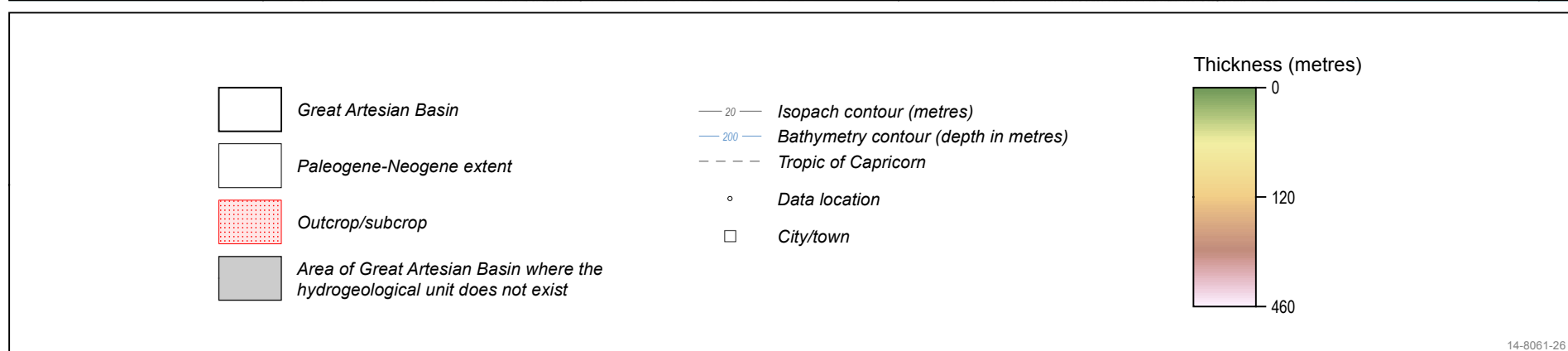
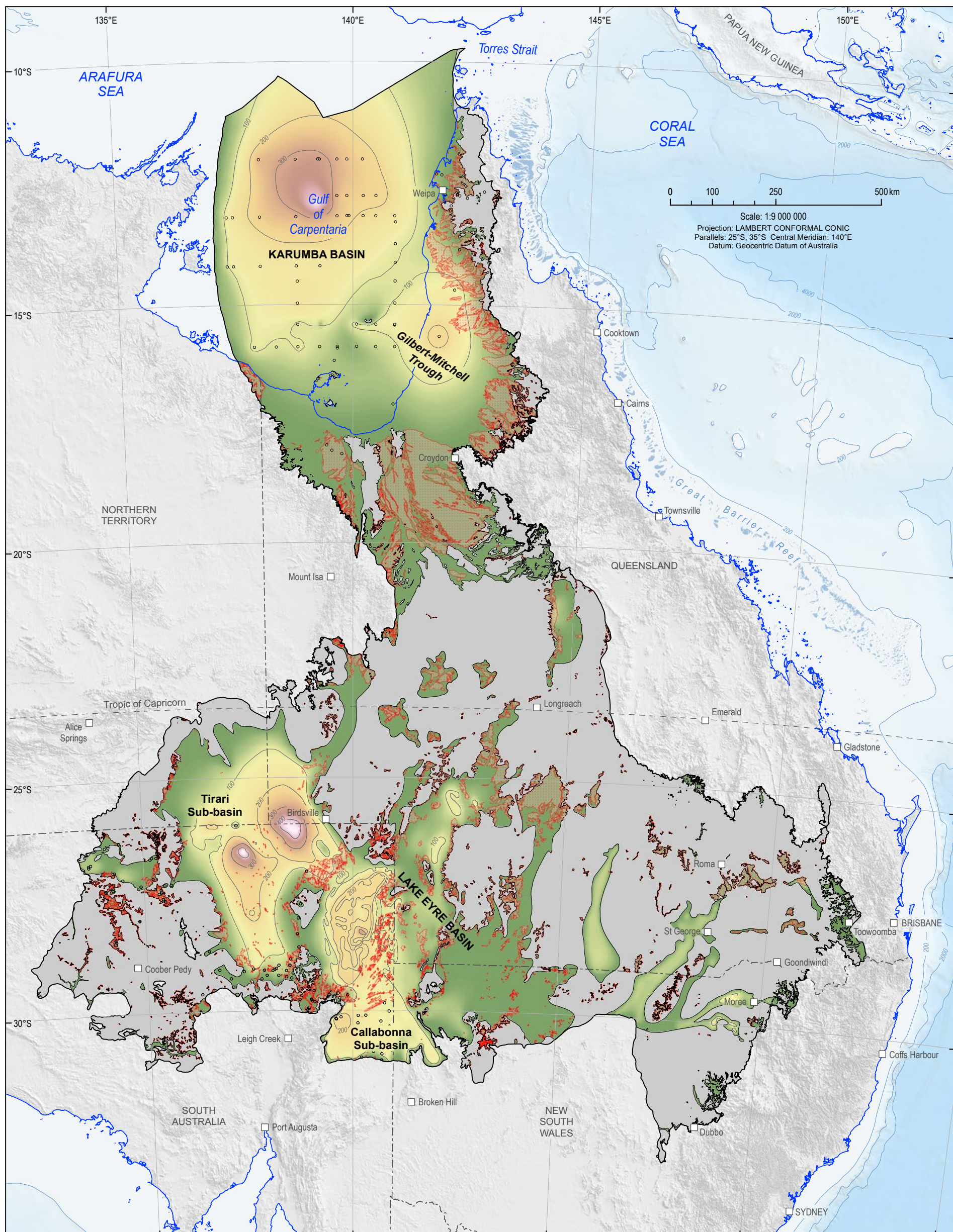
the Glendower Formation are scattered along the eastern slopes of the Eromanga and Surat sub-basins. The southwestern side of the Lake Eyre Basin is influenced by basement inliers extending northwestwards from the Flinders Ranges, through the Davenport and Denison ranges. West of this basement high, the Tallaringa and Kingoonya palaeovalleys, the Hamilton Basin and related remnants extend across the thin exposed GAB sequence which has a very thick well-developed weathering zone.

In the Surat Sub-basin, palaeovalleys and deep leads, incised up to 160 m depth, constitute localised cover over the GAB. Incision of the deep leads has generally cut through the thick saprolite developed on the GAB sequence and offers effective connectivity between Cenozoic and GAB aquifers.

Volcanic flows have created impermeable regions locally (see Map 22). These areas are located within the following 1:250 000 scale geology map sheet areas; close to the eastern basin margin of the GAB on the Hughenden and Richmond map sheets; in the northern Mimosa Syncline, on the Springsure map sheet; in the Darling Downs region on the Taroom map sheet and extending from the Chinchilla to Warwick map sheets; the Kaputar volcanics on the Inverell and Moree sheets; and the Warrumbungles on the Gilgandra map sheet.



Paleogene-Neogene cover



Map 24

Winton-Mackunda Partial Aquifer and Equivalents

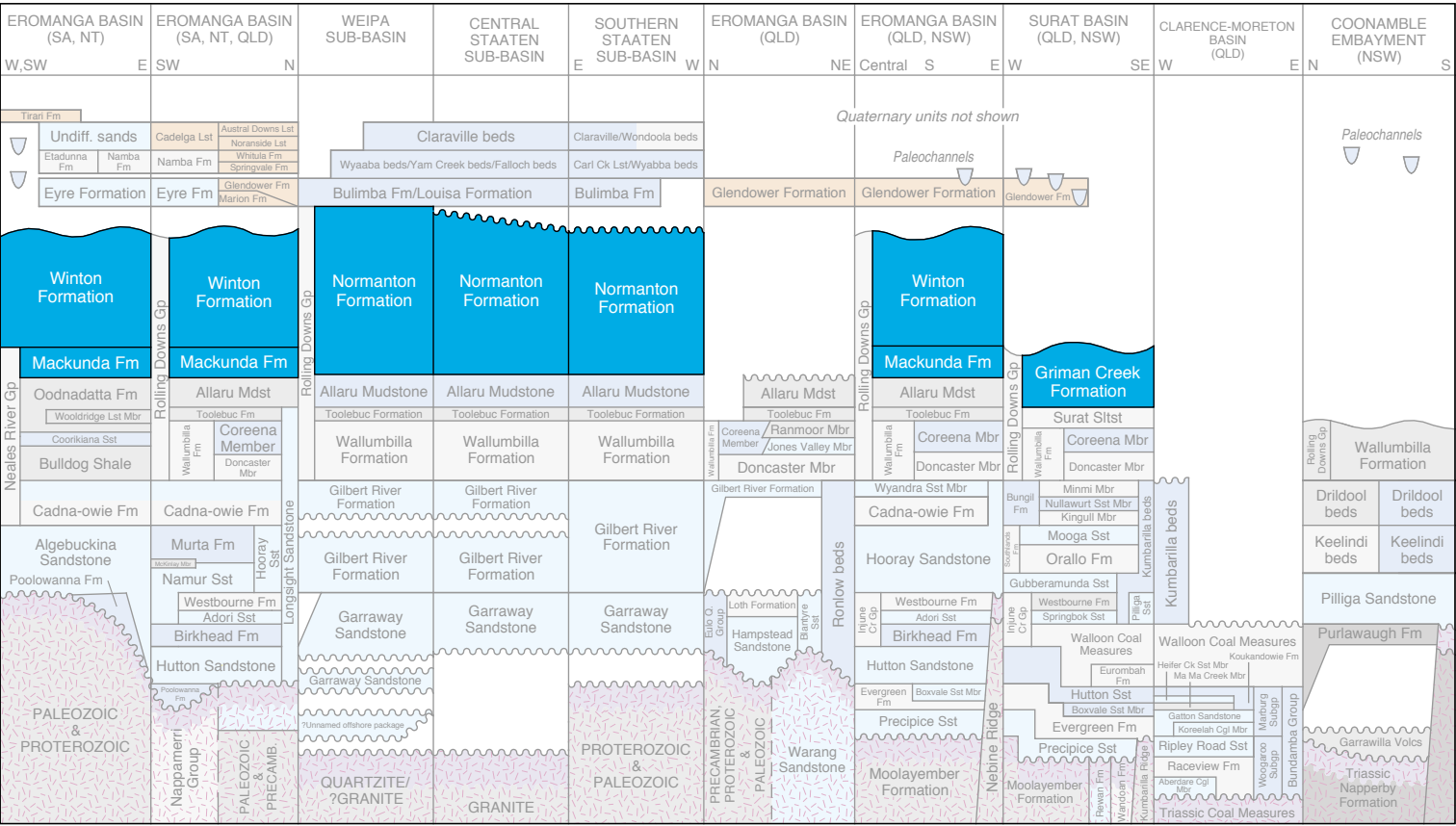
The Winton-Mackunda Partial Aquifer and equivalents has three distinct and separate extents, one in each of the main sub-basins. The broad subcrop/outcrop extent of this composite aquifer highlights the region potentially available for recharge from rainfall.

In the Eromanga Sub-basin, this composite aquifer comprises the lower marginal-marine Mackunda Formation and the overlying continental Winton Formation. Both the Mackunda Formation and the lower Winton Formation have relatively consistent and good aquifer characteristics but up sequence in the Winton Formation, aquifer sands become more sporadic as fluvial channel ribbons that lie within less permeable mudstones, siltstone and coal. The thickest region of this aquitard is within the Central Eromanga Depocentre (see Maps 4–7) with thickness exceeding 1000 m along its axis. The Poolowanna Trough, to the west, has in excess of 700 m thickness.

Northwards across the Euroka Arch into the Carpentaria Sub-basin, the equivalent of the Mackunda Formation is the marginal-marine Normanton Formation which has good aquifer characteristics onshore but transitions into a low permeability aquitard centrally offshore. Here the aquitard is predominantly

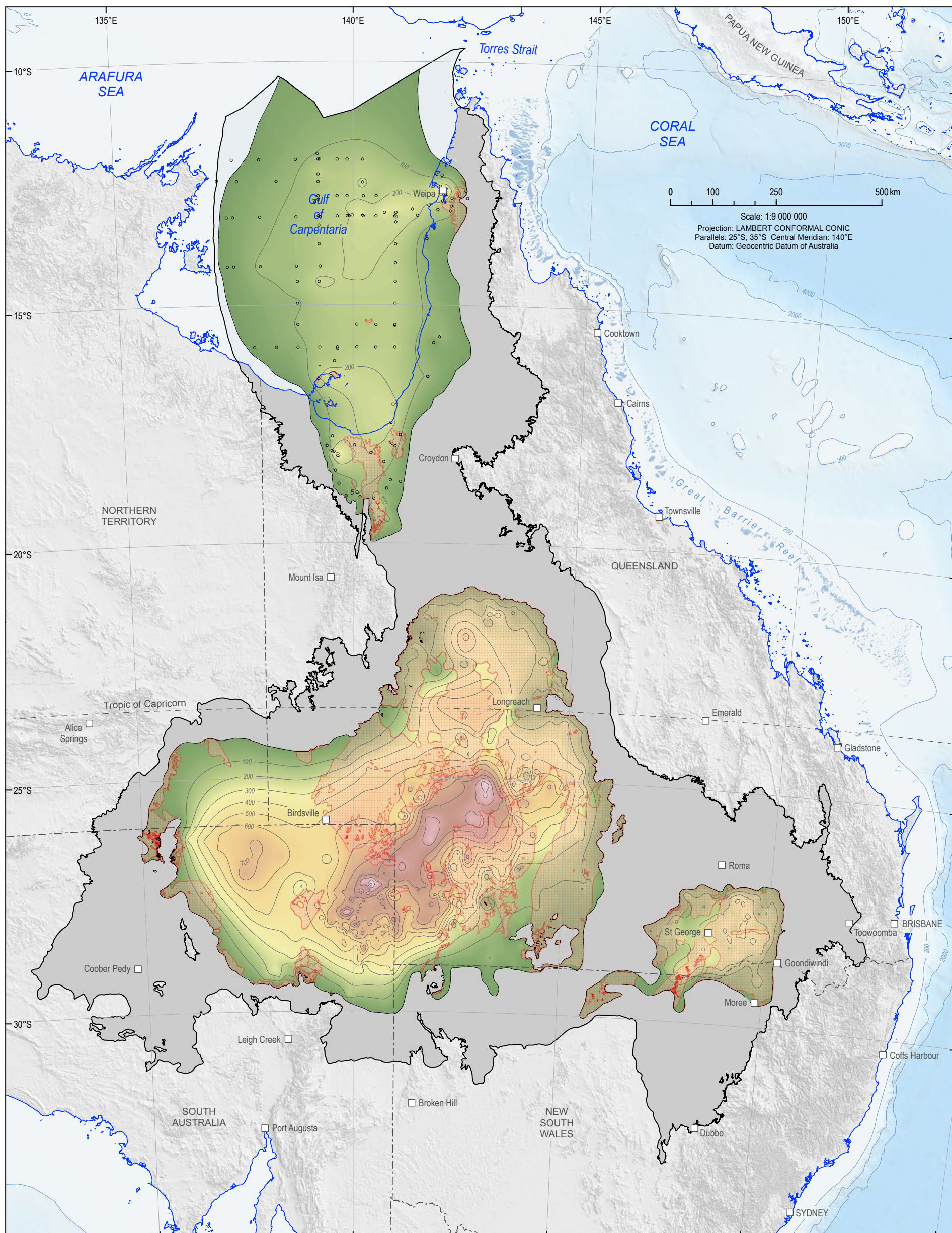
<200 m thickness with a subtle offshore thickening toward the Carpentaria Depocentre, with an increased thickness to over 250 m in an east-northeastward orientation into the Weipa Depression (see Map 5). From Mornington Island to the southern Staaten and the Boomarra sub-basins there is localised thickening of the aquifer.

The Eulo-Nebine Ridge effectively separates the Eromanga and Surat sub-basins at this stratigraphic level. In the Surat Sub-basin, the Griman Creek Formation is the equivalent of the Winton-Mackunda Aquifer. The Griman Creek Formation has internal variability comparable to that in the Winton Formation, but overall it has poorer aquifer characteristics compared to the Winton and Mackunda Formations. The greatest thickness in this sub-basin exceeds 250 m, locally >300 m, from the central Mimosa Syncline and southwestwards along the Dirranbandi Syncline.



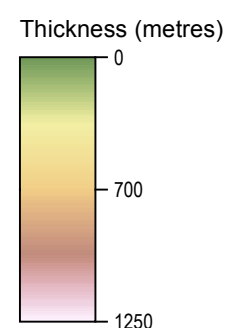
14-8061-27

Winton-Mackunda Aquifer and Equivalents



- Great Artesian Basin
- Winton-Mackunda Aquifer and Equivalents
- Outcrop/subcrop
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Isopach contour (metres)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Data location
- City/town



Map 25

Rolling Downs Aquitard

The widespread Rolling Downs Aquitard comprises marine units of fine-grained siliciclastics, mudstone and limestone, and is considered the most effective aquitard in the GAB because of its extent, thickness and low permeability of mudstones and fine-grained sediments.

Within the eastern Eromanga Sub-basin, the aquitard comprises the combined sequence of the Wallumbilla Formation, Toolebuc Formation and Allaru Mudstone. Beyond the southwestern limit of the Toolebuc Formation, the Bulldog Shale and Oodnadatta Formation constitute the aquitard, even though they contain the intervening Coorikiana Sandstone, an aquifer which has comparability with the Coreena Sandstone stringers of the Wallumbilla Formation to the east.

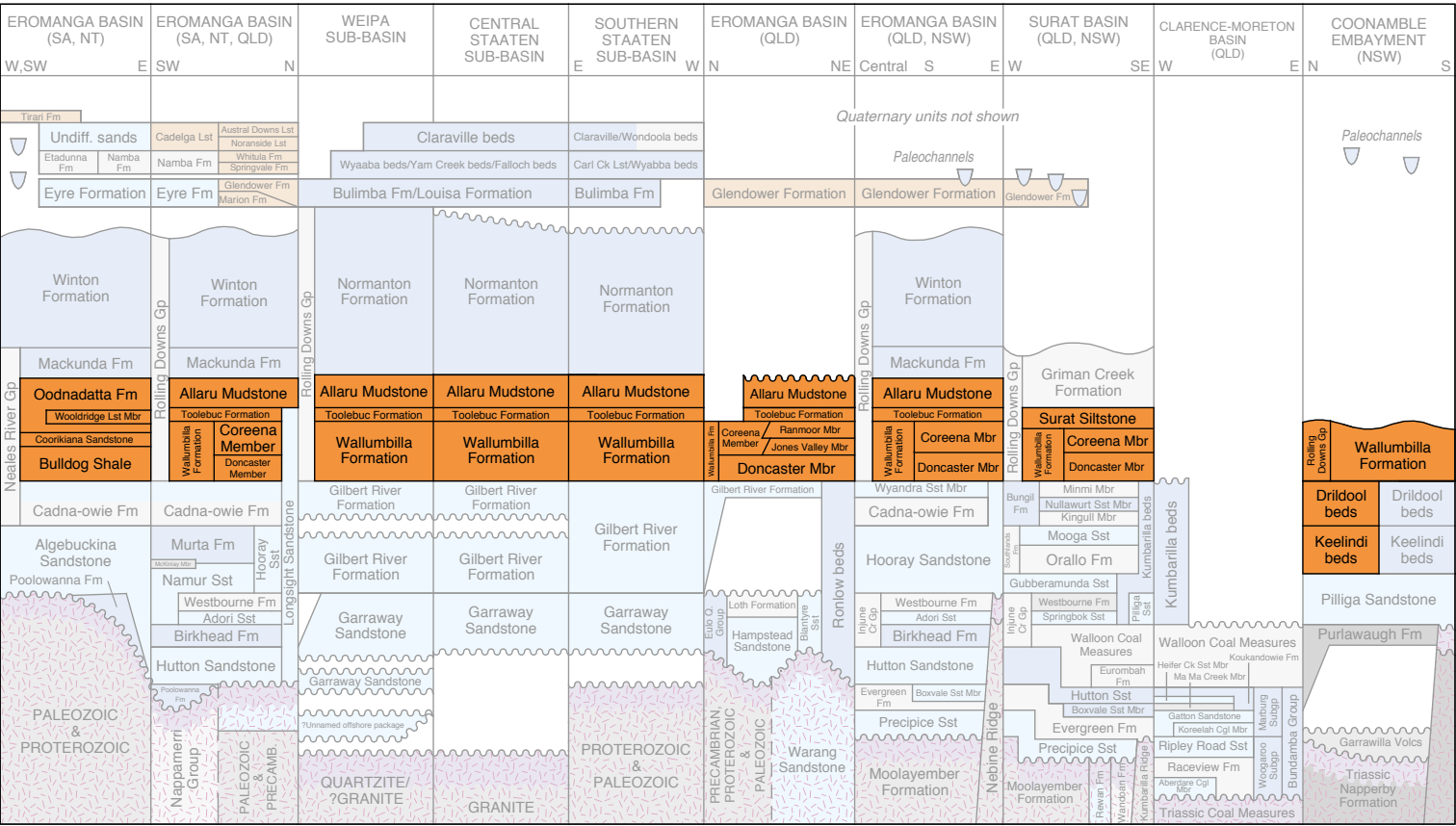
The anomalous relief of crater rims of the Tookoonooka and Talundilly structures on the southern and eastern margins of the central Eromanga Depocentre was only completely buried well into deposition of the Wallumbilla Formation, so the cratering has locally affected the thickness of Rolling Downs Aquitard.

In the Surat Sub-basin, this aquitard comprises the Wallumbilla Formation and overlying Surat Siltstone. Southwards into the Coonamble Embayment, the aquitard comprises the Wallumbilla Formation and overlying Keelindi and Drildool beds to a southern limit at 31.5°S (see Maps 4 and 6). South of this latitude, the

Keelindi and Drildool beds become sandier with good aquifer characteristics, and are thus excluded from this aquitard and included in the Cadna-owie – Hooray Aquifer and Equivalents.

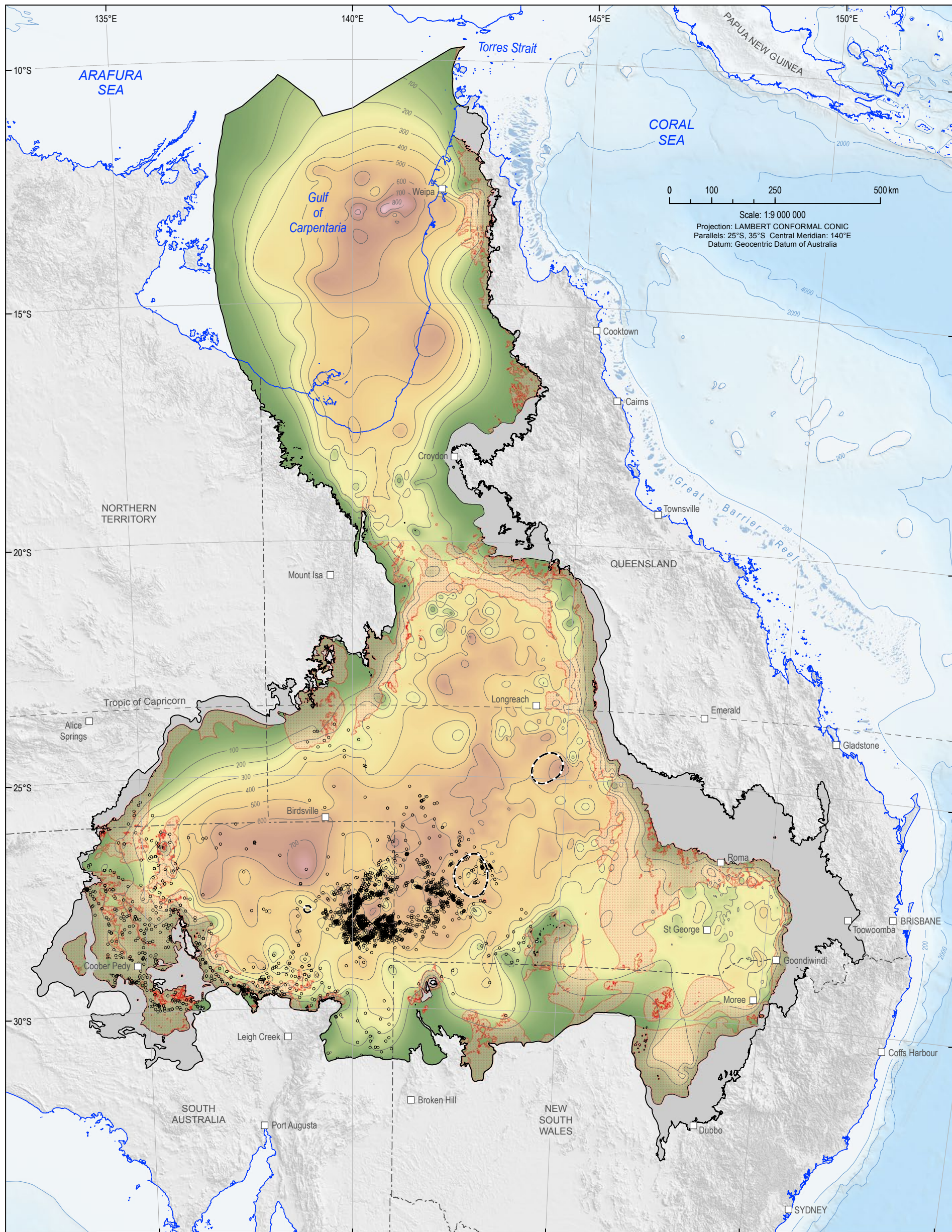
The Rolling Downs Aquitard is continuous northwards over the Euroka Arch into the Carpentaria Sub-basin. Offshore, differentiation between the Rolling Downs Aquitard and overlying Normanton Formation (Winton-Mackunda and Equivalents Aquifer) is equivocal in existing seismic coverage, so on the basis of proportional thickness of units in three control wells, the Rolling Downs Aquitard is assumed to comprise 75% of the seismic thickness of the Rolling Downs Group across the entire offshore region.

Greatest thickness of this aquitard is in the Carpentaria Depocentre (up to 800 m), the Poolowanna Trough (up to 750 m), along the Central Eromanga Depocentre and the Cork Fault (locally up to 650 m), and the onshore Staaten River Embayment (up to 650 m). In the Surat Sub-basin, the aquitard thickness is locally variable throughout, but largely between 150 m and 400 m thick.



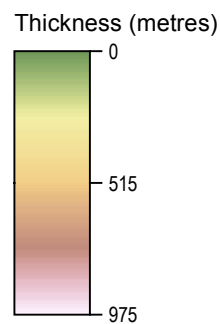
 Rolling Downs Aquitard

14-8061-29



- Great Artesian Basin
- Rolling Downs Aquitard
- Outcrop/subcrop
- Explosion structure - probable bolide impact crater

- Area of Great Artesian Basin where the hydrogeological unit does not exist
- Isopach contour (metres)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Data location
- City/town



Map 26

Cadna-owie – Hooray Aquifer and Equivalents

This composite aquifer is widespread across all sub-basins and has an extensive peripheral recharge zone as indicated by the outcrop regions. It is the shallowest and most-exploited of the artesian aquifers in the GAB.

The aquifer comprises the upper Cadna-owie Formation that includes the uppermost Wyandra Sandstone Member (Eromanga Sub-basin) and Bungil Formation (Surat Sub-basin), and the underlying Hooray Sandstone and its equivalents. These equivalents are the Longsight Sandstone, Ronlow beds, Namur Sandstone and Murta Formation, and Algebuckina Sandstone in the Eromanga Sub-basin; the Gubberamunda Sandstone, Orallo Formation and Mooga Sandstone in the Surat Sub-basin; Pilliga Sandstone, including the Keelindi and Drildool beds south of 31.5° S in the Coonamble Embayment; and in the Carpentaria Sub-basin, the Gilbert River Formation and underlying Eulo Queen Group equivalents—Garraway Sandstone, Helby beds, and Albany Pass beds. These Eulo Queen Group equivalent units are of comparable age to the Hutton Sandstone, but northwards across the Euroka Arch there is direct hydraulic connection between the overlying Gilbert River Formation and these units in the absence of intervening aquitards, so they are included in this aquifer grouping.

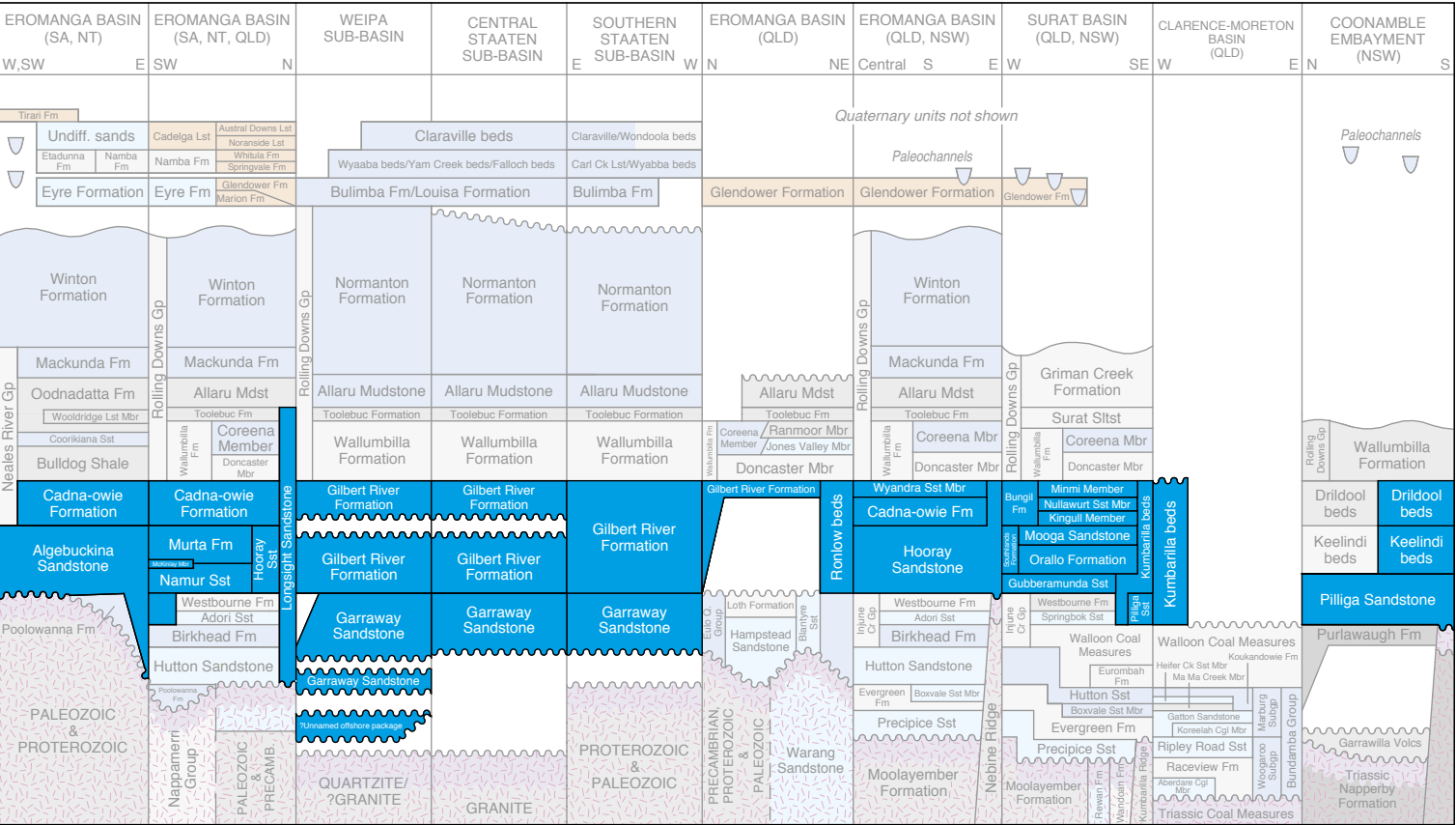
Although the Cadna-owie Formation is generally a poor aquifer, it commonly has a thin upper sandstone that is an excellent aquifer– the Wyandra Sandstone Member in the east, the Mount Anna Sandstone and Trinity Well Sandstone members in the southwest. Within the southwestern Central Eromanga Depocentre, beyond the limit of the Westbourne Aquitard, the Namur Sandstone with overlying Murta Formation form an equivalent to the Hooray Sandstone and these units extend southwestwards across into the Poolowanna Trough where the Algebuckina Sandstone is a lateral equivalent, as it is also with the Hutton Aquifer.

Two very large circular explosion features were emplaced at about 125 Ma during deposition of the Cadna-owie Formation. These are the Tookoonooka (55-60 km diameter) and Talundilly

(84 km diameter) features. Cratering and canyon development from these events redistributed thickness of the Cadna-owie – Hooray Aquifer locally and the catastrophic event also fractured the underlying GAB sequence and basement.

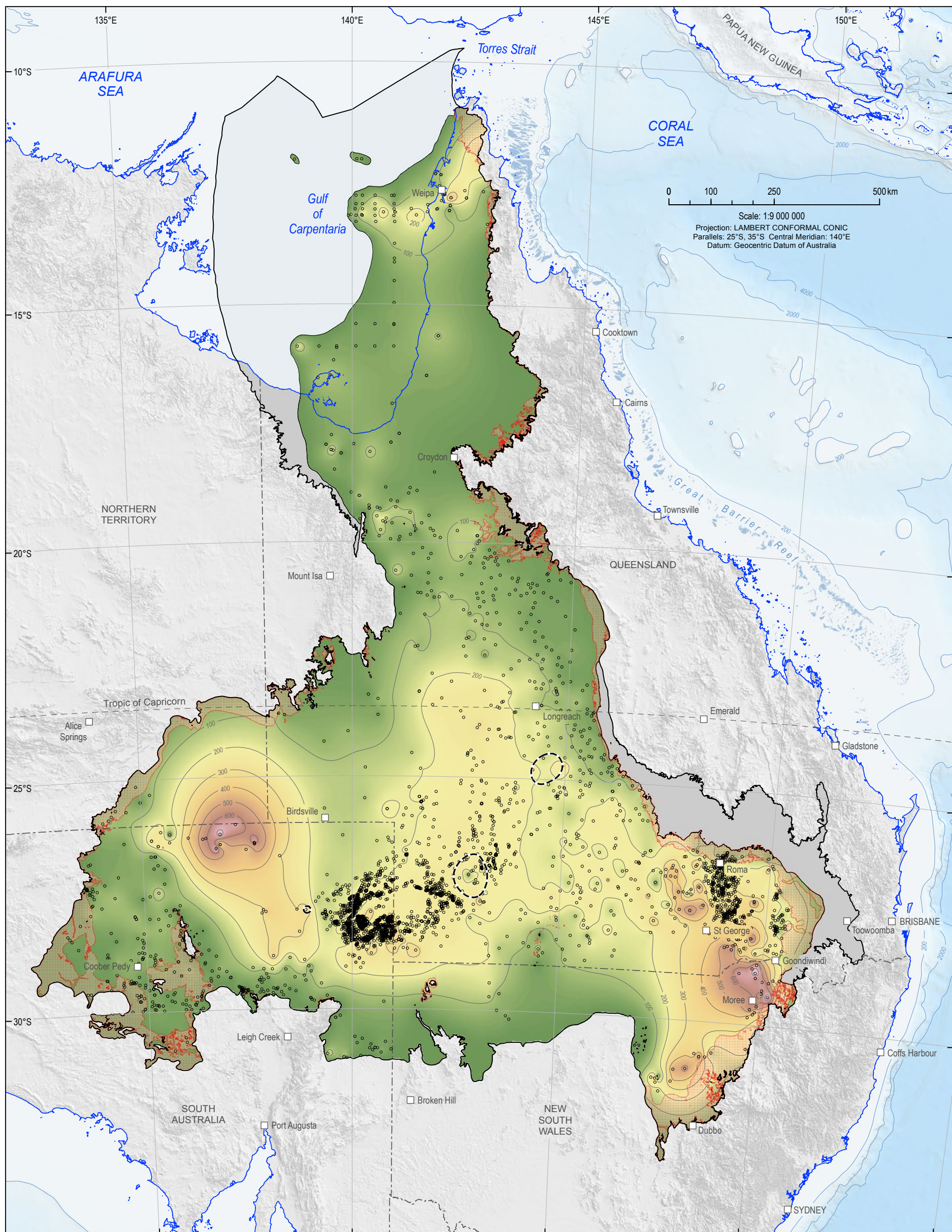
Greatest thickness of the Cadna-owie – Hooray Aquifer is in the Poolowanna Trough (>700 m) and in the Surat Sub-basin, with up to 700 m in the southern Mimosa Anticline, and locally thick regions (up to 500 m) west of the Roma Shelf and to the south in the central Coonamble Embayment. The east and central Eromanga Sub-basin has >150 m thickness. Approaching the Ronlow beds in the northeast, as well as in the southwestern region, beyond the Peake-Denison-Davenport Inlier, aquifer thicknesses are predominantly underestimates as only partially penetrating waterbores are available in these regions. Water drilling rarely reaches the formation base, usually stopping once an adequate water yield is achieved.

In the Carpentaria Sub-basin, this aquifer is largely restricted to the Staaten and Weipa sub-basins (see Map 5). During deposition of these sandstones, rugged relief in basement terrain to the west in the Western Gulf Sub-basin precluded deposition of sands except within narrow deep gorges which are not readily delineated by the existing seismic imagery. The thickest region of this composite aquifer is an arc of ~200 m thickness along the southern side of the Weipa Sub-basin that thickens northeastward across the Bramwell Arch into the adjoining Papuan Basin. To the south, a thicker composite aquifer, intermittently >100 m, is apparent over the western edge of the Staaten Sub-basin, south into the Boomarra Sub-basin and southeastward onto the Euroka Arch. These thicker areas coincide with sandstones of the Eulo Queen Group present in the underlying Burketown, Canobie and Millungera depressions.



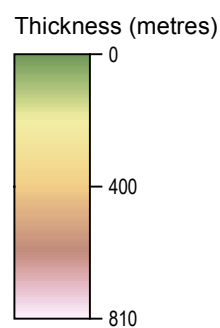
14-8061-31

Cadna-owie – Hooray Aquifer and Equivalents



- Great Artesian Basin
- Cadna-owie – Hooray Aquifer and Equivalents
- Outcrop/subcrop
- Explosion structure - probable bolide impact crater

- Area of Great Artesian Basin where the hydrogeological unit does not exist
- Isopach contour (metres)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Data location
- City/town



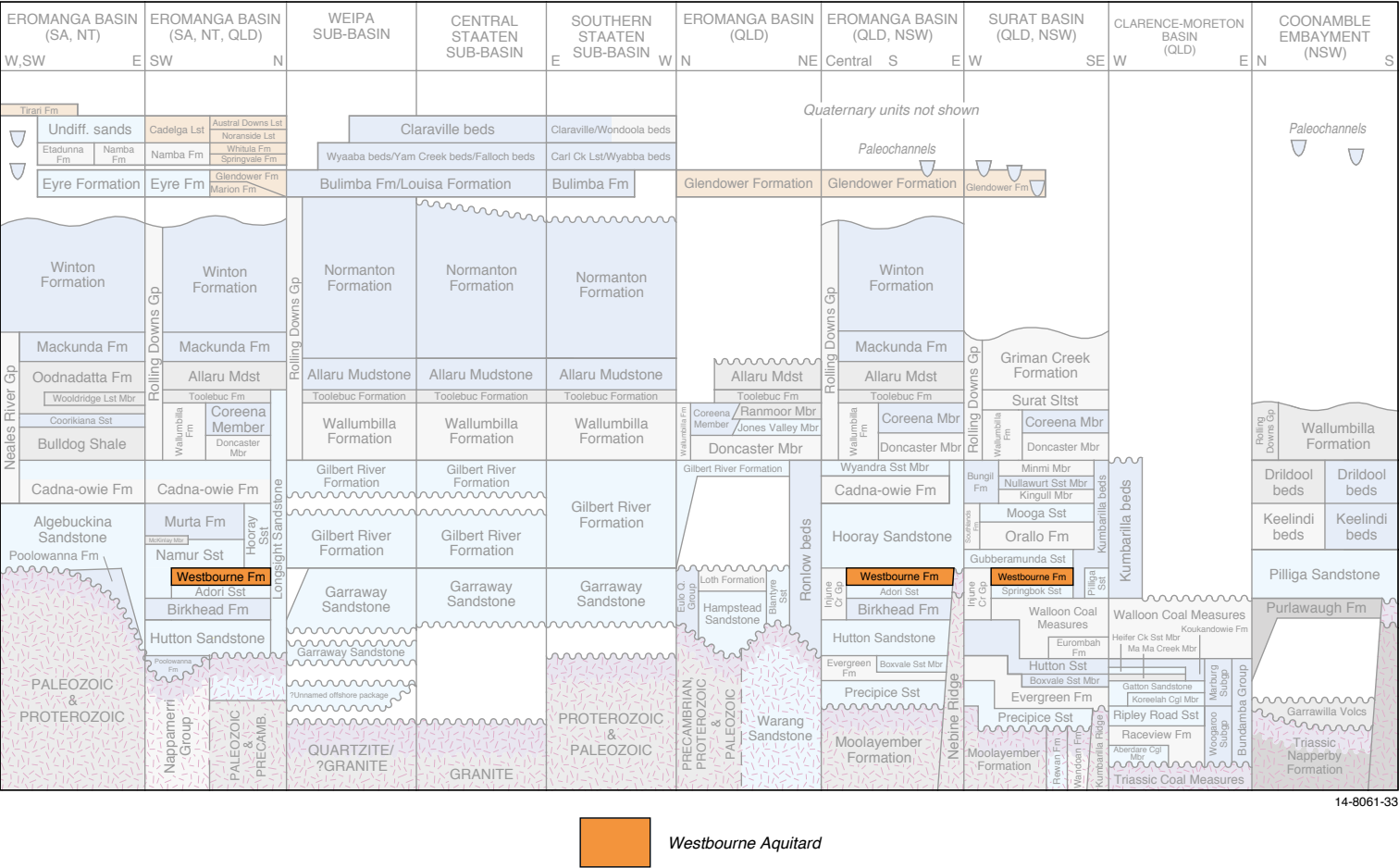
Map 27

Westbourne Aquitard

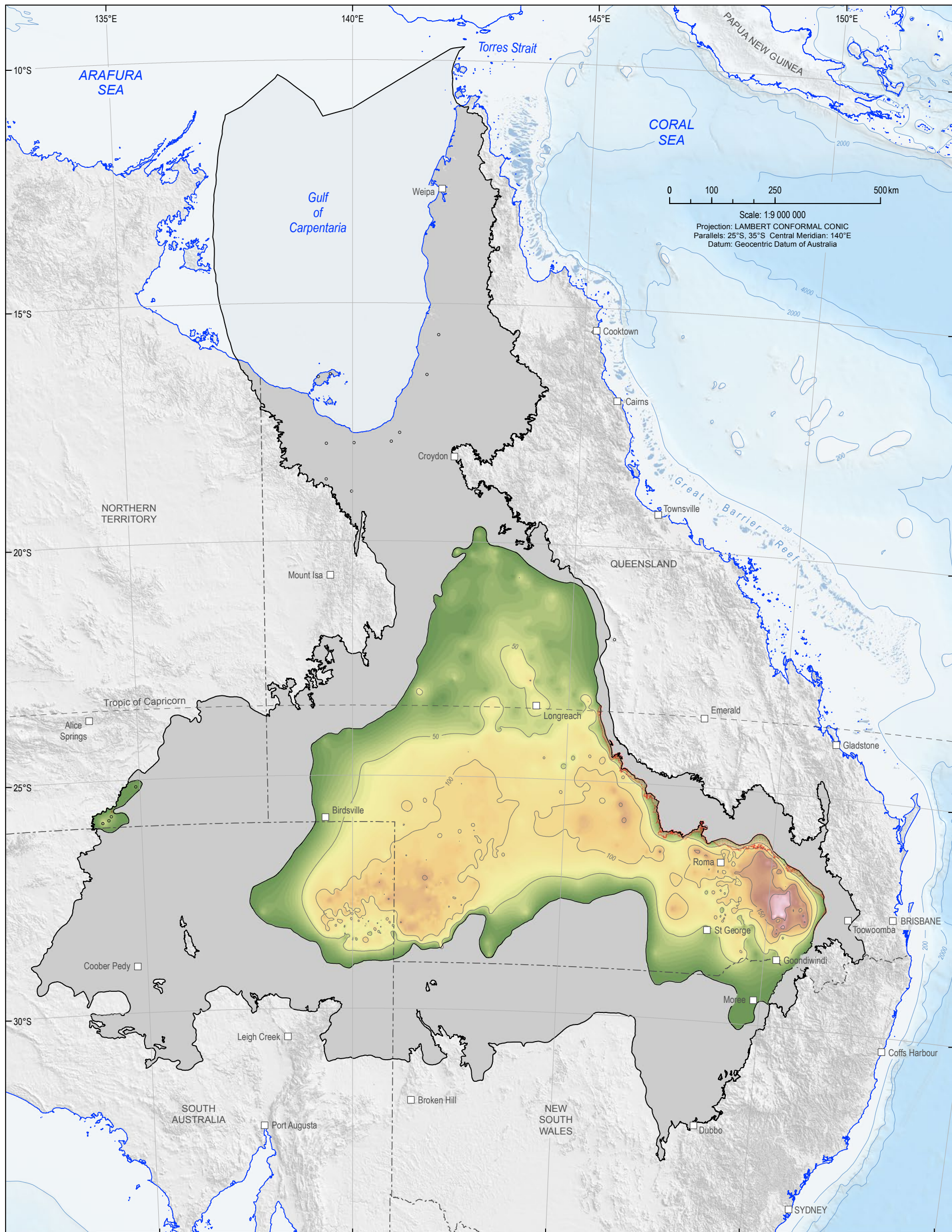
The Westbourne Aquitard comprises the Westbourne Formation which is widespread along the eastern margins and central regions of both the Eromanga and Surat sub-basins.

Thickest in the Mimosa Syncline (>200 m), but thick also across the northern Surat Sub-basin (>100 m), the aquitard thins and wedges out southwestwards, leaving the underlying Adori-Springbok, Hutton and overlying Cadna-owie – Hooray aquifers merged on the Eulo Ridge and in the southwestern part of the Surat Sub-basin.

The thicker part of the aquitard (>100 m) forms a discontinuous arc from the Surat Sub-basin towards the Canaway Fault and southwestwards along the Central Eromanga Depocentre onto the Birdsville Track Ridge (see Maps 4–7). A small isolated remnant of this aquitard at the western margin on Finke 1:250 000 scale map sheet suggests a former basin wide extent, as with the Birkhead-Walloon Aquitard, before subsequent erosion over the Poolowanna Trough region. In the northern Eromanga Sub-basin, the aquitard is generally <50 m thick.



Westbourne Aquitard



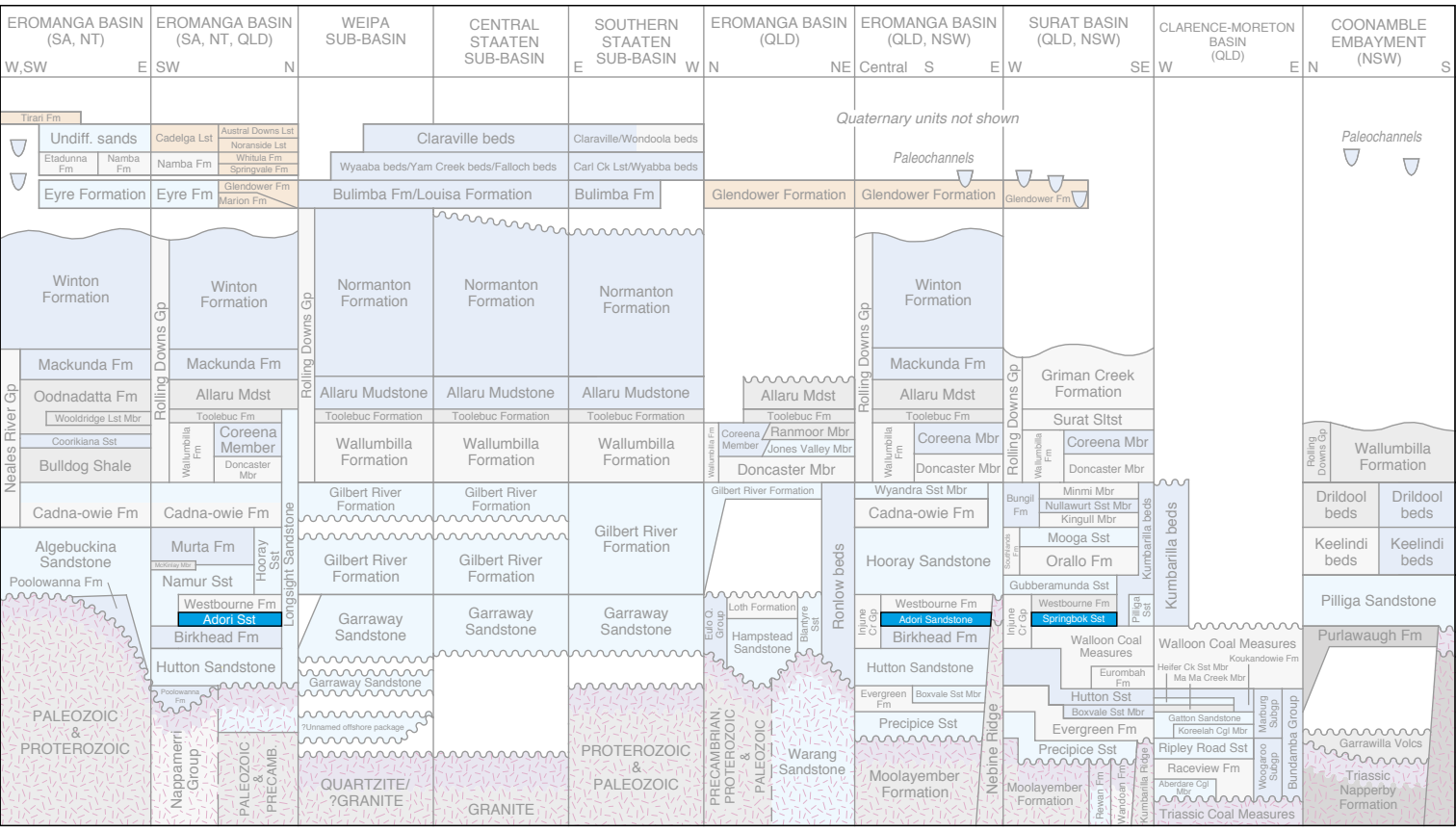
Map 28

Adori-Springbok Aquifer

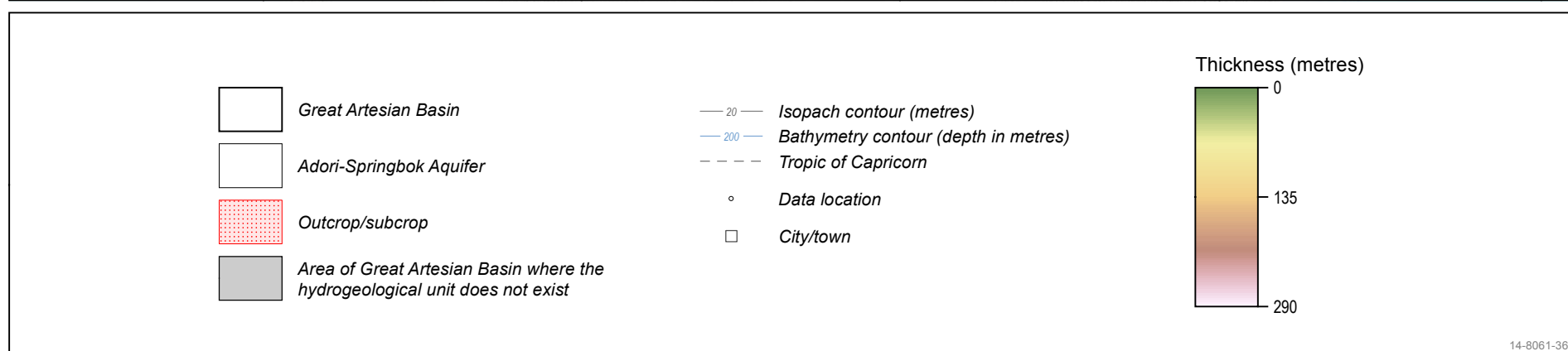
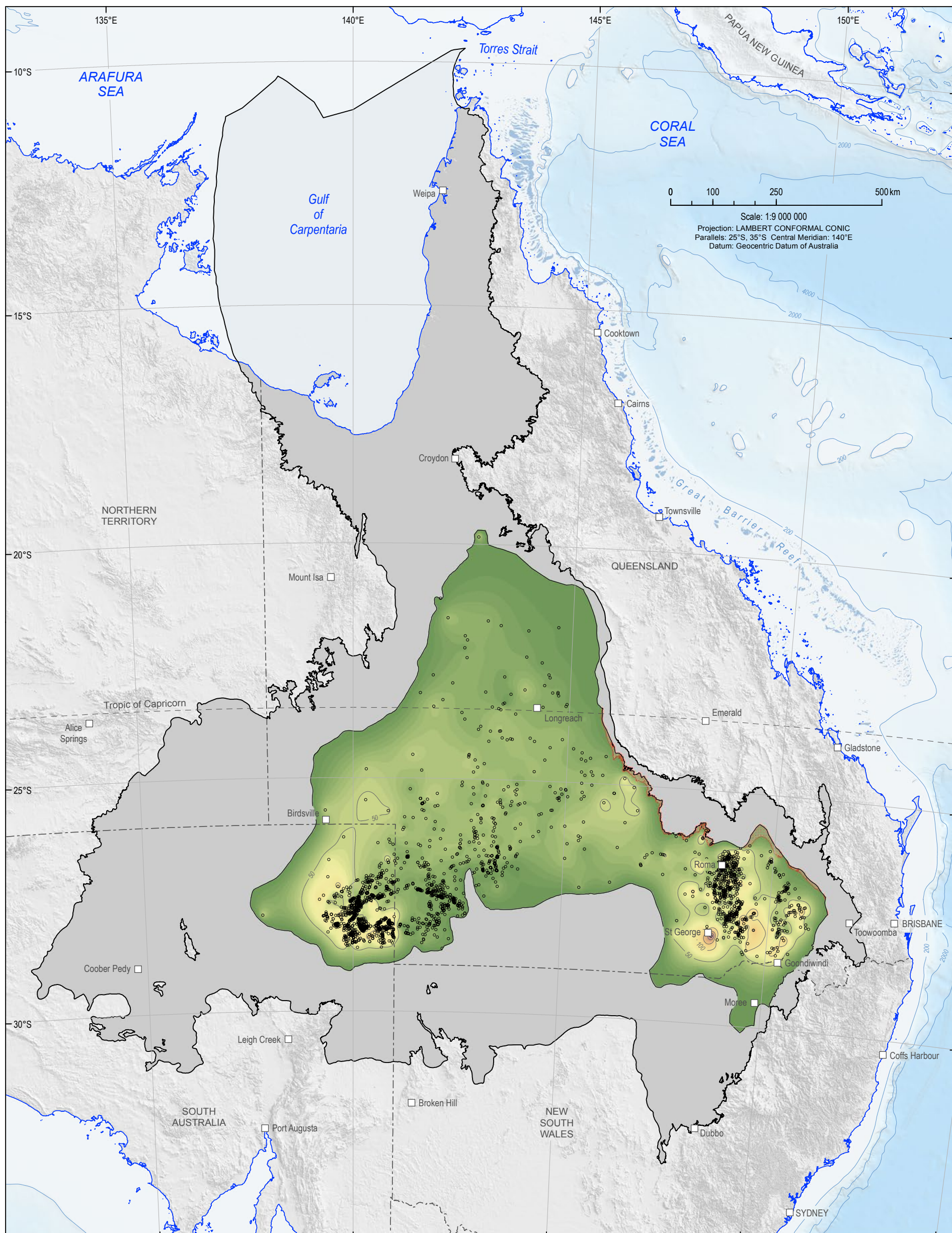
The Adori-Springbok Aquifer, comprising the Adori Sandstone in the Eromanga Sub-basin and the Springbok Sandstone in the Surat Sub-basin, has broad extent along the eastern margins of both sub-basins, comparable to the Birkhead–Walloon Aquitard and almost identical with the Westbourne Aquitard.

The aquifer is mostly uniformly thin, generally <50 m thick, but is thicker (50–100 m) over the southwestern Cooper Basin onto the Birdsville Track Ridge, as well as centrally in the Surat Sub-basin (see Maps 4–7). Present on the Nebine Ridge, it merges southwestwards with the Hutton and Cadna-owie – Hooray aquifers as the intervening Birkhead-Walloon and Westbourne aquitards wedge out along this ridge. The Adori-Springbok

Aquifer has its identifiable western limit in the Eromanga Sub-basin defined by the extent of the overlying Westbourne Aquitard. In the absence of this aquitard, the underlying Adori Sandstone and overlying Hooray Sandstone merge into the Namur Sandstone, a component of the Cadna-owie – Hooray Aquifer.



 Adori-Springbok Aquifer



Map 29

Birkhead-Walloon Aquitard

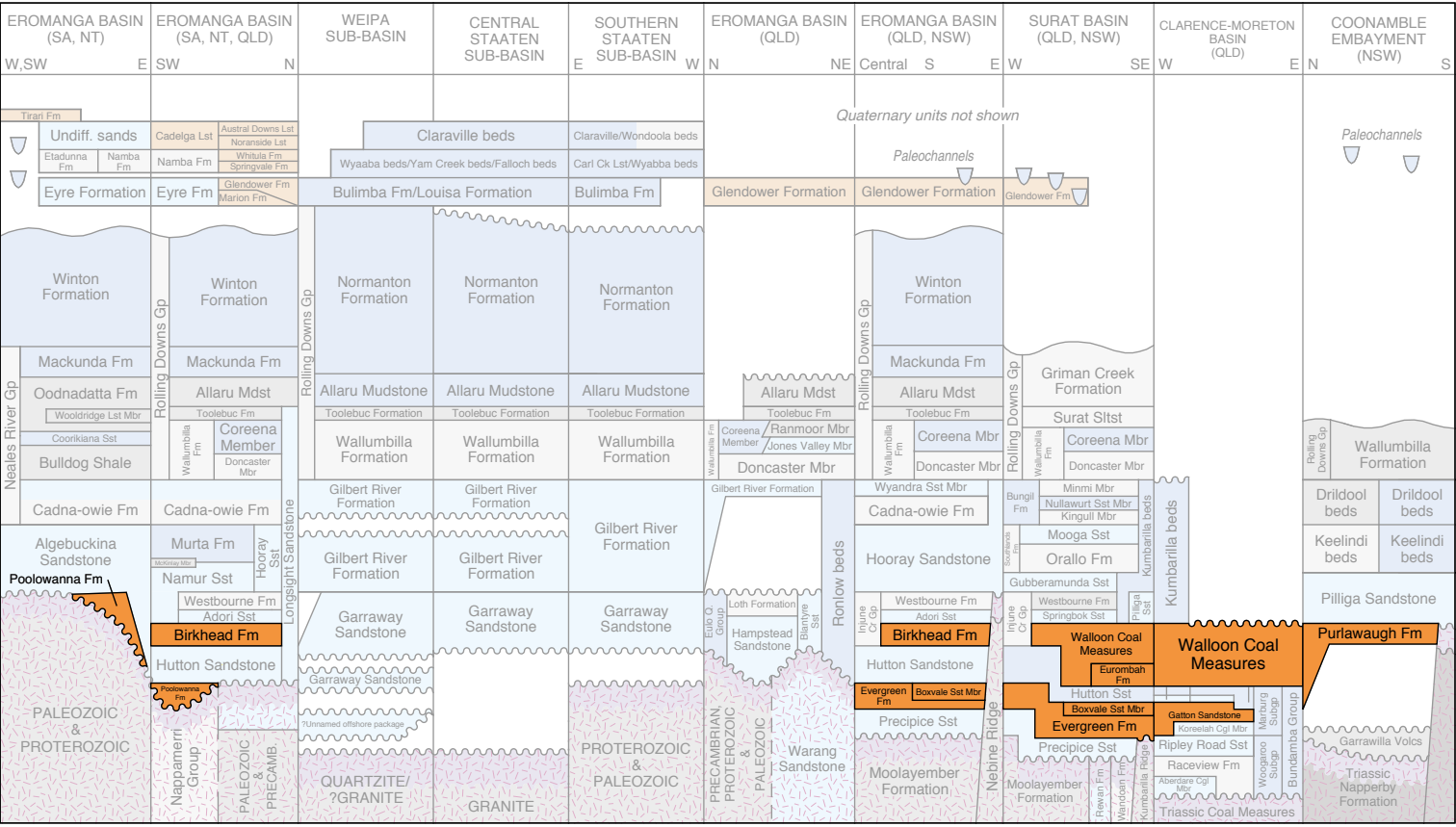
As evident by its name, the Birkhead-Walloon Aquitard comprises the Birkhead Formation in the Eromanga Sub-basin and the Walloon Coal Measures in the Surat and Clarence–Moreton sub-basins. In the Coonamble Embayment of the Surat Sub-basin, the Walloon Coal Measures transition southwards into the Purlawaugh Formation.

Between the Eromanga and Surat sub-basins, this aquitard thins away from the eastern margin and is absent southwestwards beyond the Nebine Ridge, as is the Westbourne Aquitard. Consequently there is direct connection between the Hutton Aquifer, Adori-Springbok and the Cadna-owie – Hooray Aquifers around the Eulo Ridge and the southwestern Surat Sub-basin.

In the Eromanga Sub-basin, the Birkhead Formation has broad extent along the entire northeastern margin and extends southwestwards within the Central Eromanga Depocentre, and over the Birdsville Track Ridge into the Poolowanna Trough (see

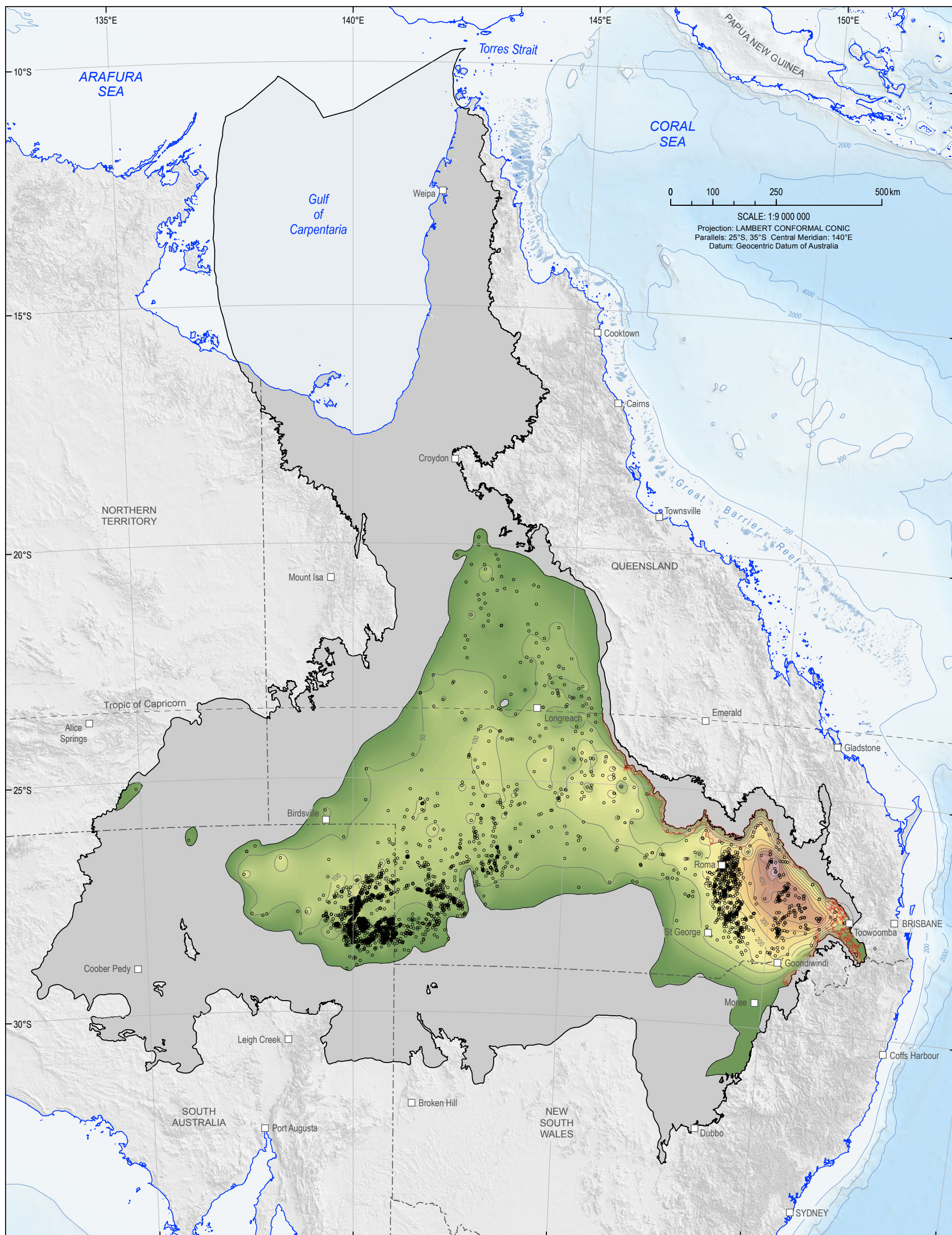
Maps 4–7). Isolated remnants of the Birkhead Formation exist toward the western margin of the basin. Former continuity with the Poolowanna Trough appears to have been lost through erosion.

This aquitard is thickest in the Surat Sub-basin within the northern Mimosa Syncline (up to >500 m) and eastwards towards the Kumbarilla Ridge, and thins steadily southwestwards. In the Eromanga Sub-basin, the thicker regions of >100 m are continuous from the central Nebine Ridge northwestwards towards the Longreach Basement High, then southwestwards along the Central Eromanga Depocentre into the Poolowanna Trough with slightly diminished thickness, rarely over 100 m.



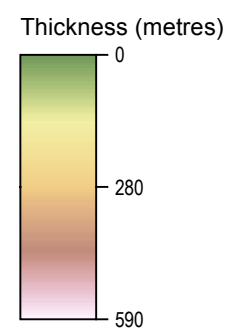
 Birkhead-Walloon Aquitard

14-8061-37



-  Great Artesian Basin
-  Birkhead-Walloon Aquitard
-  Outcrop/subcrop
-  Area of Great Artesian Basin where the hydrogeological unit does not exist

-  20 Isopach contour (metres)
-  200 Bathymetry contour (depth in metres)
-  Tropic of Capricorn
-  Data location
-  City/town



Map 30

Hutton Aquifer and Equivalents

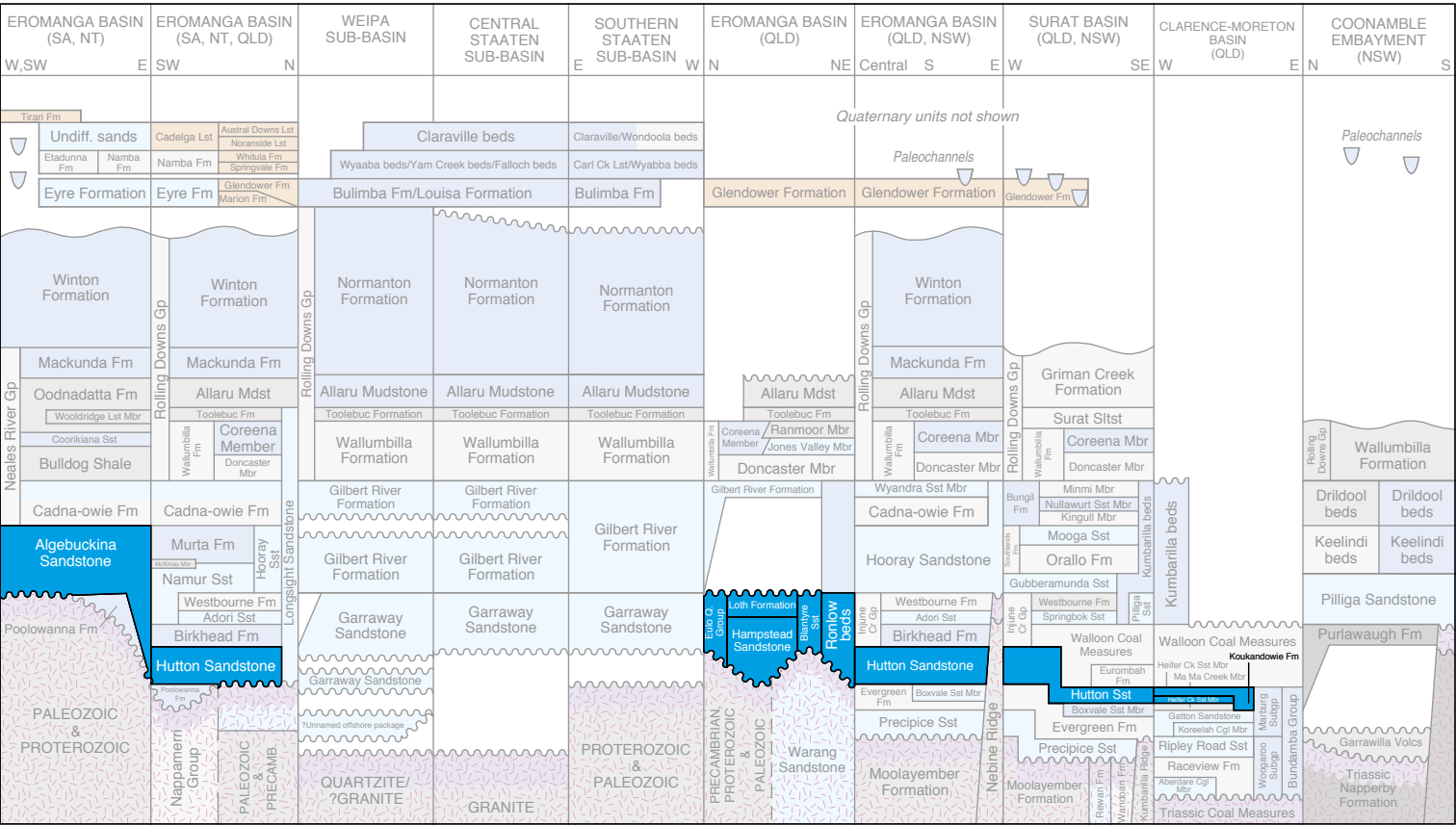
The Hutton Aquifer and Equivalents comprises predominantly the Hutton Sandstone which has broad extent in the Eromanga and Surat sub-basins (see Maps 4–7), and further extension to the southeast across the Kumbarilla Ridge into the Clarence-Moreton Basin where it is represented by the Heifer Creek Member of the Koukandowie Formation.

The axis of its greater thickness (>150 m) forms a slightly sinusoidal east-west tract across the GAB that closely follows the extent of the underlying Poolowanna-Evergreen Aquitard.

To the southwest in the Eromanga Sub-basin, the Hutton Sandstone, which is up to 600 m thick in the Poolowanna Trough, transitions laterally into the Algebuckina Sandstone. The Algebuckina Sandstone extends to the GAB margin in the west, and has common lateral connection with both the Hutton and Cadna-owie – Hooray aquifers. Accordingly, the Algebuckina Sandstone is included in both aquifer packages because of its lateral continuity, but here it is demarcated from the Hutton Sandstone to indicate their separate extents. In the northern Eromanga Sub-basin, the Hutton Sandstone provides modest cover (>50 m and up to 100 m thickness) over the underlying Galilee Basin and thin cover over the Longreach Basement High.

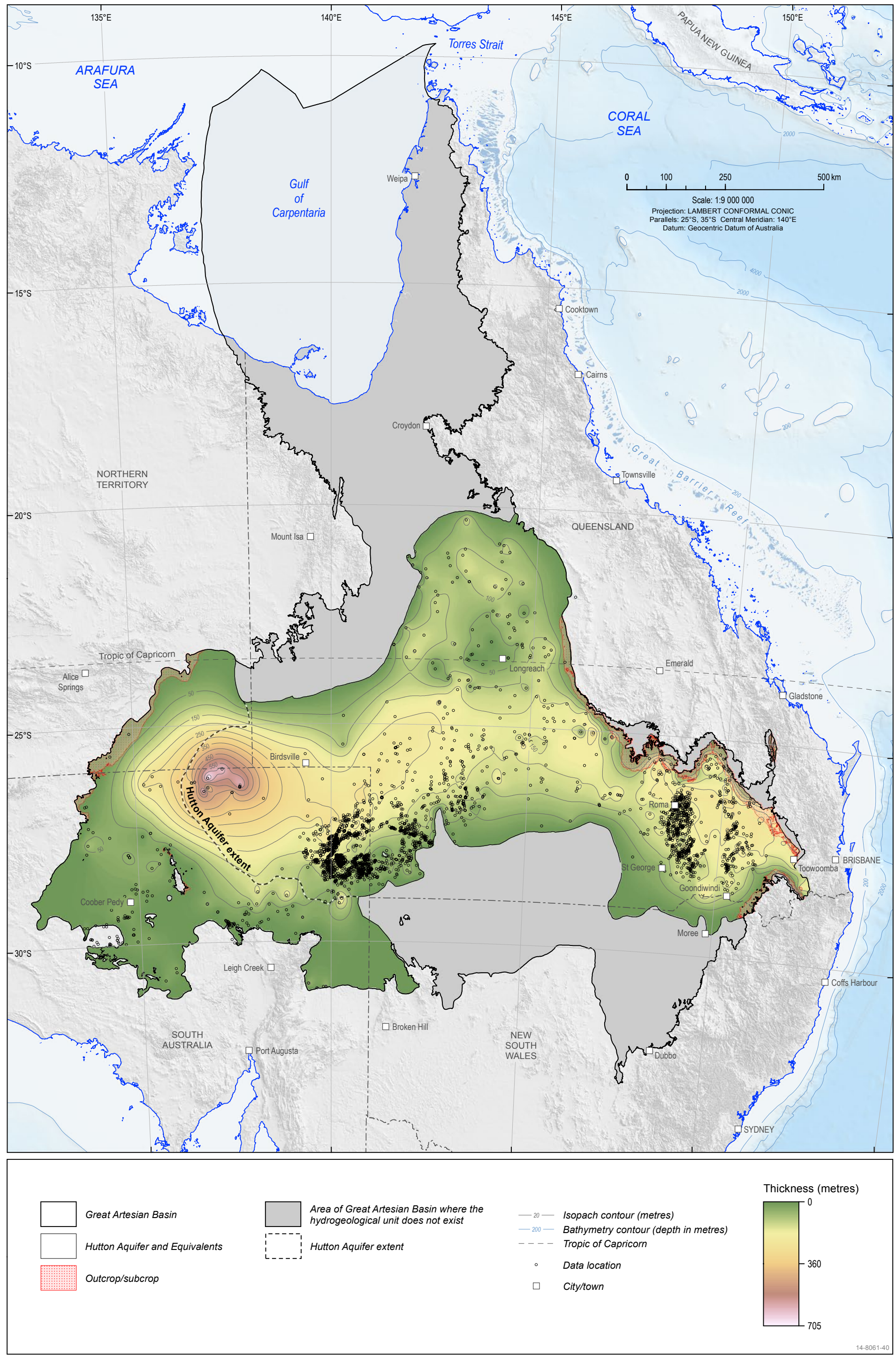
This aquifer thins over the Nebine Ridge but again thickens (>200 m) across the northern Surat Sub-basin. It thins southward in the Mimosa Syncline, as well as southeastwards across the Kumbarilla Arch. Southwestwards from the Nebine Ridge and northern Surat Sub-basin, the aquifer thins and then merges with the Adori-Springbok and Cadna-owie – Hooray aquifers beyond the extent of the intervening Westbourne and Birkhead-Walloon aquitards.

Northwards over the Eureka Arch into the Carpentaria Sub-basin, there is direct hydraulic connection between the Eulo Queen Group equivalents of the Hutton Sandstone and the overlying Cadna-owie – Hooray Aquifer as both Birkhead-Walloon and Westbourne aquitards wedge out and are absent over this basement high. Consequently in the Carpentaria Sub-basin, isolated remnants of the Eulo Queen Group in the southern Staaten Sub-basin and further north, although age equivalents of the Hutton Sandstone, are included in the Cadna-owie – Hooray Aquifer.



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 Hutton Aquifer and Equivalents



Map 31

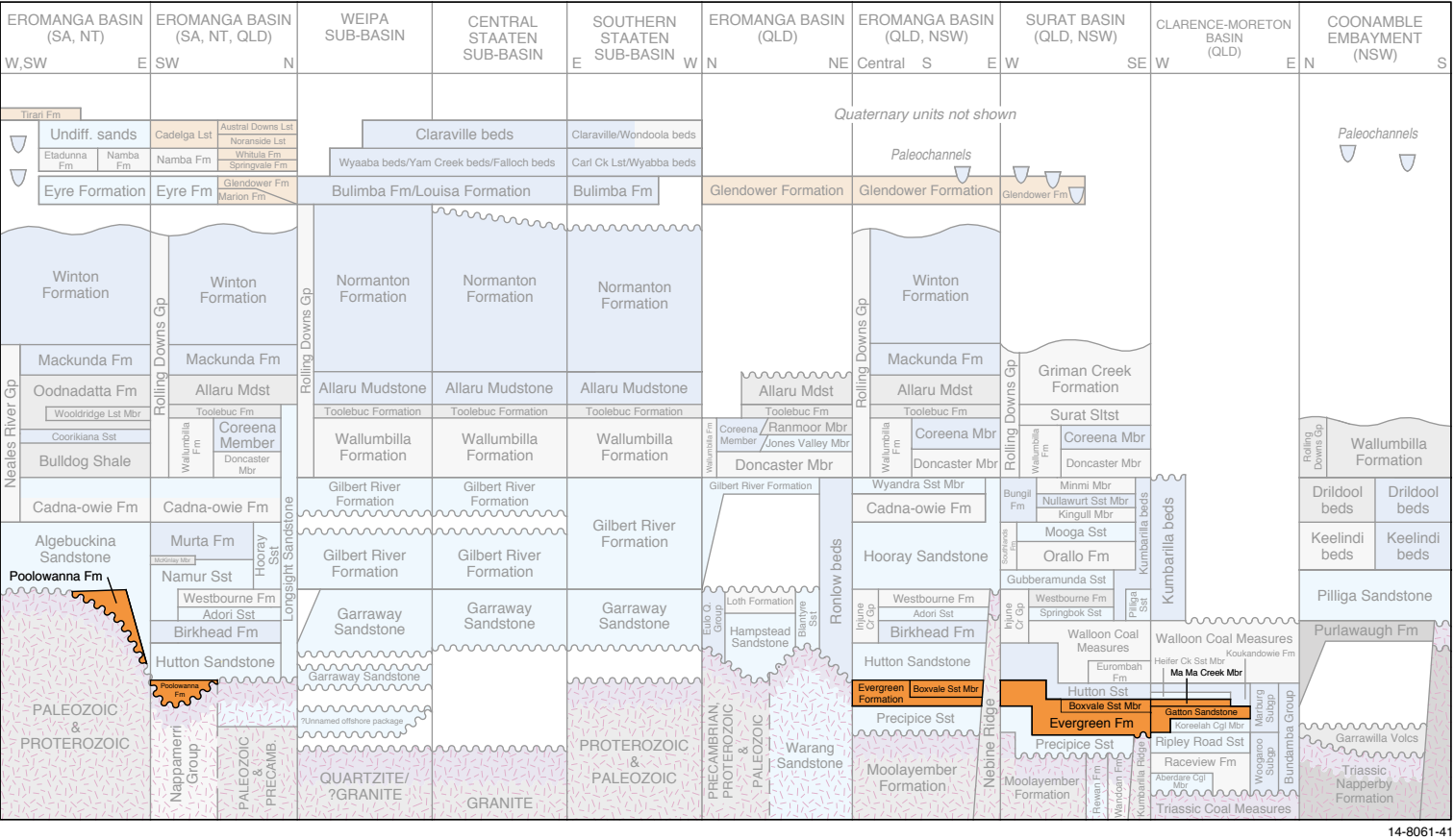
Evergreen-Poolowanna Aquitard and Equivalents

The Evergreen-Poolowanna Aquitard and Equivalents has a slightly sinusoidal east-west linear extent across the GAB.

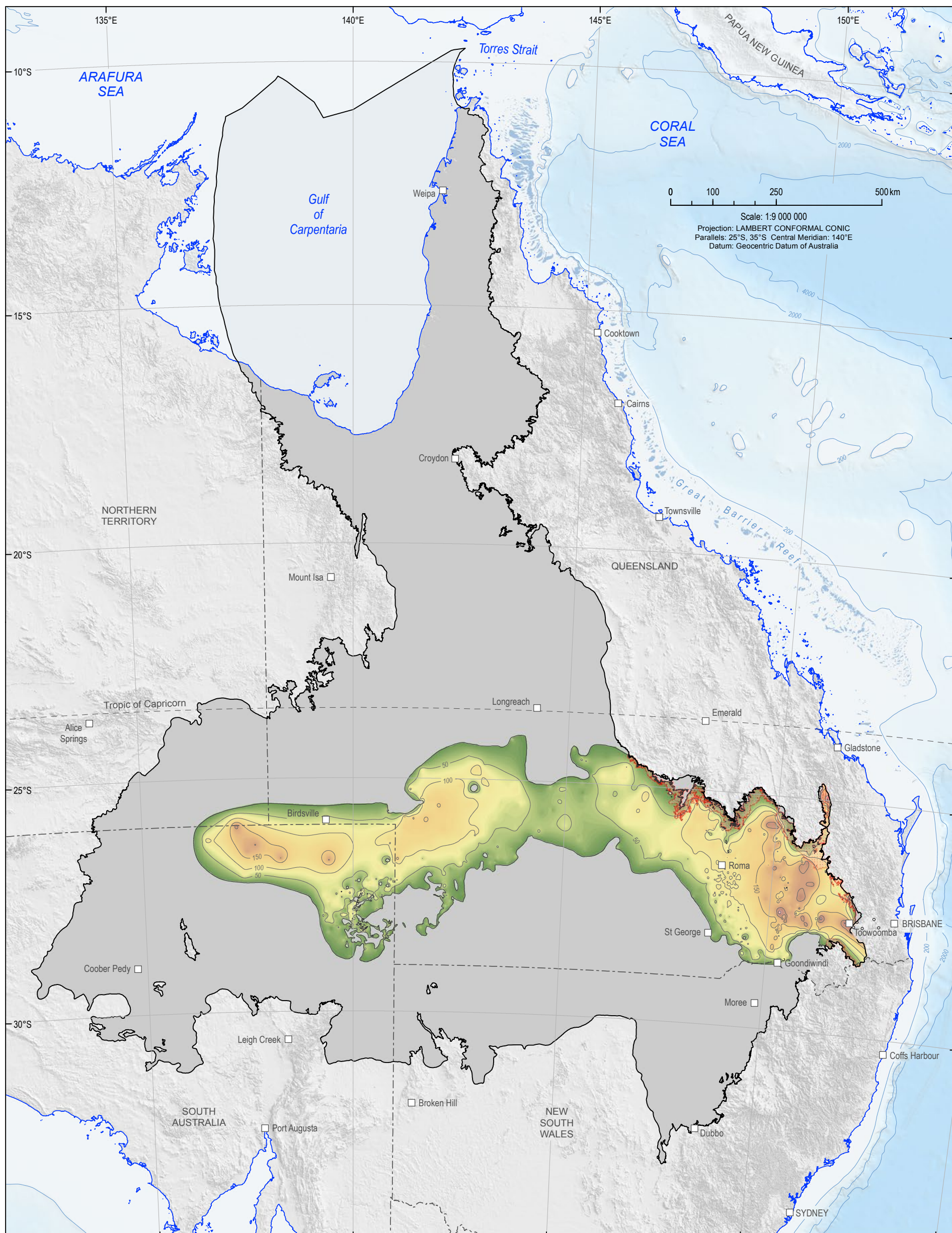
The Poolowanna Formation is the constituent rock unit in the west and extends eastward from the northern part of the Poolowanna Trough, across the deepest region of the Birdsville Track Ridge into the Central Eromanga Depocentre up to the Canaway Ridge (see Maps 4, 6 and 7).

The Evergreen Formation is contiguous across this structure into the eastern Eromanga Sub-basin and northern Surat Sub-basin, and then extends across the Kumberilla Arch into the Clarence-Moreton Basin where the Gatton Sandstone and overlying Ma Ma Creek Member of the Koukandowie Formation are equivalents.

This aquitard is thickest along the axis of the Mimosa Syncline in the Surat Sub-basin, in the north-central Poolowanna Trough, and to a lesser extent along the northwestern side of the Central Eromanga Depocentre (>100 m). South of here, over the Gidgealpa-Merrimelia-Innaminka (GMI) Ridge and above the Wilson Depression, Nappamerri and Tenappera troughs of the Cooper Basin, the aquitard is largely absent through erosion, so that the overlying Hutton Aquifer lies in direct contact with the Cooper Basin.

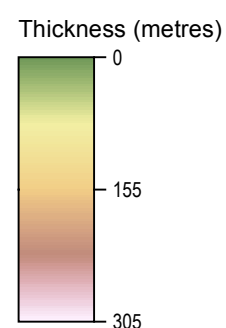


Evergreen-Poolowanna Aquitard and Equivalents



- Great Artesian Basin
- Evergreen-Poolowanna Aquitard and Equivalents
- Outcrop/subcrop
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Isopach contour (metres)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Data location
- City/town



Map 32

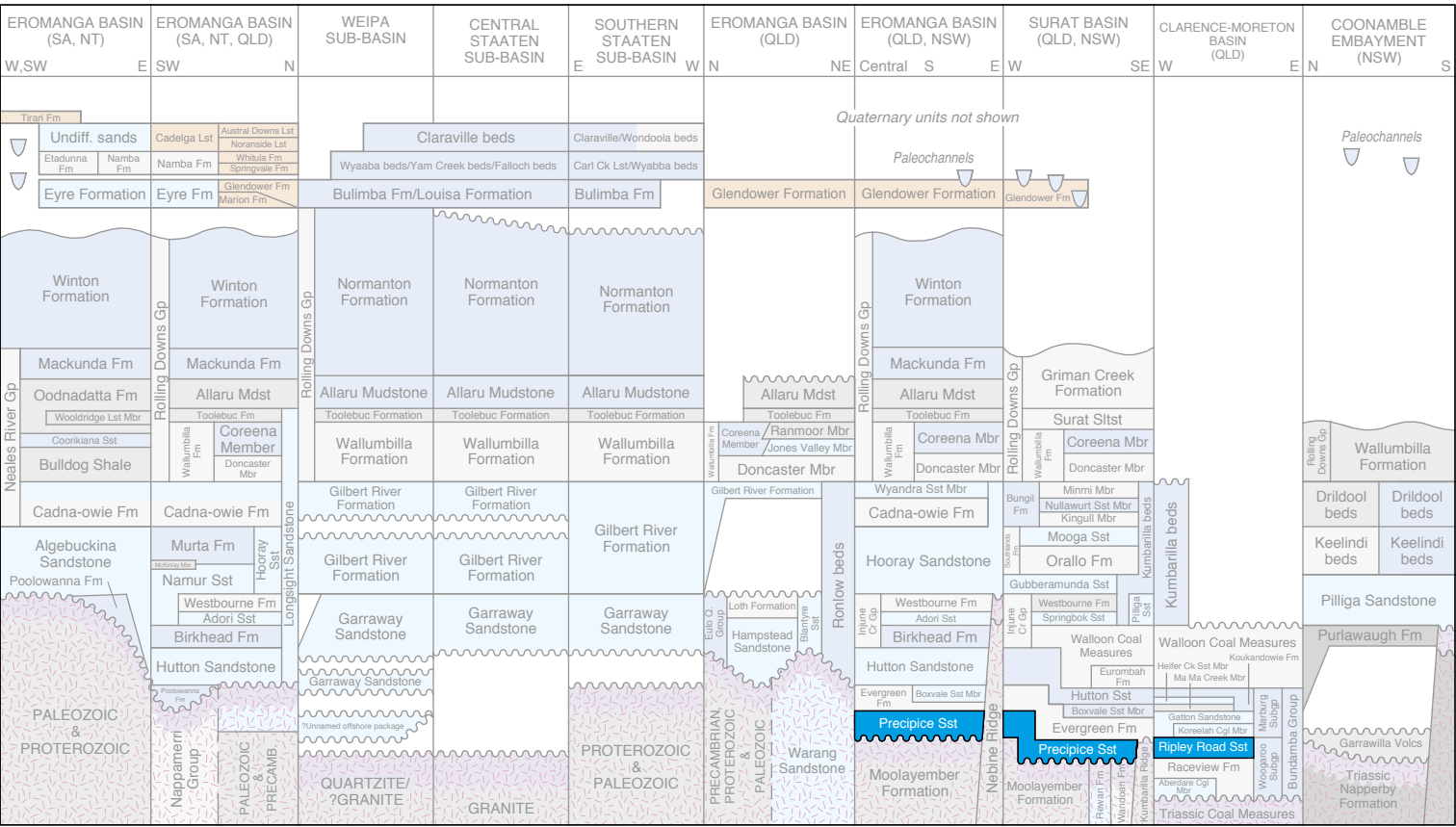
Precipice Aquifer and Equivalents

The Precipice Sandstone is the basal aquifer and is present only in the eastern GAB where it parallels the northeastern side of the Surat Sub-basin, and extends over the Nebine Ridge into the northeastern side of the Eromanga Sub-basin up to the Longreach Basement High where its western limit is against the Canaway Ridge (see Maps 4–7).

From the Surat Sub-basin this aquifer also extends southeastwards around the Kumbarilla Arch into the northeastern side of the Clarence-Moreton Basin where the equivalent aquifer unit is the Ripley Road Sandstone.

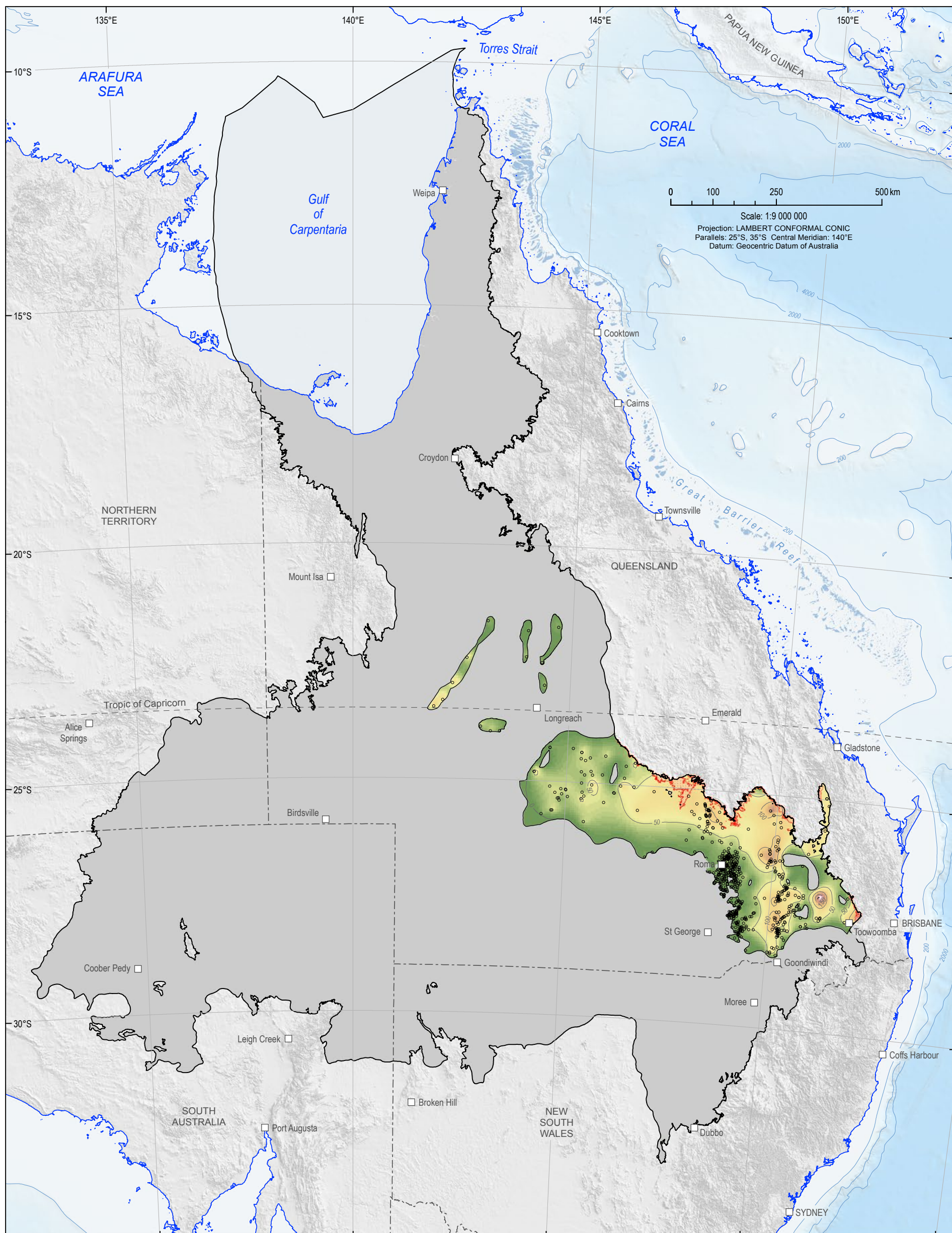
The Precipice Aquifer and Equivalents rarely exceeds 150 m thickness. It is thicker near outcrop in the northern Surat Sub-basin and within the Mimosa Syncline, as well as into the easternmost Eromanga Sub-basin. The aquifer thins and wedges out to the southwest of these regions.

A basal Lower Jurassic sandstone has been identified as an equivalent underlying the Hutton Sandstone around the Longreach Basement High into the Lovelle Depression where these thin outliers, possible erosional remnants, tend to adjoin major faults.



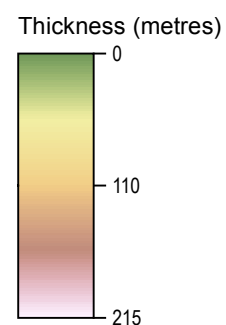
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 Precipice Aquifer and Equivalents



- Great Artesian Basin
- Precipice Aquifer and Equivalents
- Outcrop/subcrop
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Isopach contour (metres)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Data location
- City/town



Hydrochemistry of the regional aquifers of the Great Artesian Basin

Introduction

Groundwater hydrochemical analysis can significantly improve understanding of processes controlling groundwater movement, recharge mechanisms, the age of groundwater, inter-aquifer connectivity and the likely chemical compositions of the aquifer material. A brief summary of some of the key hydrochemical parameters that are used to assist the understanding of groundwater systems are included below.

Total dissolved solids (TDS)

Total dissolved solids (TDS) is a measure of the total amount of salts dissolved in water and very fine particulate matter and is an indicator of salinity. As groundwater flows through an aquifer its chemistry evolves due to a combination of processes and interactions with the aquifer rocks, such as dissolution and precipitation of minerals. This generally results in a gradual increase in TDS down-flow, which can be used to approximate groundwater geochemical evolution paths and flow directions.

pH

pH is a fundamental property that describes groundwater acidity and is a measure of the activity of the hydrogen ion (H^+). The pH largely controls the amount and chemical form of many organic and inorganic substances dissolved in groundwater. Many important properties of water are determined by pH; for example, both the suitability of groundwater for domestic and commercial uses and the occurrence and mobility of minor and trace elements.

Alkalinity

Alkalinity is a measure of the acid neutralizing capacity of water. Examples of alkaline ions include hydroxide, bicarbonate and carbonate ions. When an acid is added to water, these compounds combine with hydrogen ions (H^+), to resist sudden changes in the pH of the water. This buffering action prevents waters from becoming acidic.

Alkalinity in groundwater is dependent on the following: recharge processes and rainfall composition; interactions with the aquifer material (dissolution/precipitation of minerals); and biological processes. As groundwater flows through an aquifer it may dissolve carbonates, giving rise to an increase in the alkalinity and the calcium concentration of the waters. Further reactions, namely exchange of calcium for sodium, potassium or hydrogen ions from clay minerals and biologically mediated generation of methane may drive sustained dissolution of carbonates and further rises in alkalinity.

Calcium

Calcium primarily results from the dissolution of carbonate minerals. Non-carbonate sources include evaporite rocks with gypsum or anhydrite, and reactive silicate minerals such as plagioclase feldspar sourced from granitic and other igneous rocks. Elevated levels of calcium are typically found in volcanic-sourced sediments or evaporated waters with a marine origin.

Calcium is useful for studying chemical weathering. Following the infiltration of rainfall, the evolutionary path of groundwater generally begins from low salinity, low alkalinity, slightly acidic groundwater, to Ca-Mg- HCO_3 -Cl groundwater to Na- HCO_3 -Cl dominant groundwater and finally Na-Cl and Na-Cl- SO_4 type groundwater. The relatively faster weathering rate of carbonate rocks compared to silicate rocks exercises an important control on water chemistry. The Ca+Mg/ HCO_3 ratio can be used to indicate a source of carbonate.

Dissolution of carbonate minerals lead to elevated alkalinity levels and Ca^{2+} and Mg^{2+} ion concentrations. As the groundwater progresses basinwards, ion exchange occurs and Na present in clays is exchanged for Ca and Mg.

Magnesium

Magnesium in solution originates from water-rock interactions with igneous or metamorphic minerals (amphiboles, pyroxenes, olivine and biotite) or from the dissolution of dolomite or magnesium-enriched calcite in sedimentary environments. Elevated levels of magnesium are found in volcanic-sourced sediments or waters with a marine origin.

The ratio Mg/Ca is a useful tracer of water origin as distinctly high values are found in seawater (Mg:Ca is 5.43:1) whereas a typical ratio in groundwater is 1:1 due to equilibrium with dolomite and calcite. Decreases in magnesium concentration are largely due to ion exchange in clays.

Sodium

Sodium in groundwater is derived from atmospheric deposition (from sea salt), silicate weathering, halite dissolution, seawater or brine intrusion, or cation exchange for Ca^{2+} or Mg^{2+} with Na^+ on clay minerals. Sodium is generally the dominant cation in groundwater. It is also an excellent tracer of groundwater processes taking place along flow lines in aquifers. Sodium in irrigation water is harmful to crops and can adversely affect soil structure. The sodium absorption ratio (SAR) is often used as an indicator of water quality for irrigation.

Sodium concentration is often used with reference to chloride in groundwater samples to differentiate sources of salinity. Seawater has a molar Na/Cl ratio of 0.85:1 and, if Na/Cl values lie above the seawater-dilution line, this indicates that sodium is derived from water-rock interaction such as silicate weathering or cation exchange. Values above the seawater-dilution line can often be found at lower sodium concentrations whereas high sodium concentrations are often strongly correlated with a marine signature.

Chloride

Chloride (Cl) is considered to be a conservative ion. Once it is introduced into the groundwater it remains dissolved because there are no water-rock interactions that can remove chloride from the groundwater, although halite dissolution may increase the concentration of Cl ions. In contrast, the other major ions can be adsorbed, desorbed, precipitated or dissolved in solution by various hydrochemical and/or biochemical processes. Decreases in chloride concentration in aquifers typically indicate mixing whereas increases in chloride concentration, in confined aquifers, typically results from diffusion of chloride ions from marine-derived mudstones or sediments or ingress of saline water.

Sulphate

The concentration of sulphate and sulphide in groundwater or surface water is primarily controlled by mineral dissolution/precipitation and redox reactions between sulphate and sulphide minerals. In shallow groundwater, sulphur mainly occurs as sulphate (SO_4^{2-}) but can be reduced to sulphide (HS^-) under strongly reducing conditions. Due to the very low solubility of metal sulphides, these minerals precipitate out of solution and there is a net removal of sulphur from the groundwater. Highly reducing conditions typically occur at depth in the presence of organics such as coal or oil but can also occur in organic rich lake and river sediments.

There are a number of processes that can lead to an increase in sulphate concentration. These include anhydrite or gypsum dissolution; oxidation of sulphide-bearing materials such as pyrite; and mixing with marine waters.

Potassium

The primary source of potassium in groundwater is from weathering of silicate minerals such as feldspars and micas. Initial concentrations of potassium in the recharge zones closely reflect the mineralogy of the outcropping rock. As water moves down gradient, the original signature of the groundwater undergoes transformation due to secondary reactions (dissolution-precipitation or ion exchange) and mixing.

Oxygen and hydrogen isotopes

The stable isotopes of water (H₂O) commonly used for groundwater studies are oxygen-18 (¹⁸O) and deuterium (²H). Using the isotopes of water itself allows the sources and processes of groundwater to be traced through isotopic fractionation. The oxygen-18 and deuterium composition of precipitation throughout the world is correlated and distributed along the global meteoric water line (GMWL). Due to the strong connection between oxygen and hydrogen, the GMWL is linearly related for precipitation that has not undergone evaporation. The GMWL provides a useful reference against which regional and/or local waters can be compared.

Several factors can cause water to plot above or below the GMWL including evaporation, water-rock interactions and geothermal mixing. Evaporation tends to produce $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values below the GMWL that sit along a line that intersects the GMWL at the location of the non-evaporated waters. This type of water is commonly found in the GAB and can be useful for understanding groundwater recharge processes. Groundwater with sufficient separation of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values can also be used to trace the water movement between aquifers.

Carbon isotopes

Carbon-13 (¹³C) is an excellent tracer of carbonate evolution in groundwater because of the large variations in carbon reservoirs. The $\delta^{13}\text{C}$ values of dissolved inorganic carbon (DIC) in groundwater are generally in the range of -5 to -25 ‰. The dissolved inorganic carbon of groundwater in contact with soil in recharge zones will have a $\delta^{13}\text{C}$ of approximately -20 ‰, although this can vary depending on the nature of the plants and soil. Alternatively, carbonate minerals typically have a $\delta^{13}\text{C}$ typically close to 0 ‰, thus as groundwater increasingly reacts with carbonate minerals down flowpaths it acquires a heavier $\delta^{13}\text{C}$ signature.

Highly enriched $\delta^{13}\text{C}$ can also be found where bacterial reduction of carbonate to methane occurs. This process preferentially uses ¹²CO₂ over ¹³CO₂ resulting in an enrichment of ¹³CO₂ in the dissolved inorganic carbon. The process only occurs in the absence of sulphate and $\delta^{13}\text{C}$ values as high as +20 ‰ can be found in coal seam gas fields. Where the process occurs at depth, in the absence of coal and other organics, a $\delta^{13}\text{C}$ for the DIC of up to +2 ‰ typically results.

Chlorine isotopes

The high solubility, conservative behaviour in groundwater and the natural occurrence of chlorine-36 (³⁶Cl) in the environment, make this radioisotope useful for studying salt and water transport within an aquifer system. Groundwater dating using ³⁶Cl is based on (1) decay of cosmogenic ³⁶Cl over long periods in the subsurface, or (2) ³⁶Cl produced radiogenically in the subsurface. Chlorine-36 has a half-life of 301 000 years.

Groundwater in recharge areas derives cosmogenic ³⁶Cl from atmospheric production or surface production. Chlorine-36 isotope is produced naturally in the atmosphere by the bombardment of argon gas by cosmic radiation. Subsequently, ³⁶Cl will enter the hydrological cycle through rainfall or as dry fallout. In the subsurface, the decay of (mainly) U, Th and K irradiates light elements and produces an *in situ* neutron flux, which acts upon ³⁵Cl in the subsurface to produce a low background flux of ³⁶Cl which will vary between aquifers and geological settings. A background ³⁶Cl/Cl value of approximately 10 x 10⁻¹⁵ is the typical minimum value encountered in the GAB due to subsurface contributions.

There is a general trend of decreasing ³⁶Cl/Cl ratio in the GAB from recharge areas to discharge areas down regional flowpaths. In combination with chloride measurements and assumptions about mixing, flowrates can be determined using the half-life of chlorine-36.

Spatial mapping of groundwater chemistry

To allow interpretation and visualisation of the spatial distribution of various chemical and physical parameters of groundwater, spatial interpolation of point data representing concentration or magnitude is routinely used. The result is a continuous surface or grid with cells that represent a concentration or magnitude of the parameter. Recharge areas shown on the following maps correspond to the outcrop areas for the respective units, as defined in the preceding section—*Hydrostratigraphic units—outcrop, extent and thickness*.

The following maps depict groundwater chemistry concentration grids produced using a kriging surface interpolation method implemented via ArcGIS Geostatistical Analyst tool. Prediction standard error maps are included for each map to indicate prediction confidence levels. These maps illustrate the spatial standard error for a parameter and should be compared to the corresponding spatial maps. Where there is greater density of sample points, the prediction error is generally low. Interpolating over large distances, however, can lead to large prediction errors.

Map 33

Wallumbilla-Rolling Downs Group

Aquifers—Alkalinity

The Rolling Downs Group (excluding the Winton and Mackunda formations) and Wallumbilla Formation are considered to act regionally as leaky aquitards. However, these units contain partial aquifers that have been sampled within the Coreena and Doncaster members of the Wallumbilla Formation and Surat Siltstone.

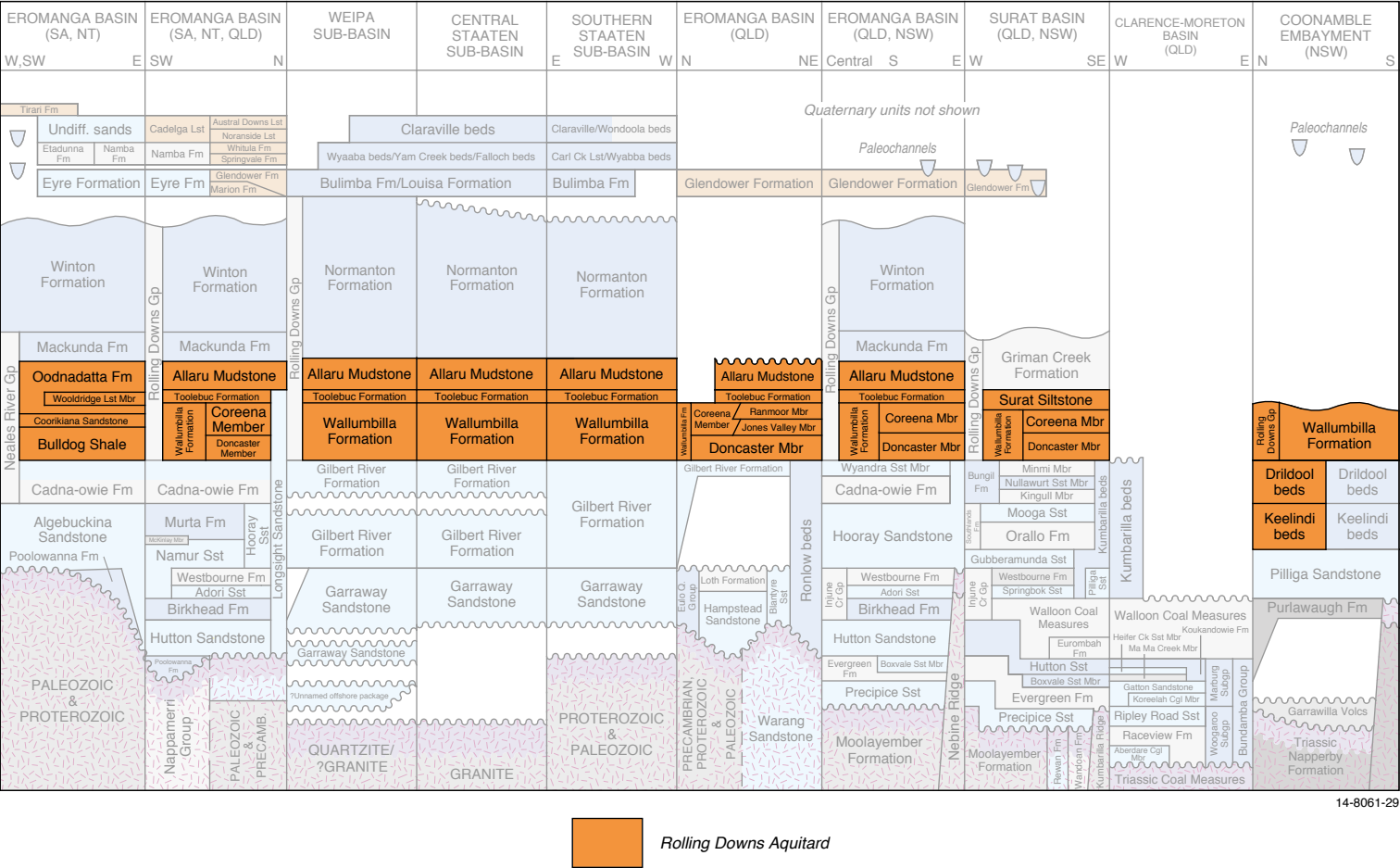
Low to moderate alkalinity values dominate the Wallumbilla-Rolling Downs Group Aquifers.

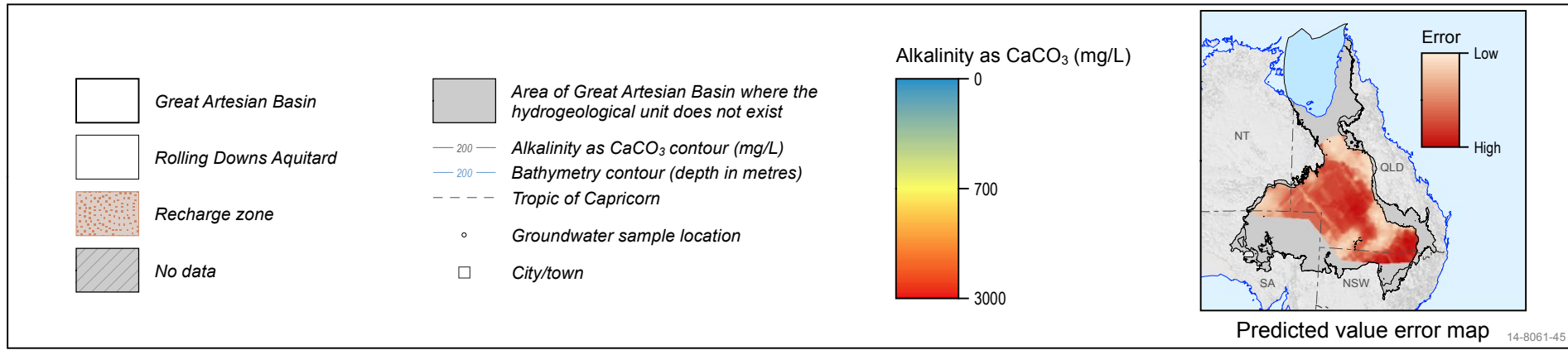
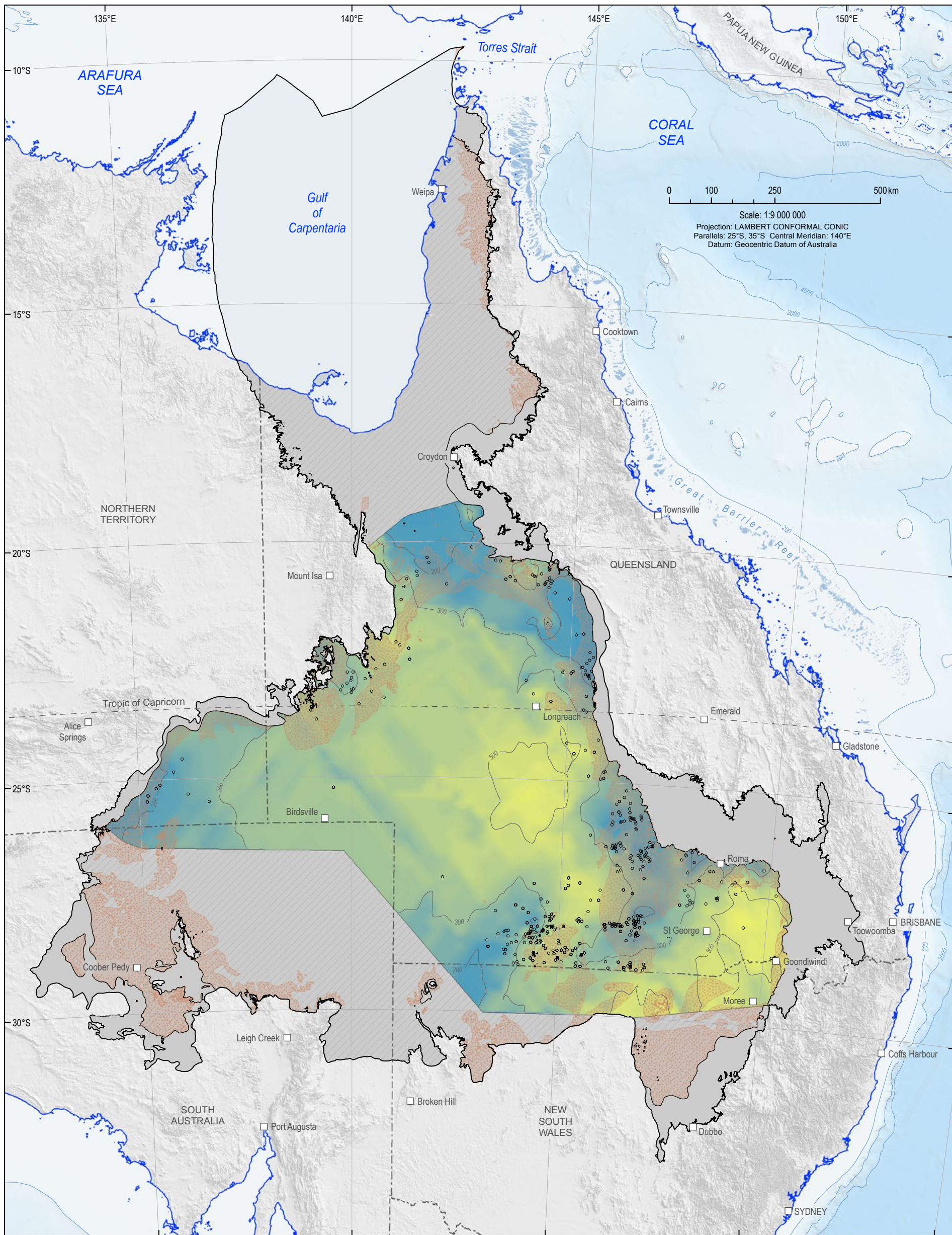
Areas of low alkalinity (<300 mg/L) are found in the recharge zones in the northeast of the Eromanga Basin, across the Eureka Arch, the Eulo-Nebine Ridge area, northern Surat Sub-basin, and the western margin of the Eromanga Sub-basin. Alkalinity values rarely exceed 500 mg/L across the basin.

Very low alkalinity values are observed west of the Eulo Ridge (see Map 4) and this corresponds with high calcium and sulphate concentrations and moderately high salinity. Sodium, calcium, sulphate and alkalinity plot above the seawater dilution line in this region, suggesting additional inputs from rock-water

interactions. Parts of the groundwater in this region have Ca:Mg ratios greater than 40:1, suggesting that the Ca is not due to a marine signature or in equilibrium with calcite or dolomite. The Coreena and Doncaster members in this region contain minor components of muscovite, pyrite and calcite and the dissolution and oxidation of these minerals in low alkalinity environments could account for the elevated levels of Ca ions.

A striking feature of Wallumbilla-Rolling Downs Group alkalinity is the absence of high alkalinity, especially near the Central Eromanga Depocentre. While data coverage for this region is poor, the generally shallow and non-contiguous nature of the aquifers suggests that there is an absence of the large northeast-southwest flow paths found in the other GAB aquifers.





Map 34

Wallumbilla-Rolling Downs Group

Aquifers—Total Dissolved Solids

The Wallumbilla-Rolling Down Group aquifers are shallow and generally brackish. It is an important sub-artesian stock water resource where access to underlying deep artesian aquifers is not economically viable.

The salinity as total dissolved solids (TDS) shows broadly consistent brackish character across the GAB except in isolated parts of the recharge zones. TDS values range from less than 300 mg/L to more than 2500 mg/L.

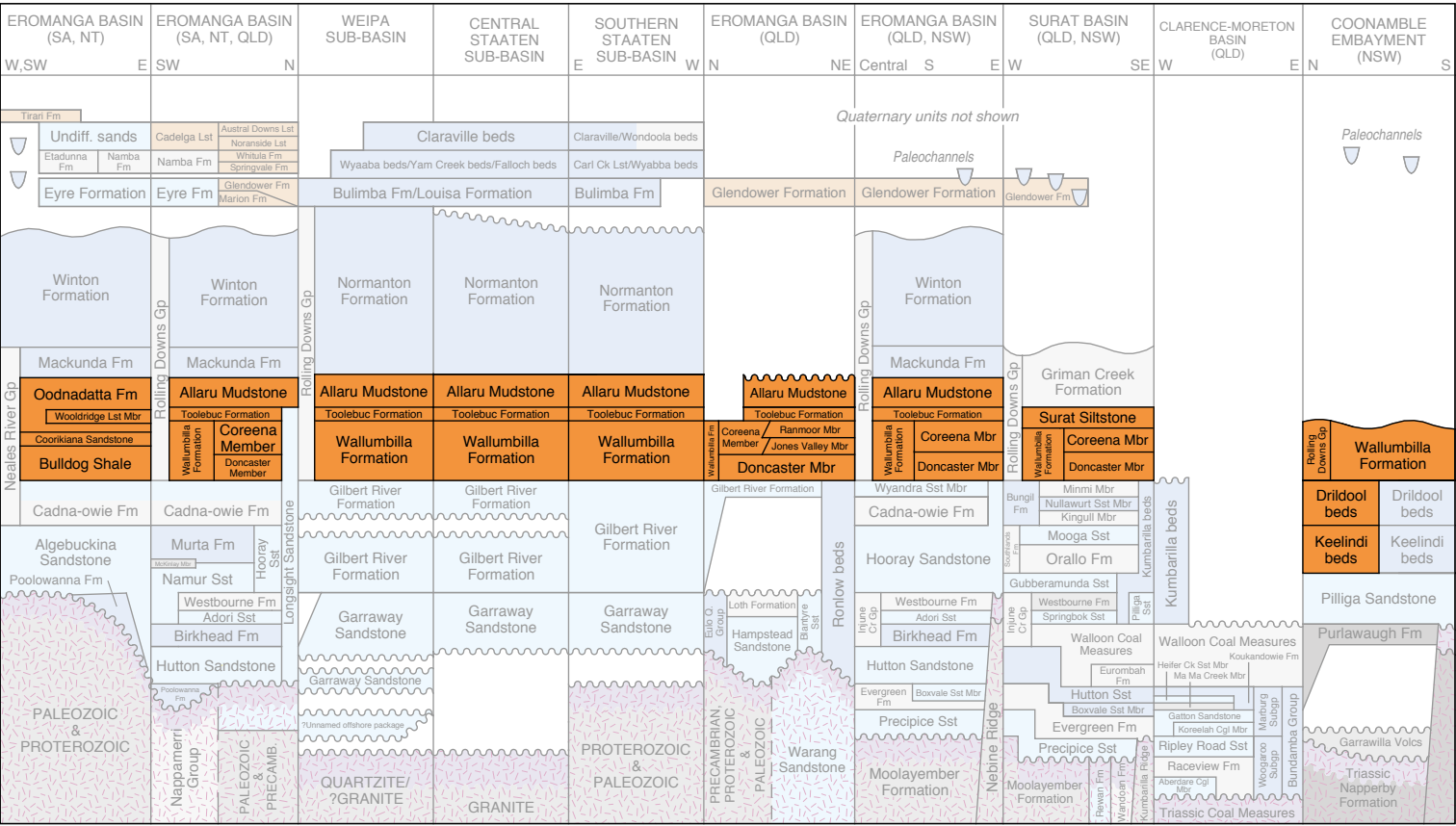
The Wallumbilla-Rolling Downs Group aquifer comprises the Toolebuc Formation, Surat Siltstone, and the Coreena and Doncaster members of the Wallumbilla Formation. These formations were deposited in a shallow muddy sea connected intermittently with the open ocean. The aquifers are characterised by fine-grained sediments, with the more productive members typically comprising interbedded siltstone, fine sandstone or limestone, and mudstone deposits.

Low salinity is isolated to the north and northeastern recharge zones of the Eromanga Sub-basin and a small pocket of low salinity near the Eulo Ridge (see Maps 4 and 7). Here the aquifer thins out across the ridge and there is mixing with groundwater from deeper formations.

Elevated salinity values are observed throughout the Surat Sub-basin and in the central and western Eromanga Sub-basin. The salinity is generally Na–Cl dominated and the alkalinity values across the aquifer are all low to moderate.

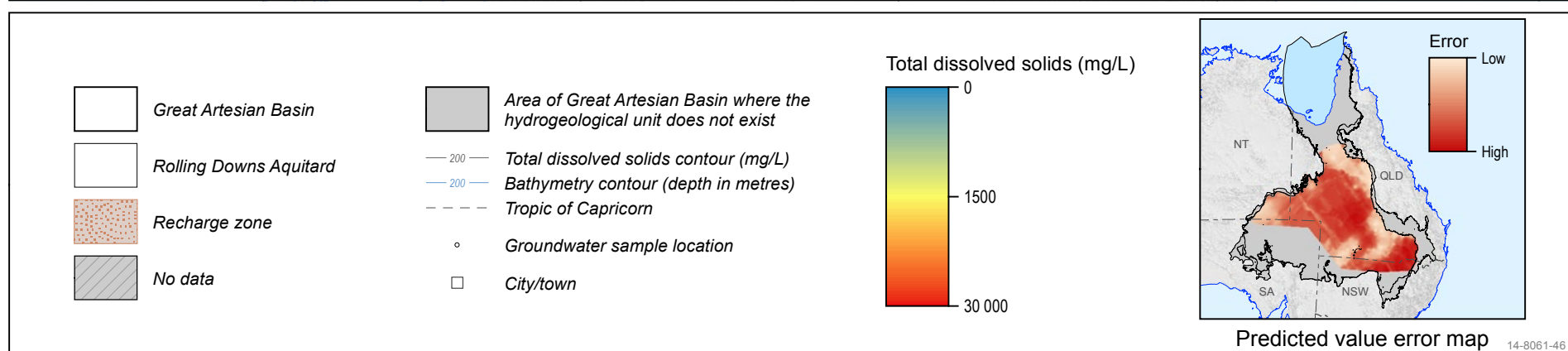
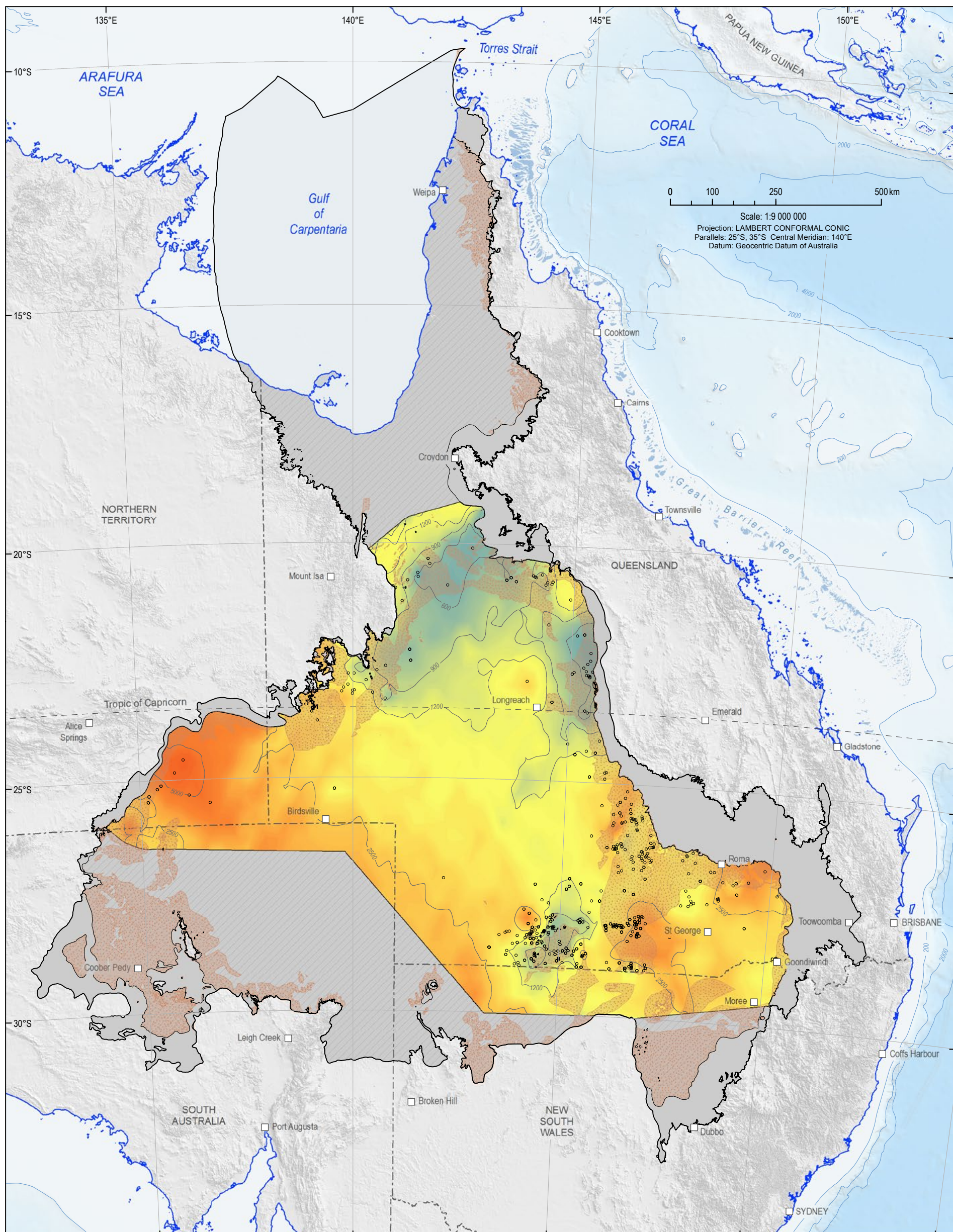
High salinity is observed on the western GAB margin in the vicinity of the Finke River recharge zone, above the co-located low salinity feature in the deeper Cadna-owie – Hooray Aquifer (see Map 36). High levels of Na, Cl, SO₄, Ca and Mg occur in the region but only calcium, sulphate and alkalinity plot above the seawater dilution line, suggesting additional inputs from rock-water interactions. The Wallumbilla aquifer (Coorikiana Sandstone) contains minor components of gypsum, pyrite and calcite in this region and the dissolution and oxidation of these minerals in low alkalinity environments would contribute to elevated levels of these ions. A similar, but less pronounced, sulphate contribution to the salinity in the northern recharge zones of the Eulo-Nebine Ridge, is consistent with low rates of recharge and an evaporated signature.

Although one of the shallowest and more accessible aquifers in the GAB, there is little data on water quality, particularly in the southwestern Eromanga, along the southern margins and into the Carpentaria Sub-basin. Apart from along the Eulo-Nebine Ridge, the generally brackish nature of the aquifer and poor yields results in a relatively sparse distribution of groundwater bores.



 Rolling Downs Aquifer

14-8061-29



Map 35

Cadna-owie – Hooray Aquifer—Alkalinity

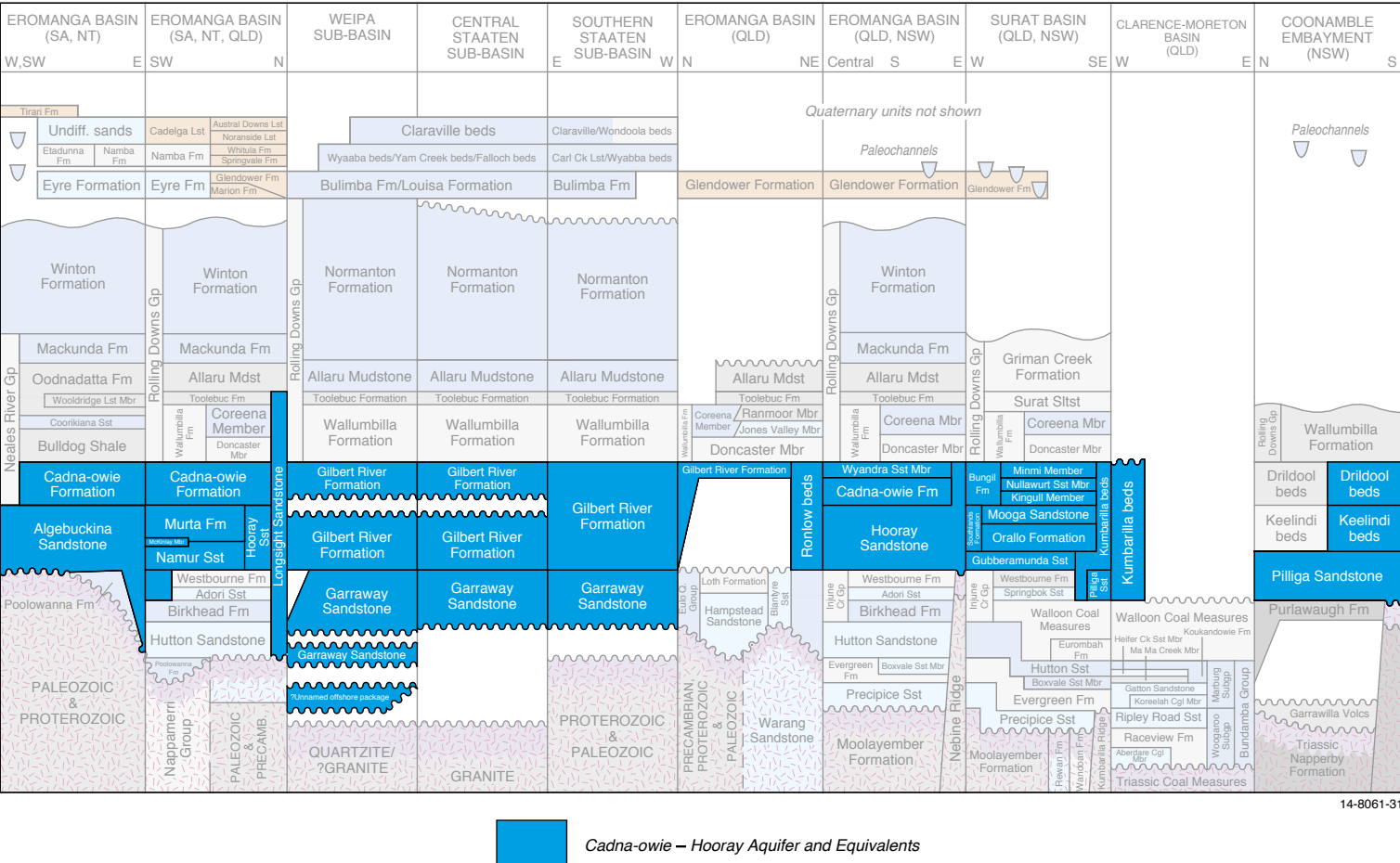
Large regions of the Cadna-owie – Hooray Aquifer display low to moderate alkalinity.

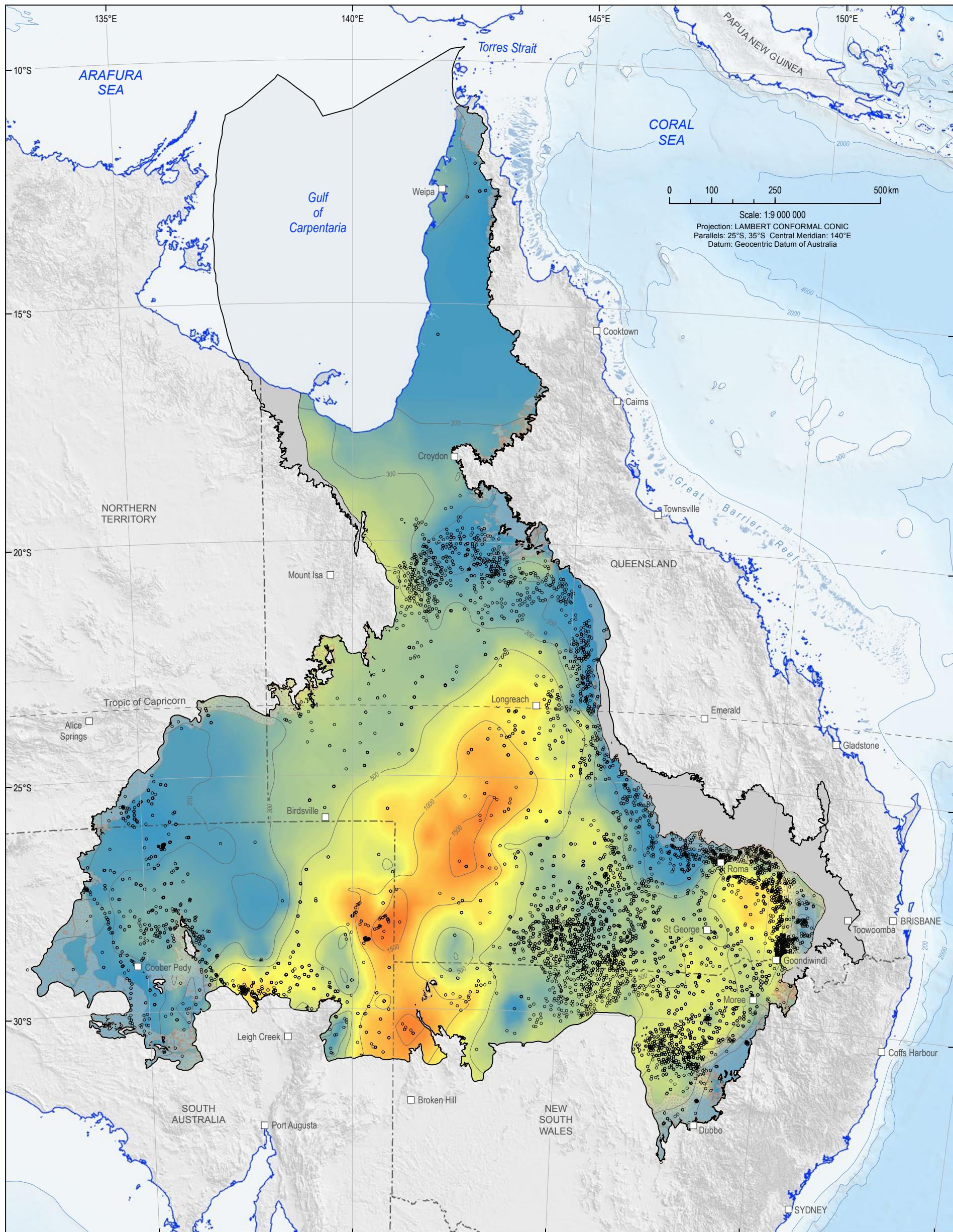
Areas of low alkalinity (<300 mg/L) include recharge zones, much of the Euroka Arch and Carpentaria Sub-basin and the western Eromanga Sub-basin. Moderate values (<500 mg/L) are observed in northwestern Eromanga Sub-basin, the Eulo-Nebine Ridge area, and the Coonamble Embayment/southern Surat Basin.

Characteristic lower alkalinity values (<200 mg/L) are observed for recharge zones and younger waters, with values gradually increasing as they flow through the basins (i.e. down potentiometric gradient). This is clearly observed in the eastern Eromanga flow system, starting with low values in the recharge zone of the northeastern Eromanga Sub-basin, increasing to high values in the Central Eromanga Depocentre, which are then maintained through to discharge in the southern margin at the Lake Frome Embayment. An additional contribution to the high alkalinity accumulated in the central Eromanga Sub-basin is the decomposition of organic matter (oil and conventional gas accumulations are present within the Cadna-owie – Hooray aquifer in this area).

A region of low-value alkalinity is observed in the central region of the Eulo-Nebine Ridge, where the Westbourne and Birkhead aquitards thin or are absent. This is likely to be a result of mixing with lower alkalinity groundwater from deeper aquifers. Low alkalinity is observed in the Poolowanna Trough where sodium, chloride, potassium, magnesium, calcium and sulphate concentrations are all high. The aquifer in the western part of the basin is relatively shallow and predominantly quartzose sandstone compared to the quartz-lithic sandstone in the eastern Eromanga Sub-basin. The southwestern region of the basin is marked by low rainfall and high evaporation, but there is also a significant freshwater recharge component from the Finke River.

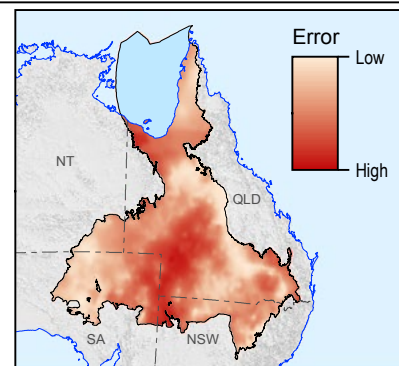
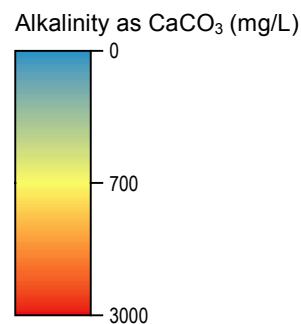
High alkalinity (>1000 mg/L) is observed in the deepest portion of the Surat Sub-basin in the vicinity of the Mimosa Syncline (see Map 4), and coincides with a strongly-depleted chloride isotope signature (Map 45), suggesting that this may be a region of low flow.





- Great Artesian Basin
- Cadna-owie – Hooray Aquifer and Equivalents
- Recharge zone
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Alkalinity as CaCO_3 contour (mg/L)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Groundwater sample location
- City/town



Predicted value error map

14-8061-47

Map 36

Cadna-owie – Hooray Aquifer

—Total Dissolved Solids

The Cadna-owie – Hooray Aquifer is one of the most widely utilised groundwater resources in the GAB. Large portions of the aquifer contain fresh groundwater that is suitable for human consumption.

The salinity as indicated by TDS, shows significant regional variability and recognizable trends. Measured TDS values range from less than 100 mg/L to more than 50 000 mg/L.

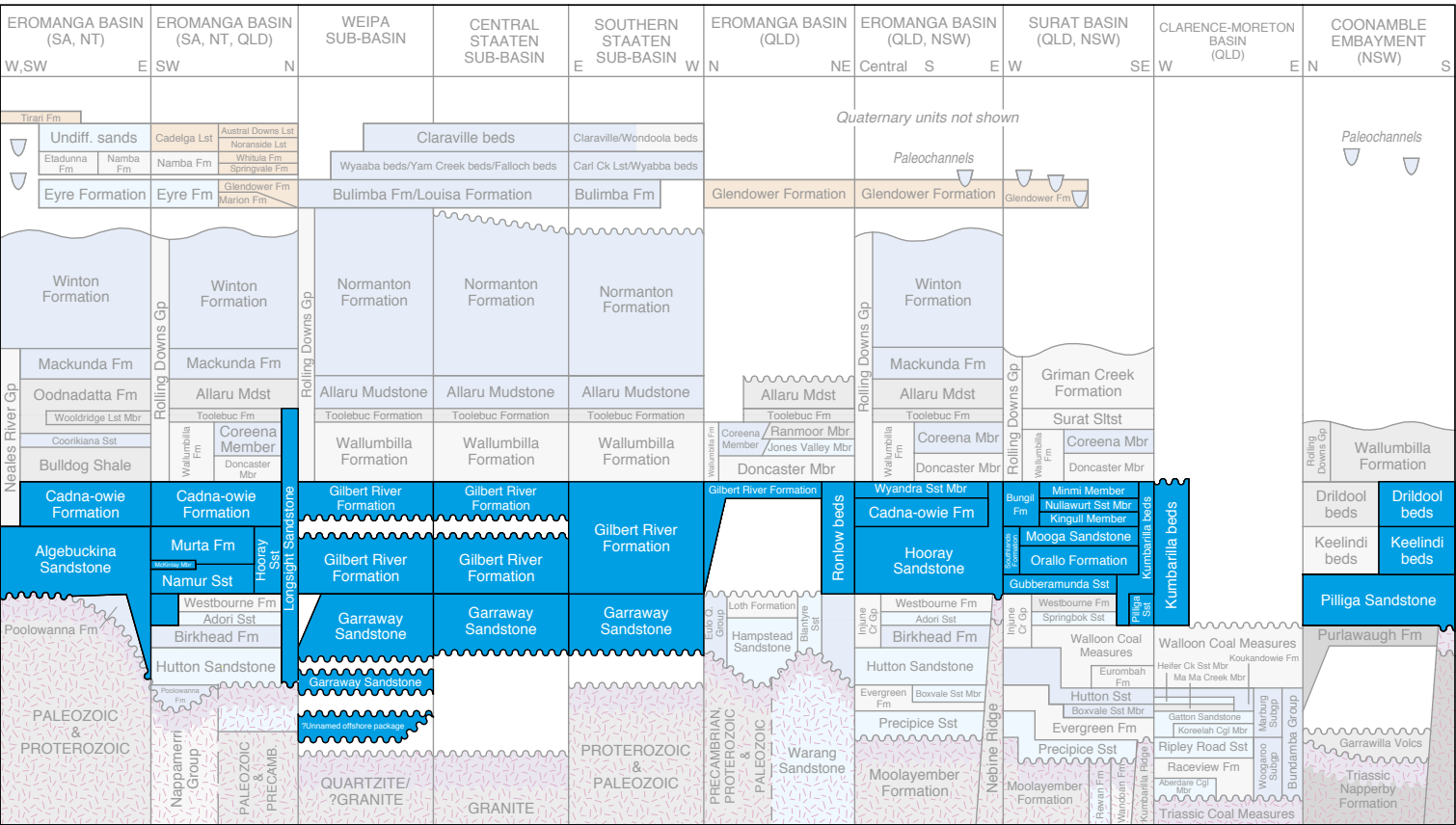
Generally low salinity is found along the eastern margins of the Eromanga, Carpentaria and Surat sub-basins, proximal to recharge zones. Cape York is dominated by low salinity due to the high annual rainfall and high rates of recharge to the groundwater.

High salinity values are observed in the southwestern Eromanga Sub-basin near the recharge zone, where recharge rates are extremely low and salt deposits are present at the surface.

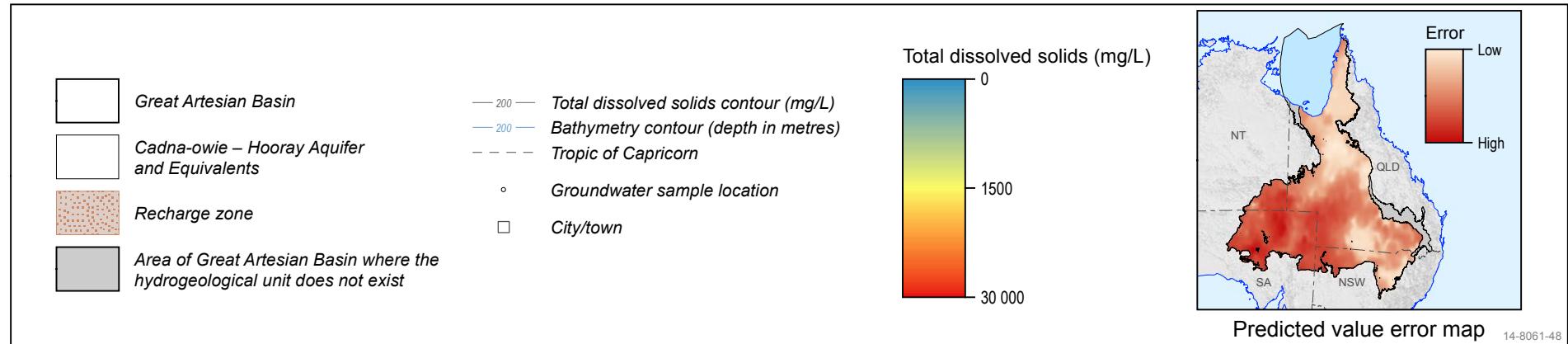
In the Eromanga Basin, increasing salinity is observed down flowpaths. Regional maxima are observed within the deeper parts of the basin coincident with the Poolowanna Trough and Central Eromanga Depocentre.

The low-salinity anomaly centred on the Eulo-Nebine Ridge is likely due to enhanced recharge and mixing with other aquifers due to thinning or the absence of the Birkhead and Westbourne aquitards in this region. A small low-salinity plume on the western margin of the Eromanga Sub-basin (immediately north of the South Australia/Northern Territory border) is associated with fresh water recharge from the Finke River during flood events.

Brackish groundwater is present in the northeastern corner of the Surat Sub-basin as the Cadna-owie – Hooray Aquifer merges with outcropping Kumbarella Beds. Typically, salinity increases along flow lines from the recharge zones to the deeper parts of the basin. The presence of higher salinity groundwater coincides with low levels of permeability and low recharge rates in this region. Compared to other parts of the basin, the aquifer source materials include higher proportions of clay and interbedding of siltstones and mudstones, which tends to reduce permeability. A strongly depleted chlorine isotope signature (see Map 45) adjacent the recharge zone is coincident with the Mimosa Syncline and suggests that this may be a region of very low flow. Additionally, it is possible that increased salinity may be a result of vertical flow from underlying higher salinity aquifers along fractures or faults.



Cadna-owie – Hooray Aquifer and Equivalents



Map 37

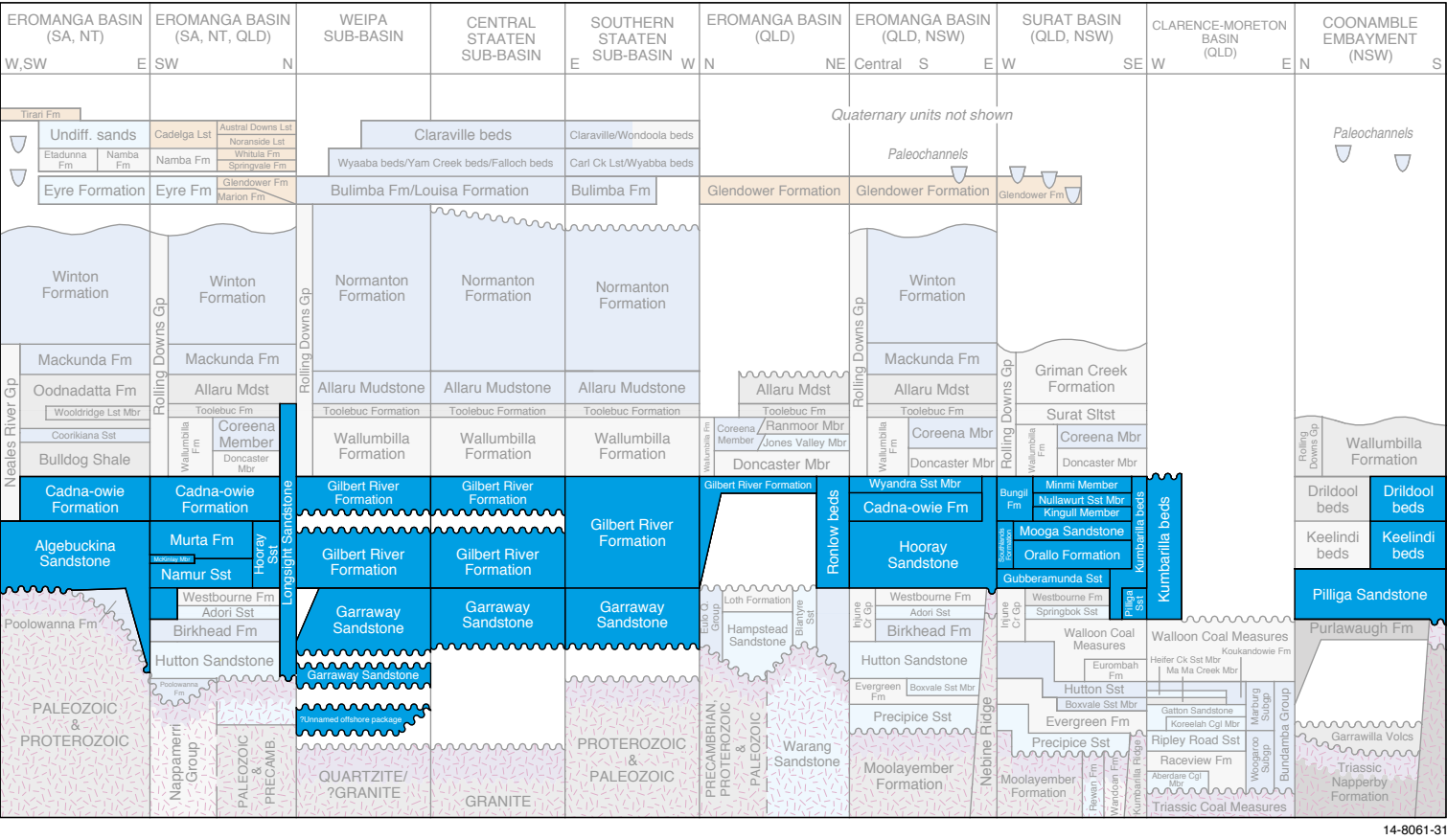
Cadna-owie – Hooray Aquifer—Chloride

Chloride concentrations in the Cadna-owie – Hooray Aquifer show significant regional variability and largely mirror the distribution of total dissolved solids concentrations.

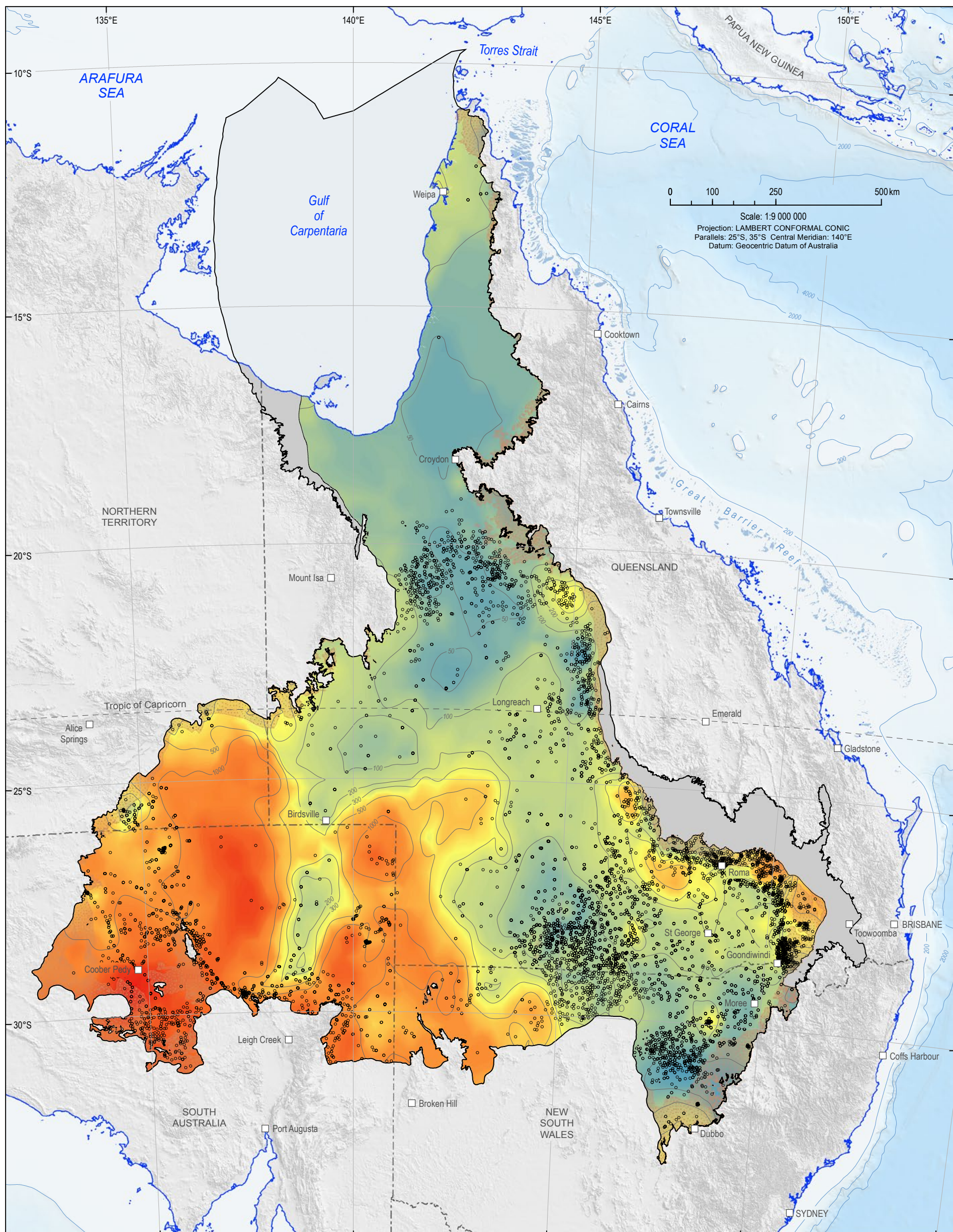
Regions of low chloride are found extending from the northeastern Eromanga recharge zone onto the central portion of the Euroka Arch; adjacent the Eulo Ridge and its associated springs; and within the Pilliga region of the eastern Coonamble Embayment. The arc of low chloride concentration, extending from the northeastern Eromanga recharge zone (north of Longreach), southwest to Birdsville, then south along the Birdsville Track Ridge, coincides with a zone of higher groundwater flow. This zone of enhanced groundwater flow transports relatively young, low-chloride waters from the northeast recharge zone along groundwater flow paths to the central parts of the basin (see Map 10). Differing inferred groundwater flow rates, between the shallow and deep parts of the basin, are likely to be due to the increased effects of compaction and cementation on the aquifer, as depth increases (see Map 3). Regions of elevated chloride (>500 mg/L) occur

within the western Eromanga Sub-basin; from the Central Eromanga Depocentre south to the southern margin; around the northeastern margin of the Surat Sub-basin; and localised regions on the Eulo-Nebine Ridge. Except for the central Eromanga Sub-basin, these regions of elevated chloride are characterised by Na-Cl type chemistry or Na-Cl-SO₄ for the western Eromanga Sub-basin. Much of the Na-Cl dominated chemistry regions are likely to be influenced by the downward diffusion of ions from the marine mudstones of the Rolling Downs Aquitard due to greater concentrations in the Rolling Downs Aquitard relative to the underlying aquifers¹⁴.

In the northeastern part of the Surat Sub-basin, low permeability and the presence of clays, siltstones and mudstones with marginal-marine depositional histories are likely to contribute to the elevated chloride concentration.

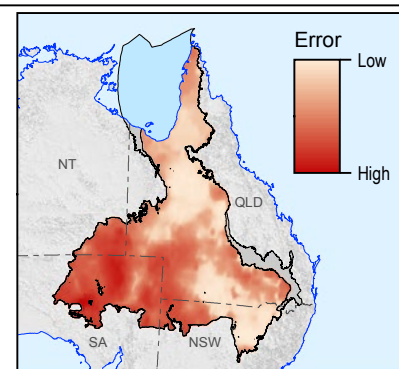
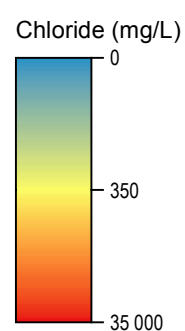


Cadna-owie – Hooray Aquifer and Equivalents



- Great Artesian Basin
- Cadna-owie – Hooray Aquifer and Equivalents
- Recharge zone
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Chloride contour (mg/L)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Groundwater sample location
- City/town



Predicted value error map

14-8061-49

Map 38

Cadna-owie – Hooray Aquifer—Sodium

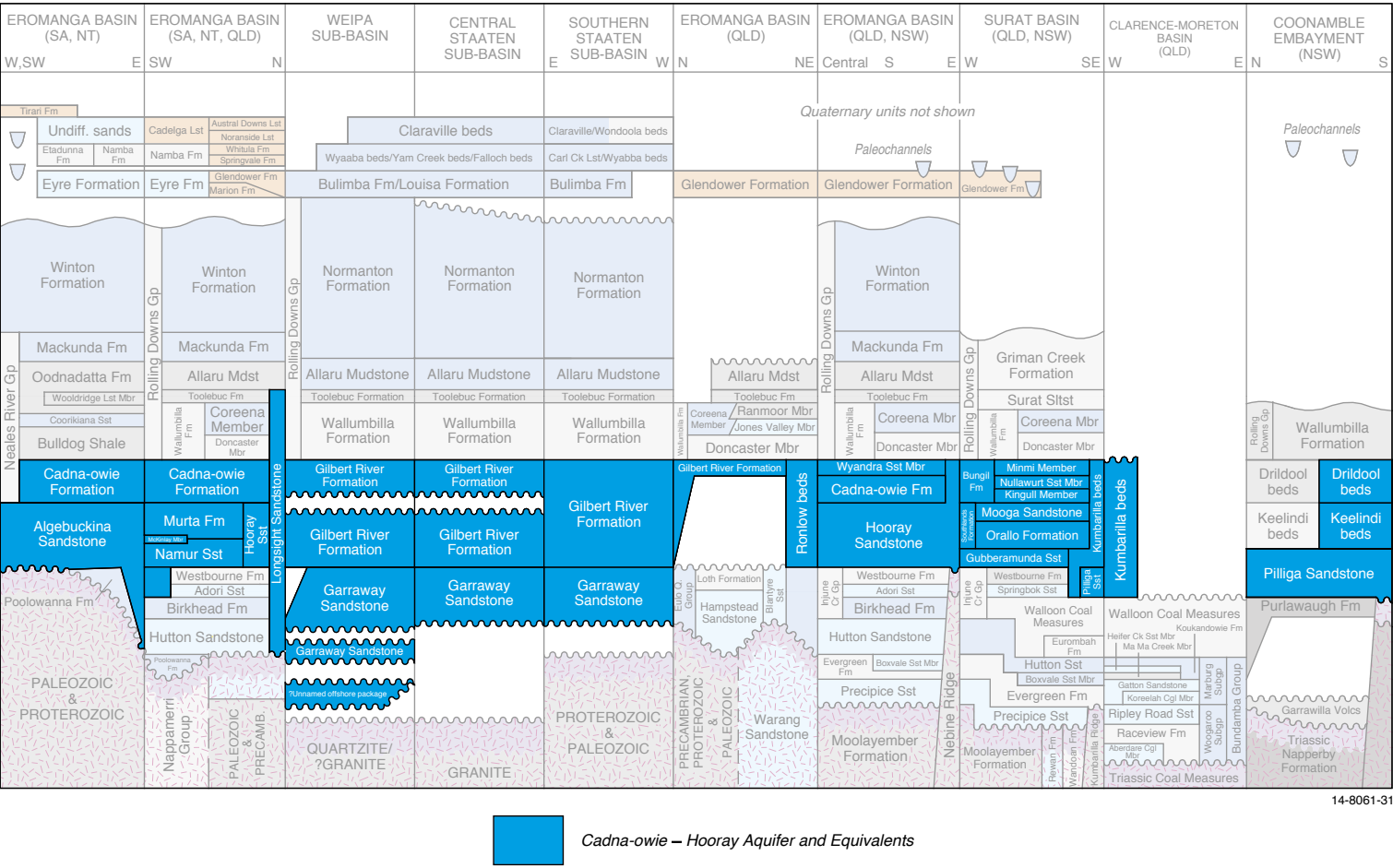
Sodium is the dominant cation in the Cadna-owie – Hooray Aquifer and its concentration is mirrored by the total dissolved salt concentration and, to a large extent, chloride concentration.

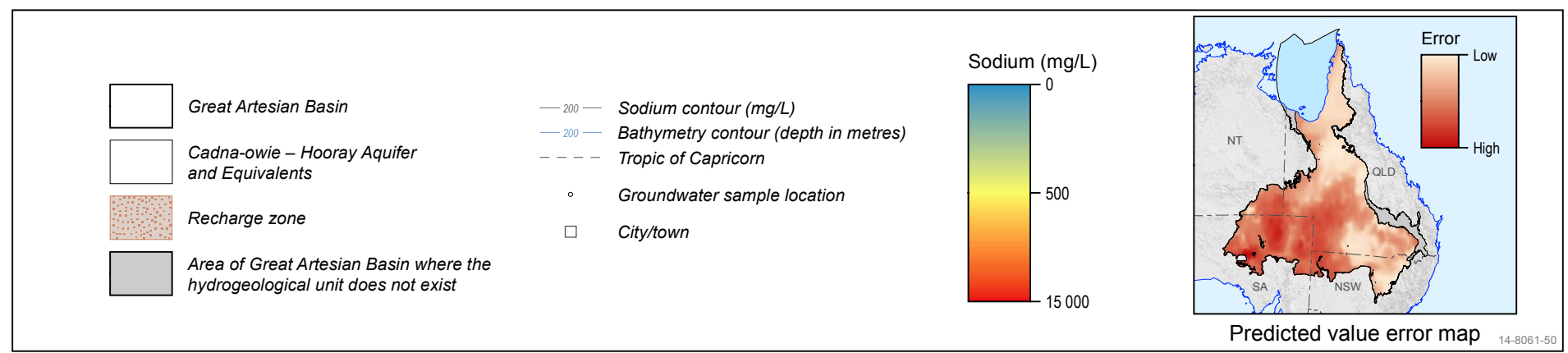
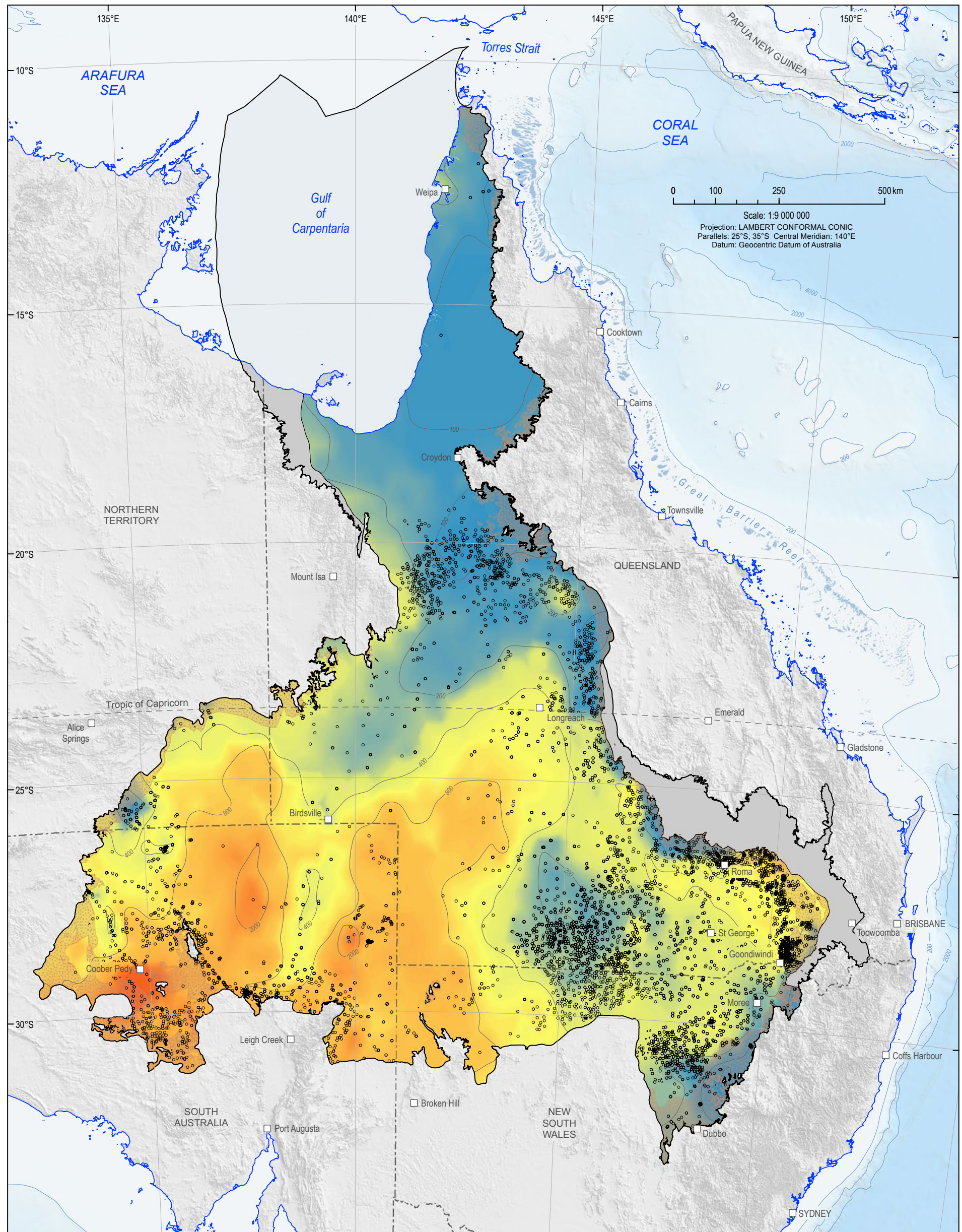
The dominance of sodium is likely related to the weathering of Na-bearing silicate minerals, cation exchange and conversion of Na-smectite to kaolinite with the release of Na to solution. The Na-dominant geochemical signature may, however, be influenced to some extent by the diffusion of salts from overlying or underlying aquitards with marginal-marine deposition.

Generally low sodium (< 200 mg/L) is found in the Carpentaria Sub-basin, the eastern margins of the Eromanga Sub-basin, proximal to the recharge zone and in the centre of the Eulo-Nebine Ridge; and large parts of the Coonamble Embayment. The significant decrease in sodium in the centre of the Eulo-Nebine Ridge can be attributed to mixing with lower-salinity waters from the deeper Hutton Aquifer. The Birkhead-Walloon Aquitard that separates these two aquifers is absent in this part of the GAB.

High sodium values are observed in the south western Eromanga Sub-basin near the recharge zone, where recharge rates are extremely low and salt deposits are present at the surface. In the Eromanga Sub-basin, increasing salinity is observed down flow paths. Regional maxima are observed within the deeper parts of the basin coincident with the Poolowanna Trough and central Eromanga Depocentre.

Elevated sodium concentrations are present in the northeastern corner of the Surat Sub-basin, within and proximal to outcrop areas. Typically, salinity increases along flow lines from the recharge zones to the deeper parts of the basin. The presence of higher-sodium groundwater coincides with regions of low levels of permeability and low recharge rates. This is supported by an evaporated water isotope signature of the groundwater and the presence of clays and interbedding of siltstones and mudstones within the sandstone formation in these areas. These features will tend to reduce permeability and the clays will be a source of additional sodium ions.





Map 39

Cadna-owie – Hooray Aquifer—pH

Weakly acidic groundwater (pH~5.5–6) clearly delineates recharge zones within the Cadna-owie – Hooray Aquifer and generally reflects lower alkalinity values (see Map 35).

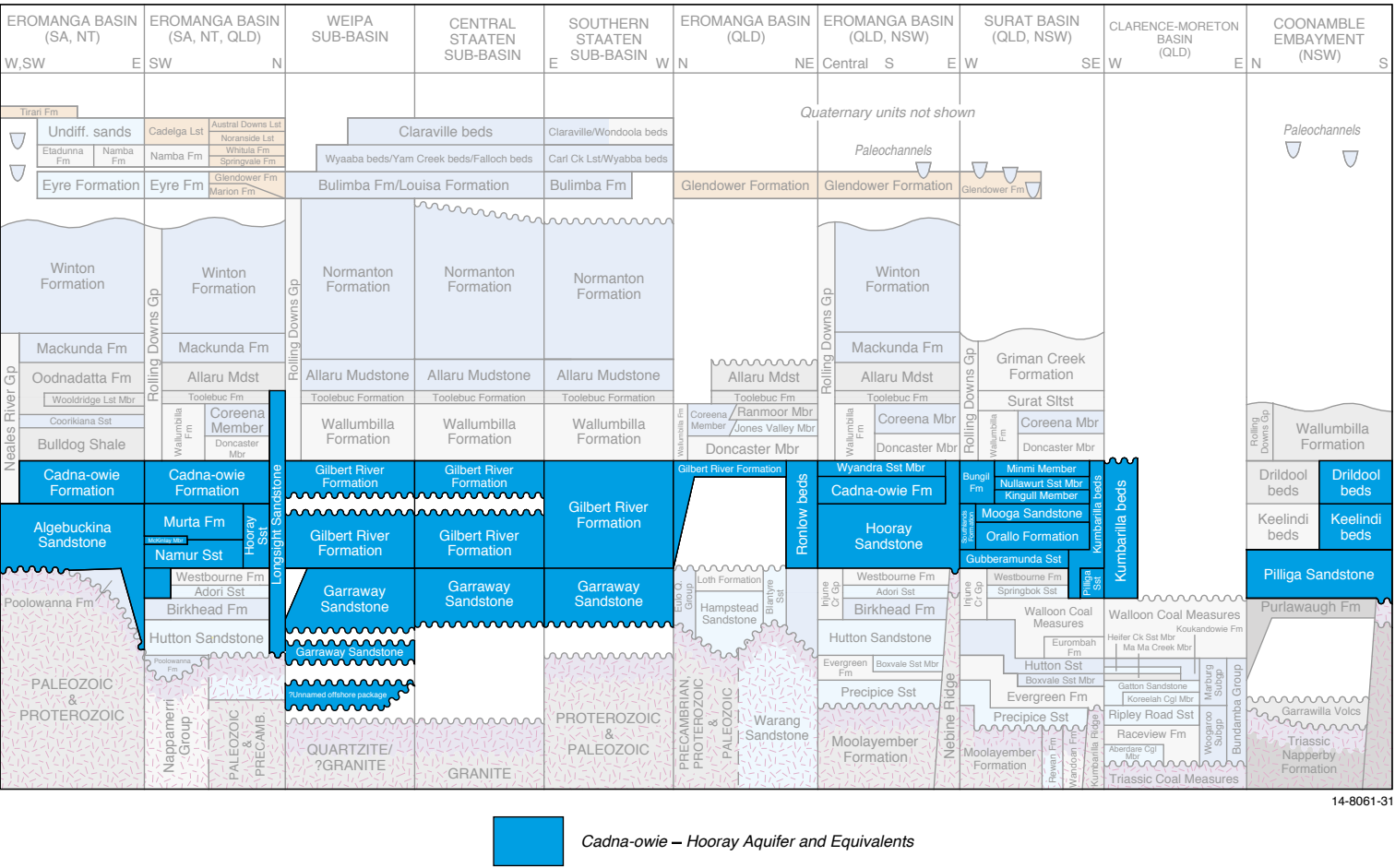
The pH values gradually increase with groundwater flow through the basin (i.e. down potentiometric gradient). This is clearly observed in the eastern Eromanga flow system, starting with pH ~ 5.5–6 in the recharge zone of the northeastern Eromanga Sub-basin, increasing to pH ~7.5–8.5 toward the central Eromanga Depocentre, which is then maintained through to discharge in the southern margin at the Lake Frome Embayment.

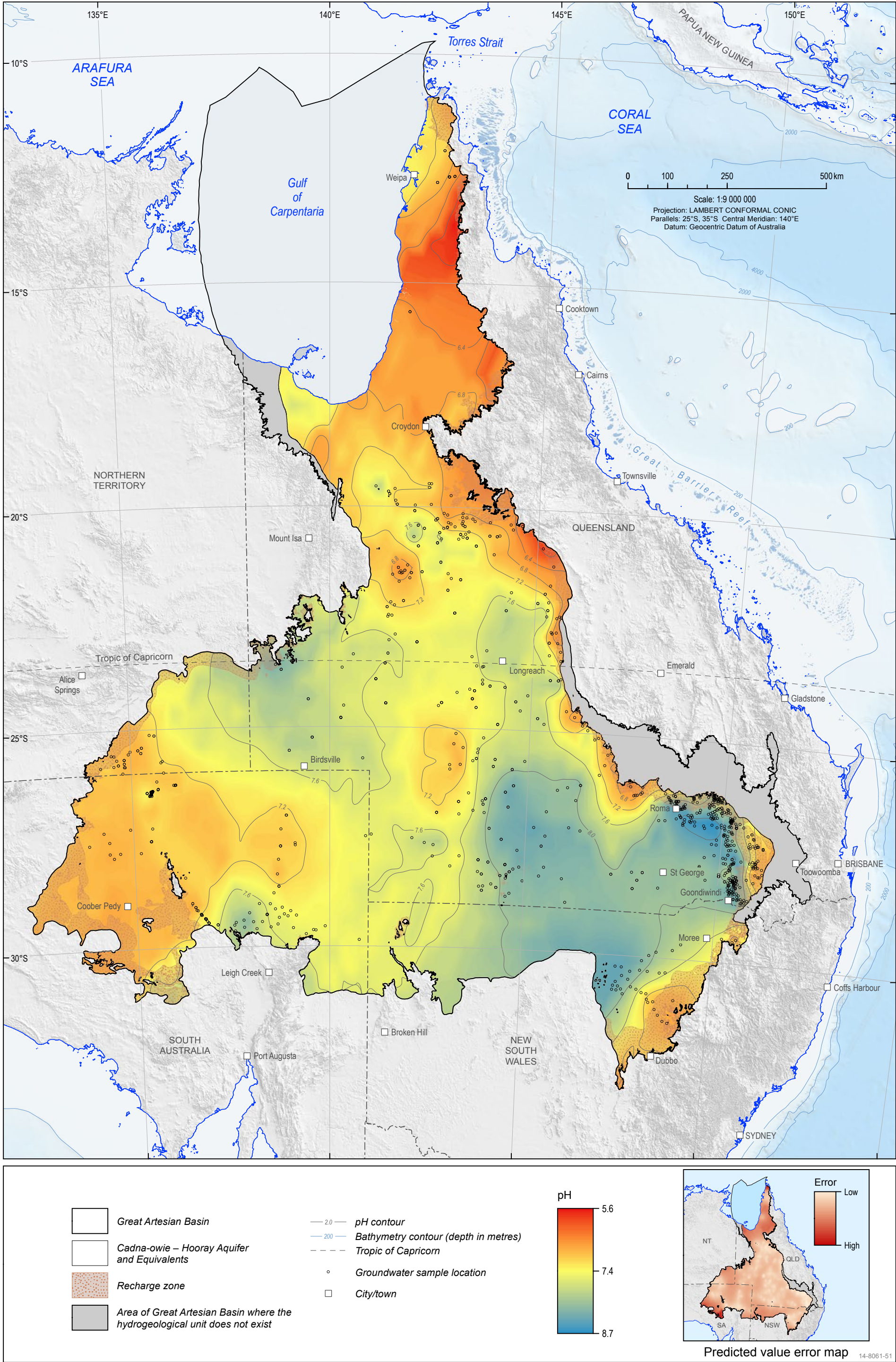
Similarly, weakly acidic groundwaters area observed in the recharge zones along the northern portion of the Eulo-Nebine Ridge, a portion of the northern margin of the Surat recharge zone, eastern margin of the Surat Sub-basin, and eastern margin of the Coonamble Embayment. All flow within the Surat Sub-basin converges to the southern margin along the Eulo-Nebine Ridge. Cape York is dominated by weakly acidic groundwater due to the high annual rainfall and high rates of recharge to the groundwater.

Alkaline conditions (pH > 7.5) exist in the northeast corner of the Surat Basin within and proximal to the aquifer outcrop areas. This region is characterised by elevated salinity and low permeability and low recharge rates. The intake beds in this

region are characterised by clayey sandstones with mudstone and siltstone interbedding and minor coal, which will tend to increase pH. High pH (> pH 8.5) groundwater and methane gas found adjacent to the Mimosa Syncline is likely to be due to the bacterial conversion of carbonate to methane and the corresponding consumption of acidity. This process is most likely responsible for most of the observed elevated pH across the deeper parts of the Surat Sub-basin.

Generally near neutral pH values are observed in the western and unconfined southwestern region of the Eromanga Sub-basin and these correspond with low alkalinity. Field pH measurements in this region are limited so predictions need to be considered with caution. The low alkalinity of the region makes the use of laboratory pH data particularly unsuitable, as it would tend to give higher readings than field measurements. The generally neutral pH values are consistent with the comparatively shallow nature of the aquifer and the paucity of evidence for methane gas or the presence of other organics. The region is also characterised by clean sandstones containing no volcanic and limited clay material, unlike the eastern region of the GAB. Given this, there is little opportunity for increased pH through dissolution of carbonate minerals or through bacterial conversion of carbonate to methane.





Map 40

Cadna-owie – Hooray Aquifer—Sulphate

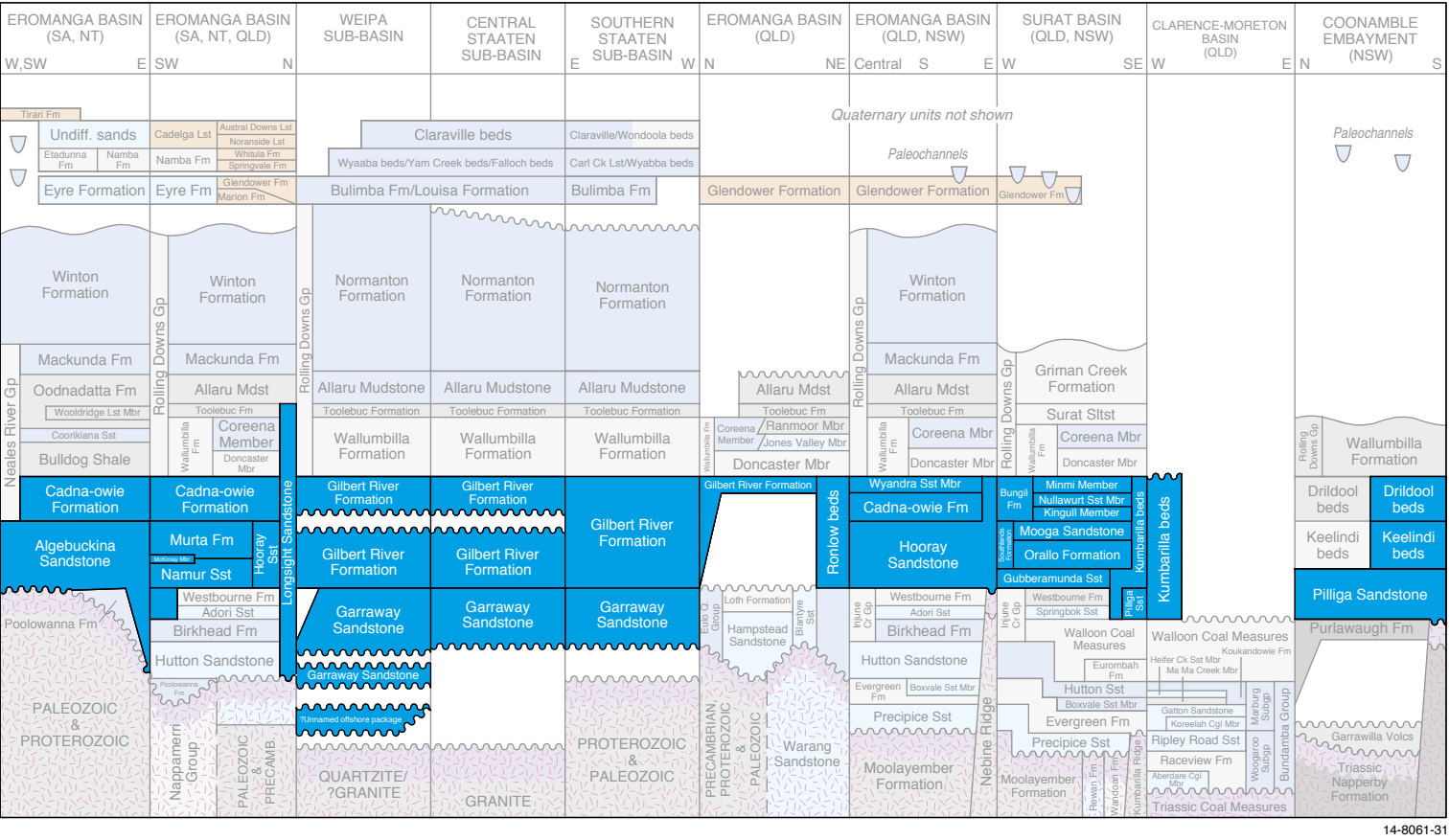
Sulphate concentrations are generally low to moderate across the majority of the Cadna-owie – Hooray Aquifer

Elevated sulphate levels are observed along the north section of the Eulo-Nebine Ridge and in the northern margin of the Surat Sub-basin. The elevated sulphate concentrations correspond with elevated concentrations of magnesium (see Map 41), calcium (see Map 42) and weakly acidic groundwater (see Map 39). This is characteristic of recharge waters and suggests that this is a zone of high recharge flow. Similar groundwater chemistry with elevated sulphate is observed in the northern Eromanga Sub-basin in the recharge zones over the Eureka Arch.

Low sulphate is observed adjacent the recharge areas near the Longreach Basement High in the northeastern recharge zones in the Eromanga Sub-basin, directly below Lake Eyre on the southern margin of the basin and against the Mount Isa Block. This is potentially due to strongly reducing conditions and the conversion of sulphate to sulphide.

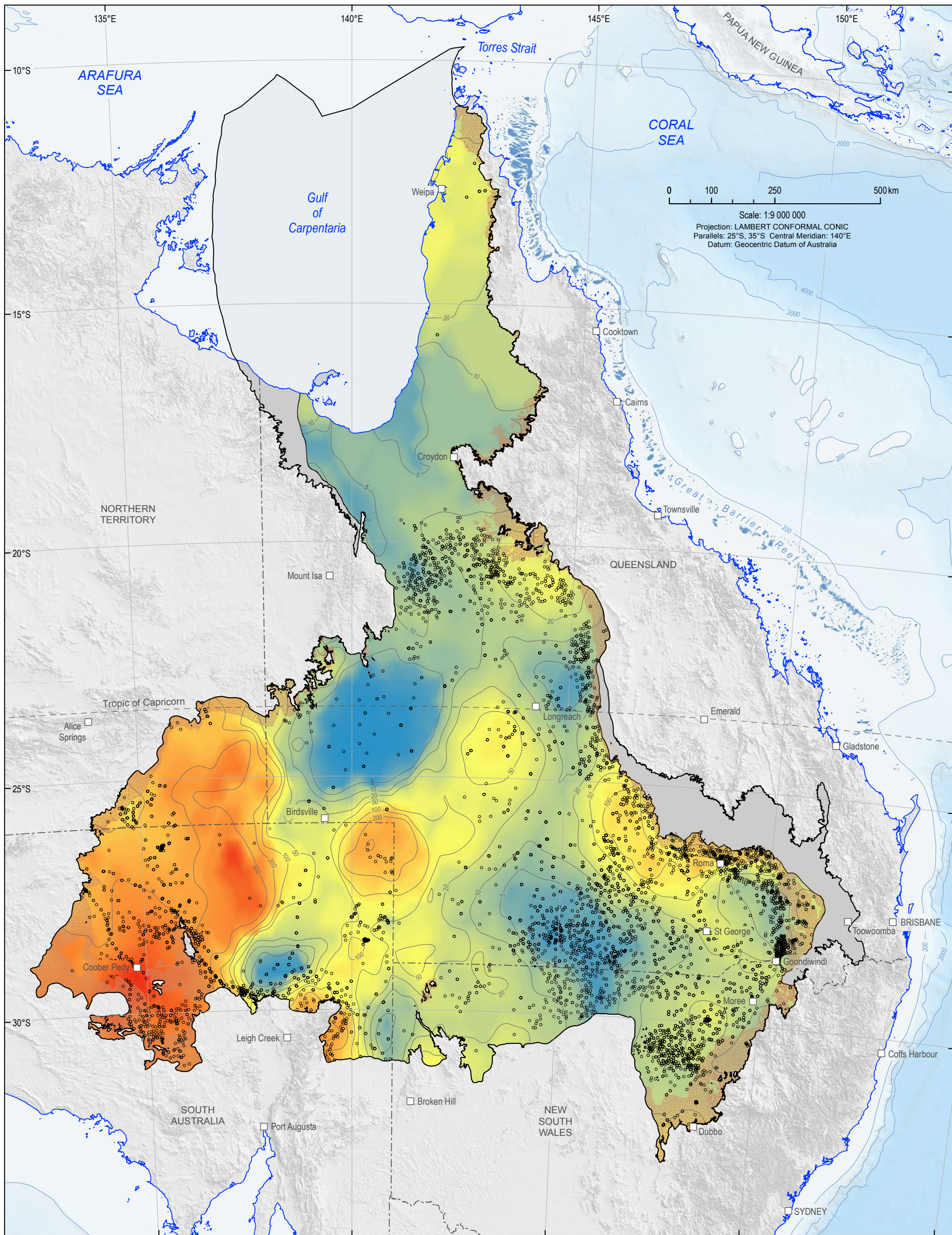
Moderate to low levels are observed for much of the Surat Basin and Coonamble Embayment. Very low levels are observed over the central and southern part of the Eulo Ridge, where Westbourne and Birkhead aquitards thin or are absent and there is likely mixing with groundwater from the deeper aquifers with low sulphate concentration.

High levels of sulphate are found in the western and southwestern recharge zones of the Eromanga Sub-basin. The very high values present basinward, away from the recharge zones where the aquifer is confined, may be due to sulphate leaching from the overlying Bulldog Shale⁷. The deuterium and oxygen-18 ratios in this region also show a strongly evaporative signal, which is consistent with the accumulation of saline groundwater and the presence of surficial gypsum deposits.



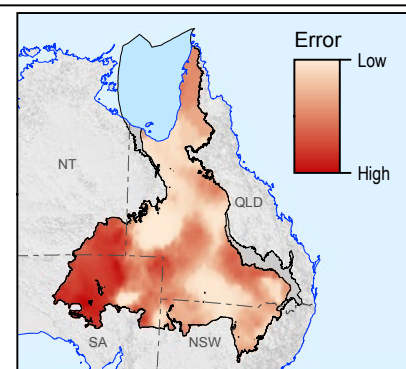
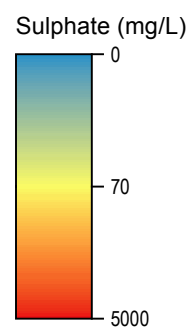
14-8061-31

Cadna-owie – Hooray Aquifer and Equivalents



- Great Artesian Basin
- Cadna-owie – Hooray Aquifer and Equivalents
- Recharge zone
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Sulphate contour (mg/L)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Groundwater sample location
- City/town



Predicted value error map 14-8061-52

Map 41

Cadna-owie – Hooray Aquifer

—Magnesium

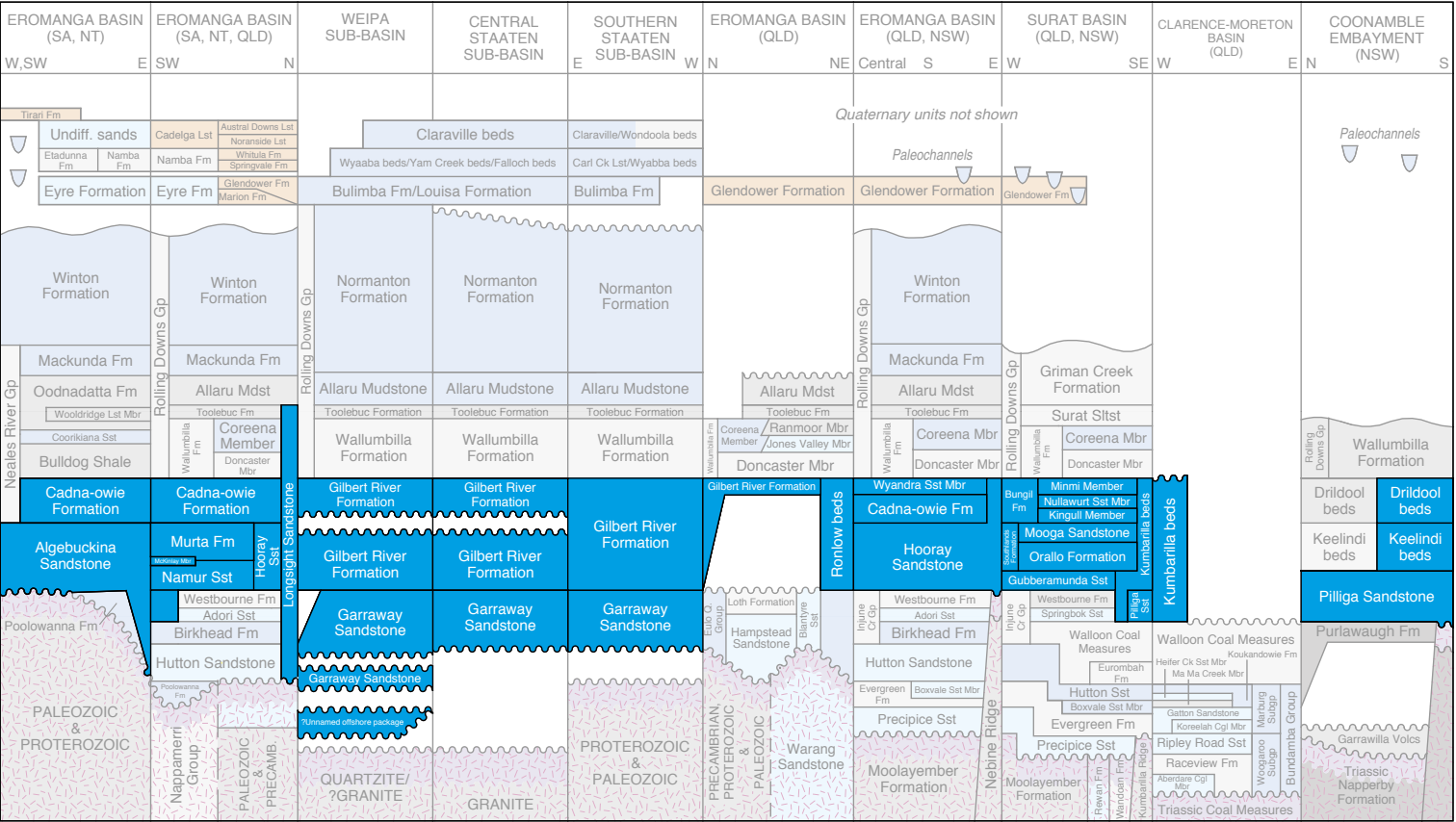
Magnesium concentrations in the Cadna-owie – Hooray Aquifer show significant regional variability with spatial trends that are generally comparable to those of calcium (see Map 42).

Moderate magnesium concentrations (>10 mg/L) are observed in or near the recharge zones along the eastern margin of the GAB, with a gradual decrease along flow lines to the west and southwest, as a result of precipitation and ion exchange with clays. Low values are observed along the Birdsville Track Ridge flowpath through to the regional discharge zone at Lake Eyre South.

Elevated magnesium concentrations are found in the Central Eromanga Depocentre which decrease marginally then remain elevated towards the southern margin and Lake Frome Embayment. Sodium, calcium, sulphate and alkalinity plot above the seawater dilution line in this central region suggesting there is significant water-rock interaction. Variable Ca:Mg ratios exist in this central region, with generally low ratios (~1.4) where Mg and Ca concentrations are high, and high ratios eastwards of the depocentre where Mg and Ca concentrations

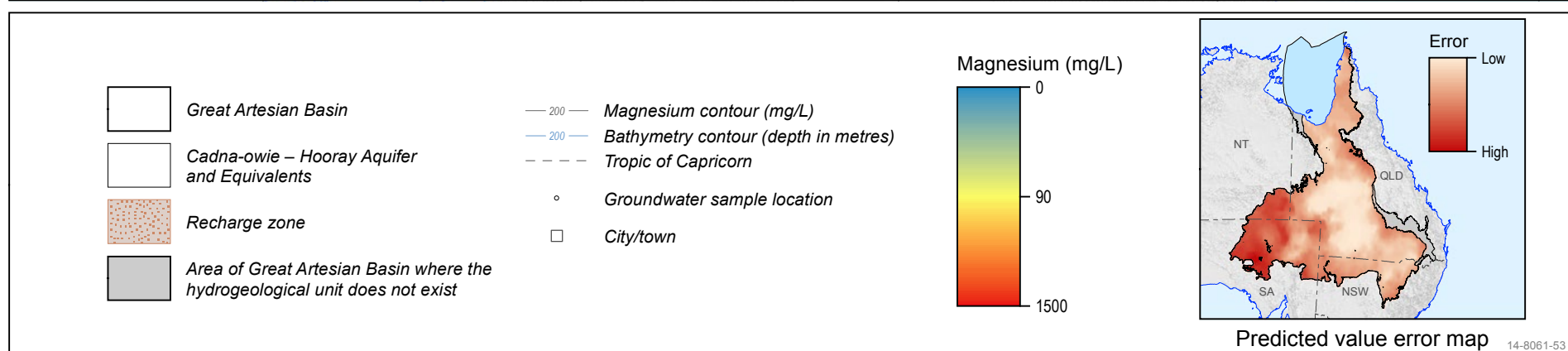
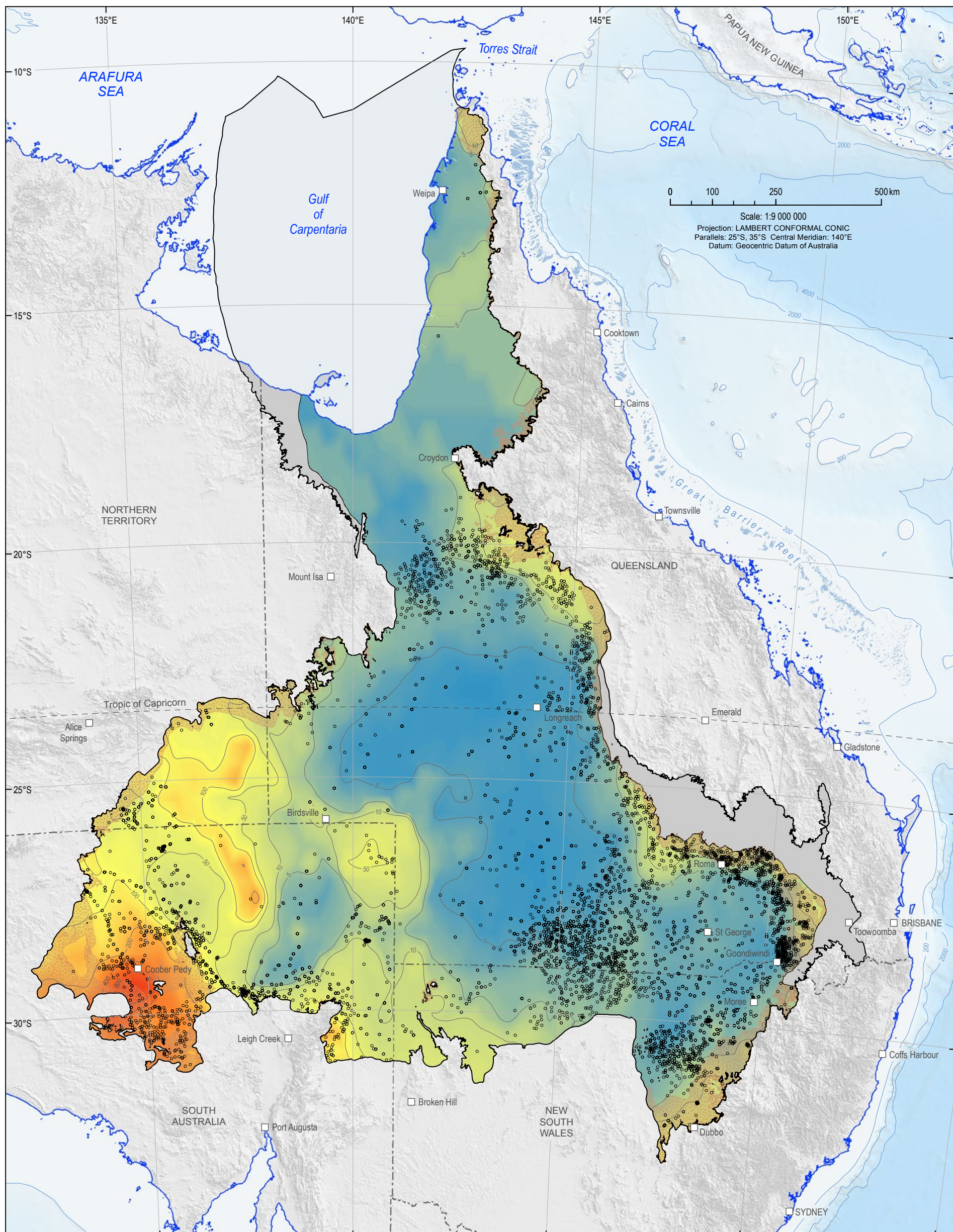
are low. There is a mixed signal south of the Central Eromanga Depocentre and generally high ratios towards the southern discharge margin. This suggests that the area of the Central Eromanga Depocentre is likely to be a zone of mixing with groundwaters originating from the eastern margins.

High magnesium concentrations are found in the southwestern region of the Eromanga Sub-basin proximal to the recharge areas where the aquifer is unconfined. The very high concentrations in the southwestern region could be due to sulphate leaching from the overlying Bulldog Shale. The influence of the Finke River groundwater recharge plume in the western Eromanga Sub-basin (east of 135° longitude) is evident in this region and results in a significant reduction of the magnesium concentration.



14-8061-31

Cadna-owie – Hooray Aquifer and Equivalents



Map 42

Cadna-owie – Hooray Aquifer—Calcium

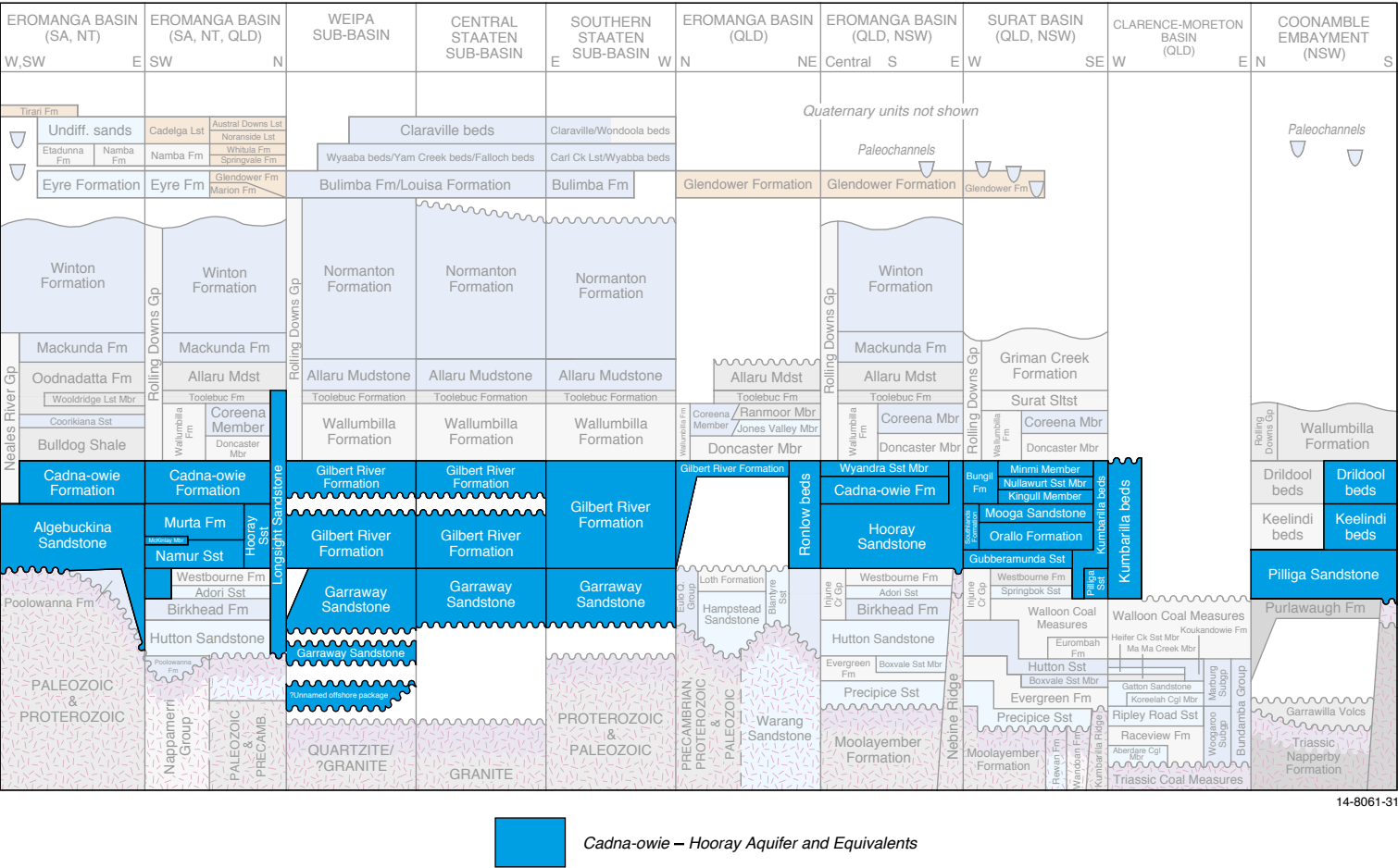
Calcium is the third most dominant cation in the Cadna-owie – Hooray Aquifer.

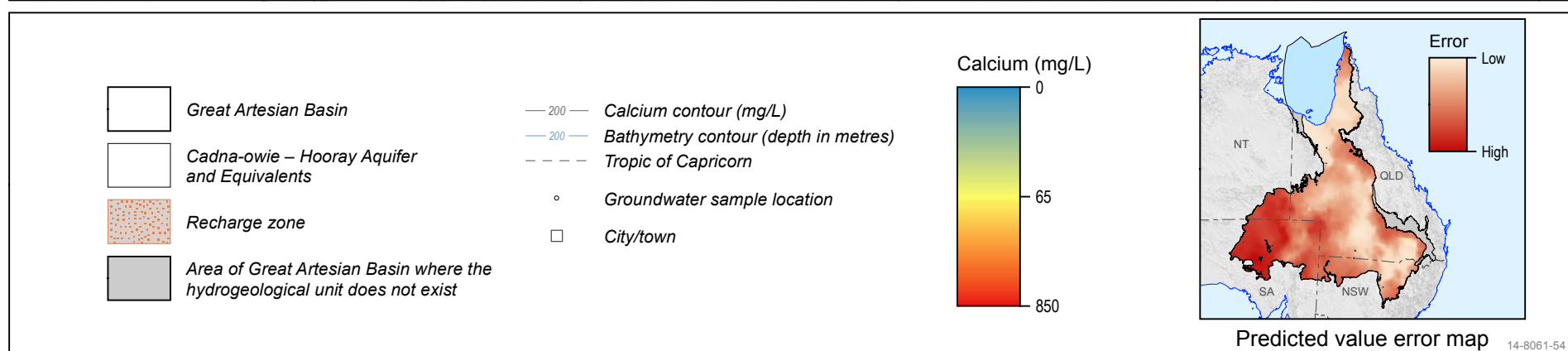
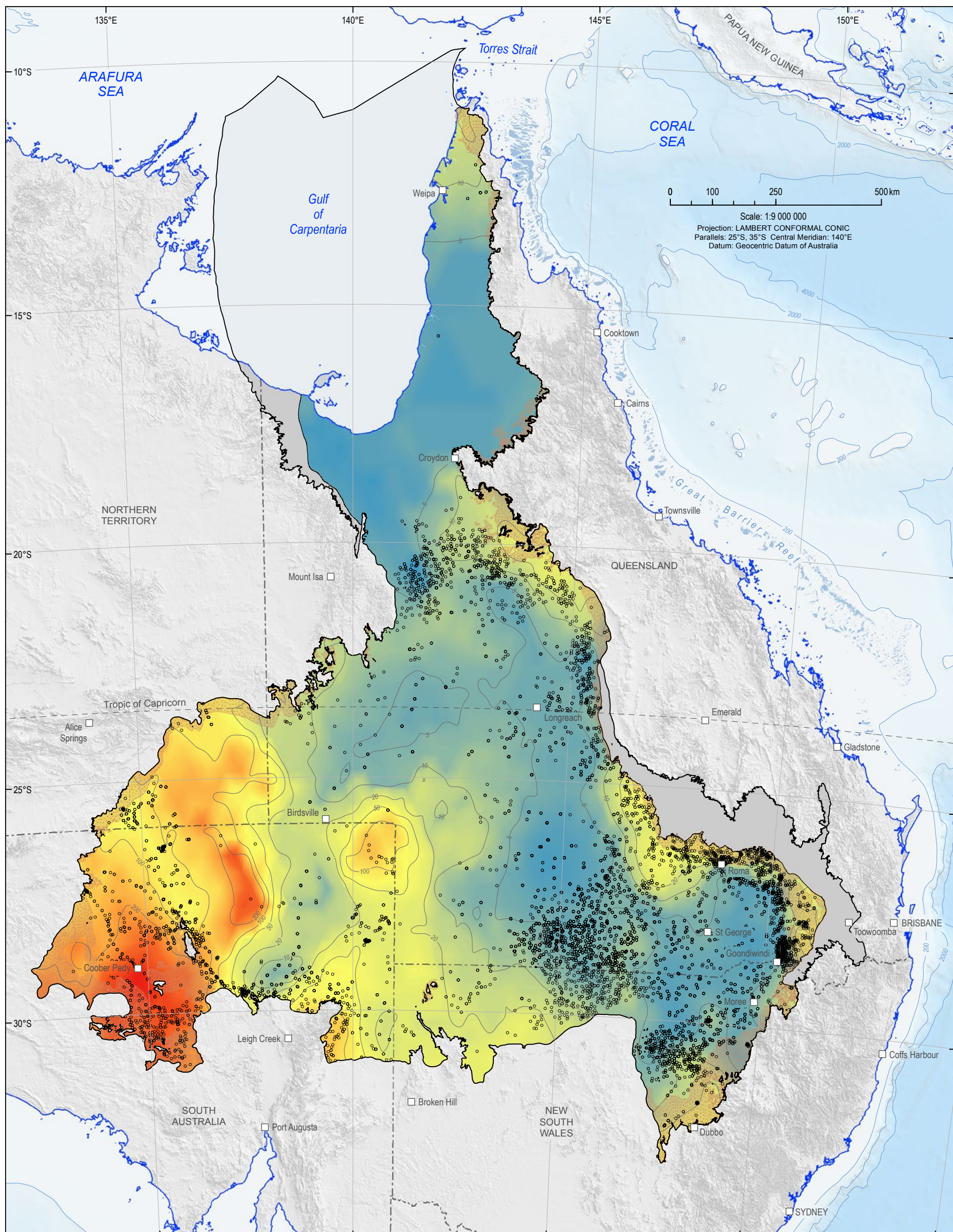
The calcium concentration is generally mirrored by the magnesium concentration (see Map 41) and, to a large extent, chloride concentration (see Map 37). Measured calcium concentrations range from less than 0.1 mg/L to 850 mg/L.

Similar to magnesium, moderate values (>10 mg/L) are observed for recharge zones and younger waters along the eastern margin of the GAB. This is clearly observed in the eastern Eromanga flow system, starting with higher values in the recharge zone of the northeastern Eromanga, decreasing to low values in the central Eromanga Sub-basin. Similarly, in the recharge zones along the northern portion of the Eulo-Nebine Ridge, northern margin of the Surat recharge zone, eastern margin of the Surat Sub-basin, and eastern margin of the Coonamble Embayment. All flow within the Surat Sub-basin converges to the southern margin along the Eulo-Nebine Ridge. Low values are observed along the Birdsville Track Ridge flowpath through to the regional discharge zone at Lake Eyre South.

Calcium concentrations greater than 100 mg/L are found in the Central Eromanga Depocentre. Sodium, calcium, sulphate and alkalinity plot above the seawater dilution line in this central region, suggesting additional inputs from rock-water interactions, potentially from dissolution of calcite and gypsum. Calcium levels decrease somewhat from the central depocentre towards the southern regional discharge zones but elevated levels are maintained towards the Lake Frome Embayment. These elevated calcium levels parallel elevated sodium and chloride concentrations in the region and are most likely due to downward diffusion of ions from the marine mudstones of the Rolling Downs Aquitard.

High calcium values are found in the southwestern unconfined region of the Eromanga Sub-basin due to a combination of weathering and evaporation. The Finke River groundwater recharge plume in the western Eromanga Sub-basin is overprinted in this region and results in a significant reduction of the calcium concentration.





Map 43

Cadna-owie – Hooray Aquifer—Potassium

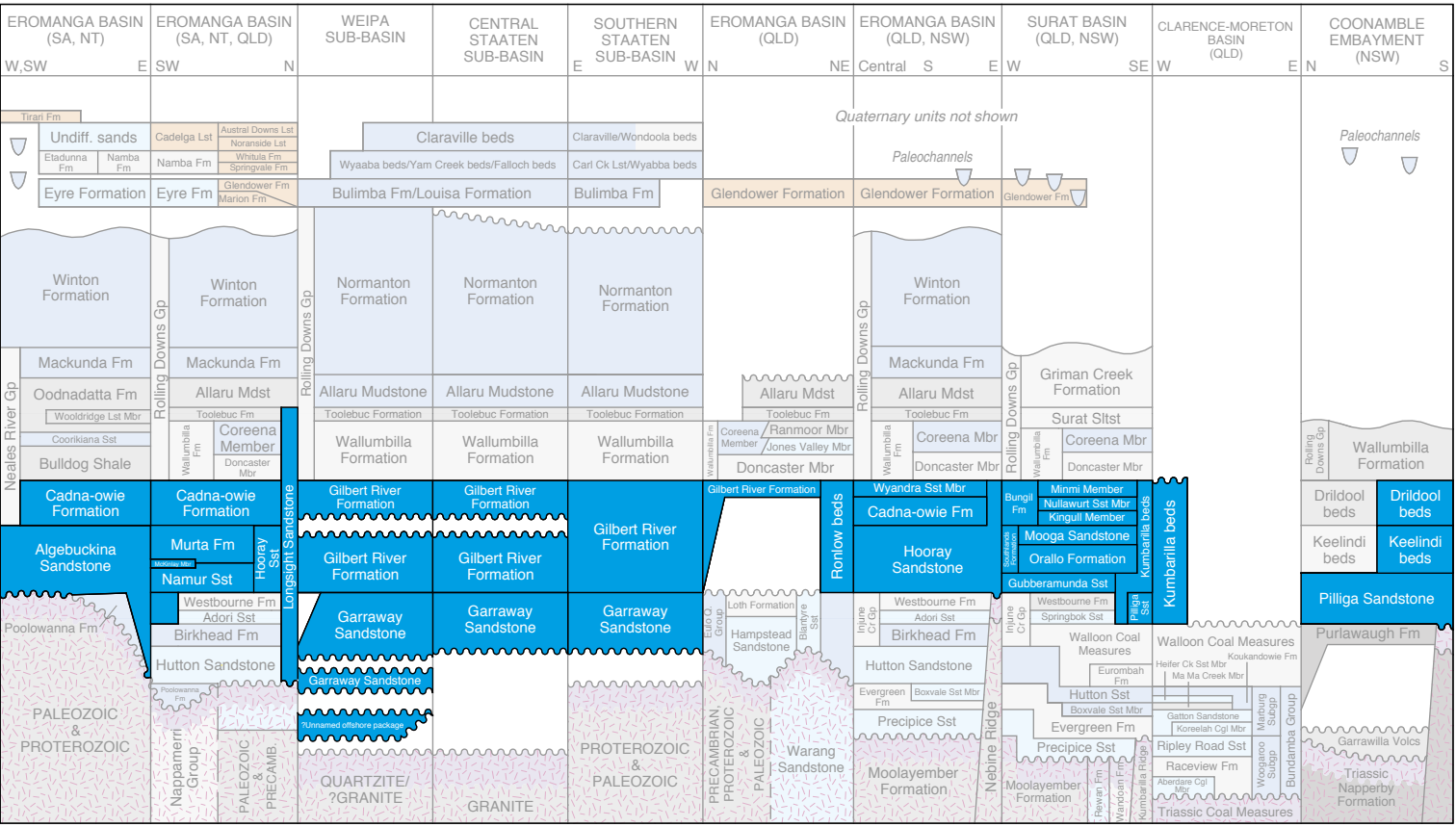
Potassium concentrations in the Cadna-owie – Hooray Aquifer show significant regional variability, with generally low levels in the Surat Sub-basin, high values in the central and western Eromanga Sub-basin and moderate values in the northern Eromanga and Carpentaria sub-basins.

Toward the southwestern boundary of the Eromanga Sub-basin, potassium values generally exceed 20 mg/L although the impact of the Finkel River plume is clearly evident with a corresponding reduction in potassium concentration. The deuterium and oxygen-18 ratios in this region also show a strongly evaporative signal and potassium is strongly correlated with chloride and the seawater dilution line. Much of the potassium is probably sourced from brine advection from surface playas.

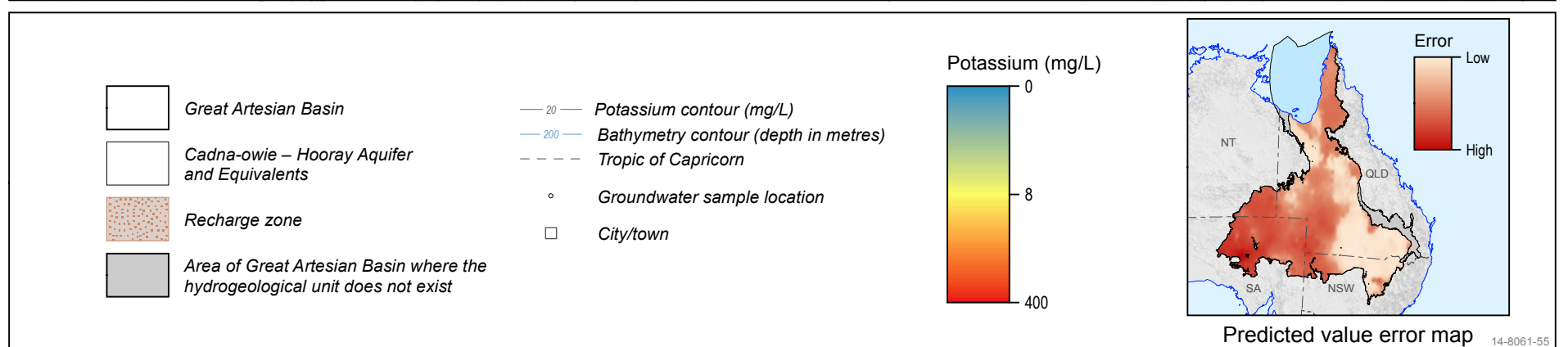
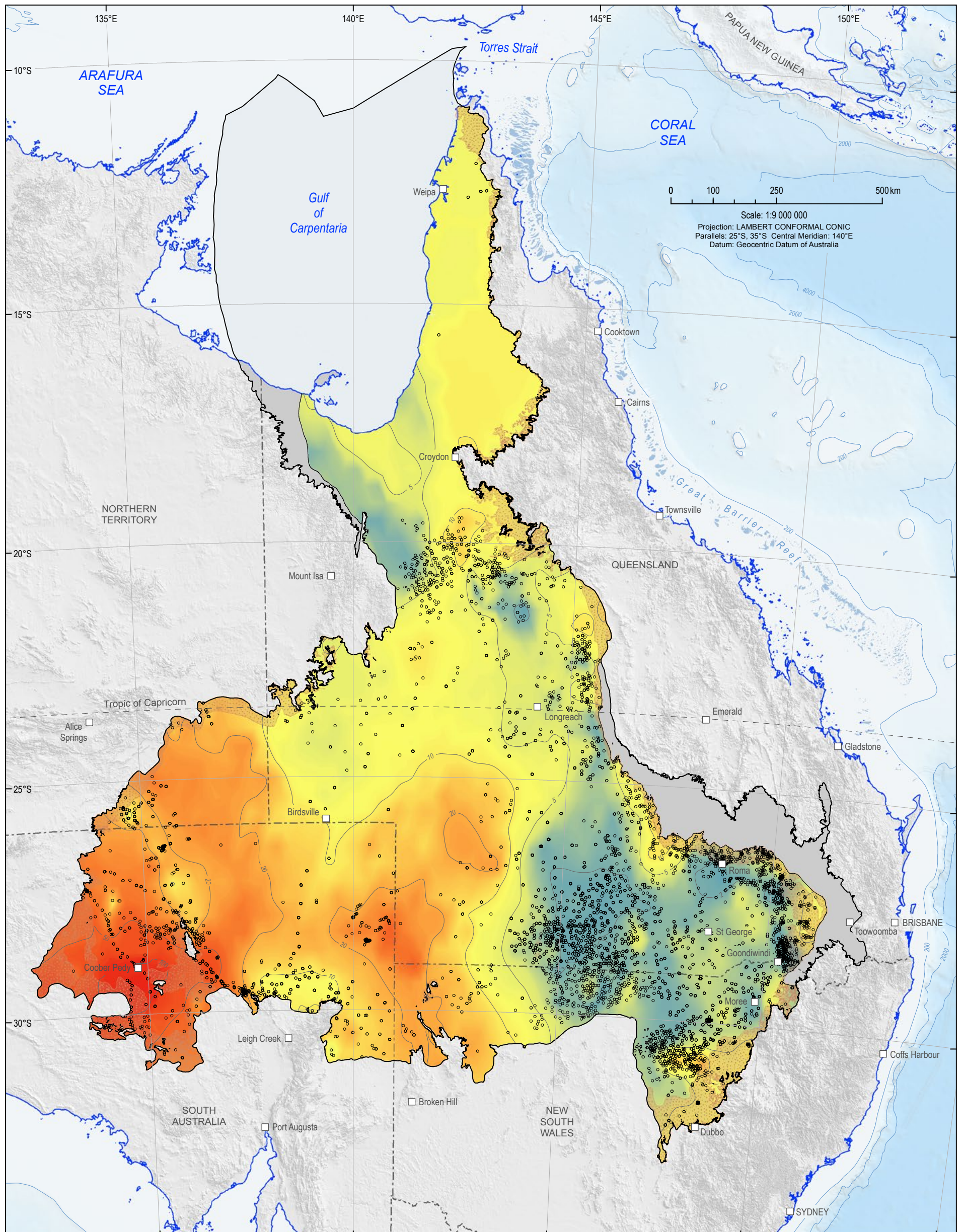
Similar to calcium and magnesium, elevated potassium concentrations (>5 mg/L) are observed for recharge zones and younger waters along the eastern margin of the GAB, particularly in the Surat Sub-basin. Higher values are observed in the recharge zones along the northern portion of the Eulo-Nebine Ridge, northern margin of the Surat recharge zone, eastern margin of the Surat Sub-basin, and eastern margin of the Coonamble Embayment. There is a strong correlation between elevated levels of potassium in the recharge zones and low alkalinity and low sodium concentrations in much

of the Surat Sub-basin. This suggests there is significant ion exchange with clays along flowpaths as groundwater moves from the recharge zones into the deeper parts of the Surat Basin. Low levels are observed on the central part of the Eulo-Nebine Ridge, corresponding with the thinning or absence of the Westbourne and Birkhead-Walloon aquitards and mixing with deeper groundwater sources.

The pattern of potassium in the central Eromanga Sub-basin is quite different to that in the Surat Sub-basin and may be a consequence of differing aquifer source sediments, containing less volcanic and clay material. Potassium levels are maintained from the recharge zones along regional flowpaths toward the Central Eromanga Depocentre, where they increase and remain relatively high through to the southern regional discharge zones within the Lake Frome Embayment. This pattern is mirrored by sodium and chloride concentrations in the region and is inferred to be due to downward diffusion of ions from the marine mudstones of the Rolling Downs Aquitard.



Cadna-owie – Hooray Aquifer and Equivalents



Map 44

Cadna-owie – Hooray Aquifer—Fluoride

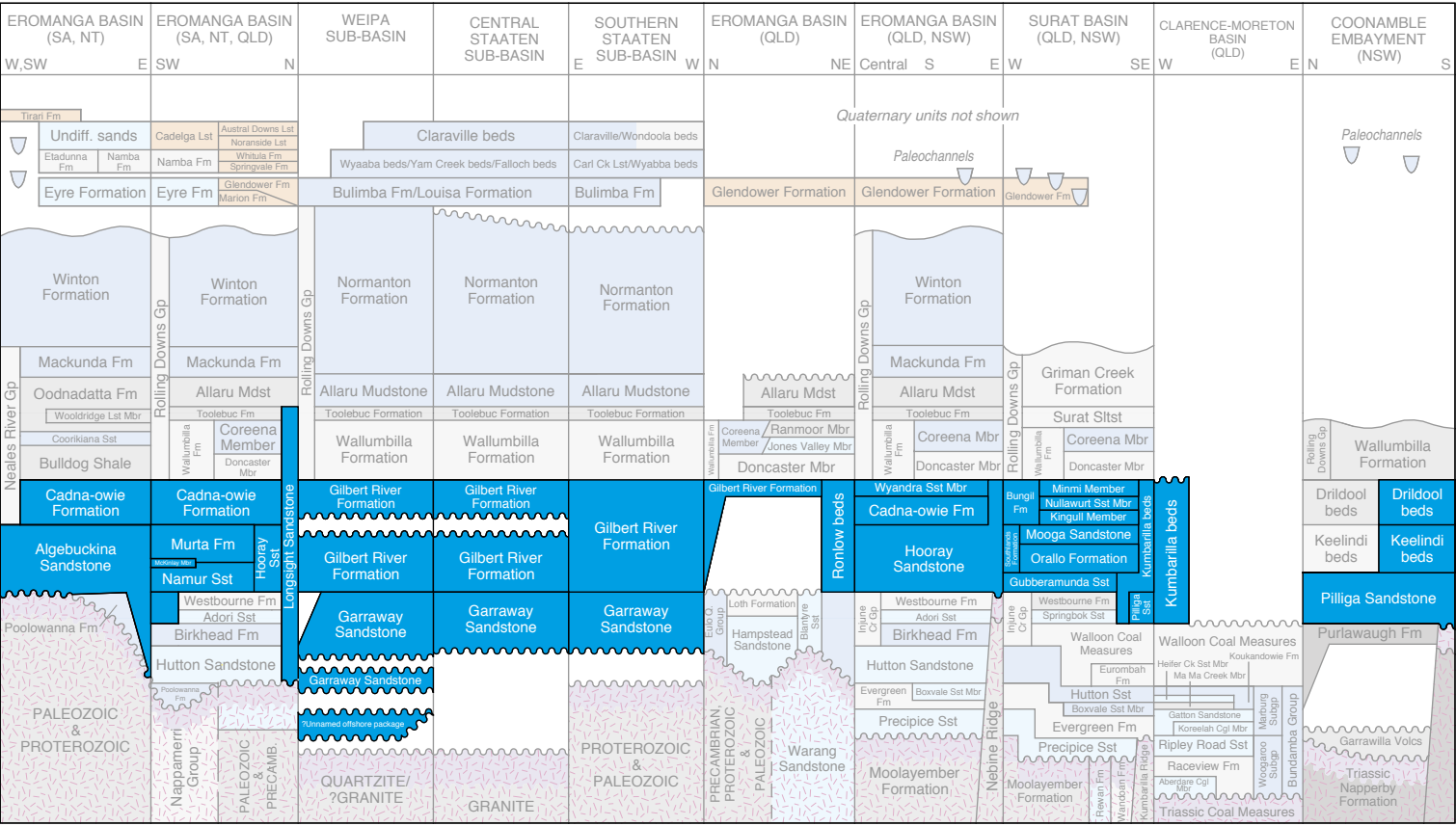
Low fluoride concentrations are found in all the recharge zones: the northern Eromanga Sub-basin; the northern Eulo-Nebine Ridge region; eastern Surat Sub-basin/Coonamble Embayment; and the western Eromanga Sub-basin.

In the Eulo-Nebine Ridge area, fluoride concentrations are low where the Westbourne and Birkhead aquitards thin or are absent, and is likely to be the result from mixing with lower fluoride groundwater from deeper aquifers. Further west, high levels of fluoride are found around the granitic basement outliers near Eulo Springs and extend further south towards the Yancannia Range. Similarly, high levels of fluoride are found on the northwestern extent of the Eromanga Sub-basin and the western margin against the Mt Isa basement terrain. The interpolated high fluoride concentrations north of the Eureka Arch into the Carpentaria Basin are based on little or no data and high prediction errors are associated with fluoride concentration in this area.

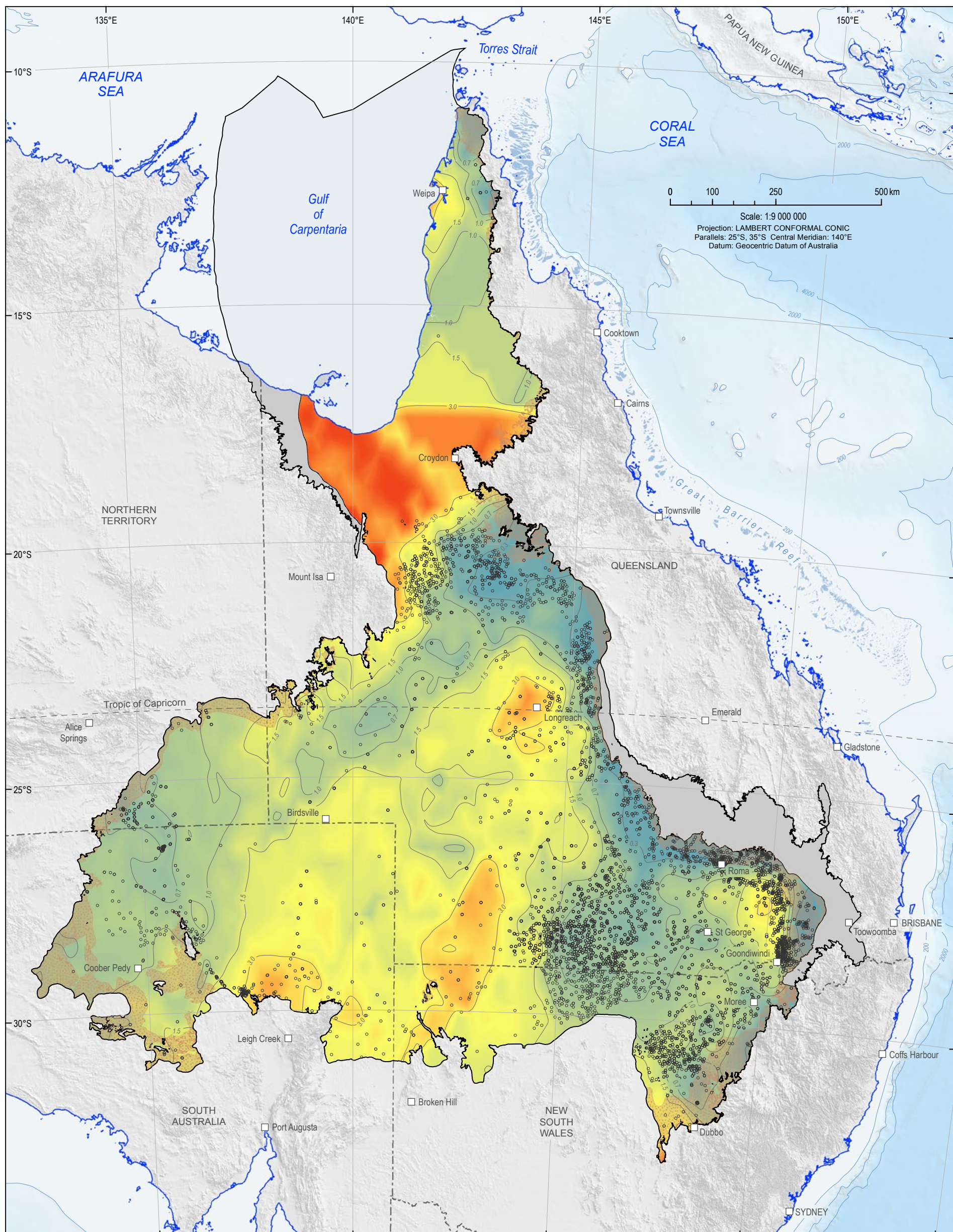
Parts of the Cadna-owie – Hooray Aquifer have fluoride levels greater than the NHMRC recommended drinking water guideline of 1.5 mg/L.

High fluoride concentrations in the artesian groundwater have been attributed to groundwater being in contact with igneous (hydrogeological basement) rocks or with clay minerals and micas.

The elevated fluoride concentrations in the eastern-part of the Surat Sub-basin have been previously attributed to mixing with groundwater from deeper aquifers along the Leichhardt-Burunga and Goondiwindi-Moonie Fault system¹⁵. Recent mapping has found these faults do not extend to any significant degree into the Surat Sub-basin sequence but basin folding during the Late Cretaceous resulted in reactivation of earlier structures and potential small-scale fracturing in the upper sequences¹⁶. While it is possible that there is connection between adjacent aquifers, an alternative explanation is that fluoride is released from the weathering of micas and clays within the source sediments. The northeastern boundary of the Surat Sub-basin is an area of low recharge and groundwater flow and the aquifer material has a volcanogenic sediment source. Weathering of the source material and conversion of kaolinite to illite would tend to release fluoride ions which could accumulate in the adjacent stagnant flow conditions of the Mimosa Syncline. A similarly high level of fluoride is observed down flowpaths from the northeastern recharge zones in the Eromanga Sub-basin in the Longreach Basement High and has been attributed to weathering of micas and facies control¹⁴.

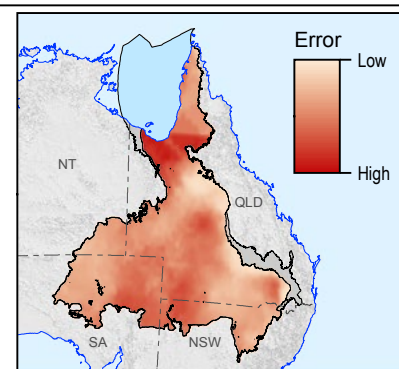
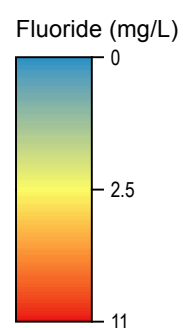


Cadna-owie – Hooray Aquifer and Equivalents



-  Great Artesian Basin
-  Cadna-owie – Hooray Aquifer and Equivalents
-  Recharge zone
-  Area of Great Artesian Basin where the hydrogeological unit does not exist

- Fluoride contour (mg/L)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
-  Groundwater sample location
-  City/town



Predicted value error map

14-8061-56

Map 45

Cadna-owie – Hooray Aquifer

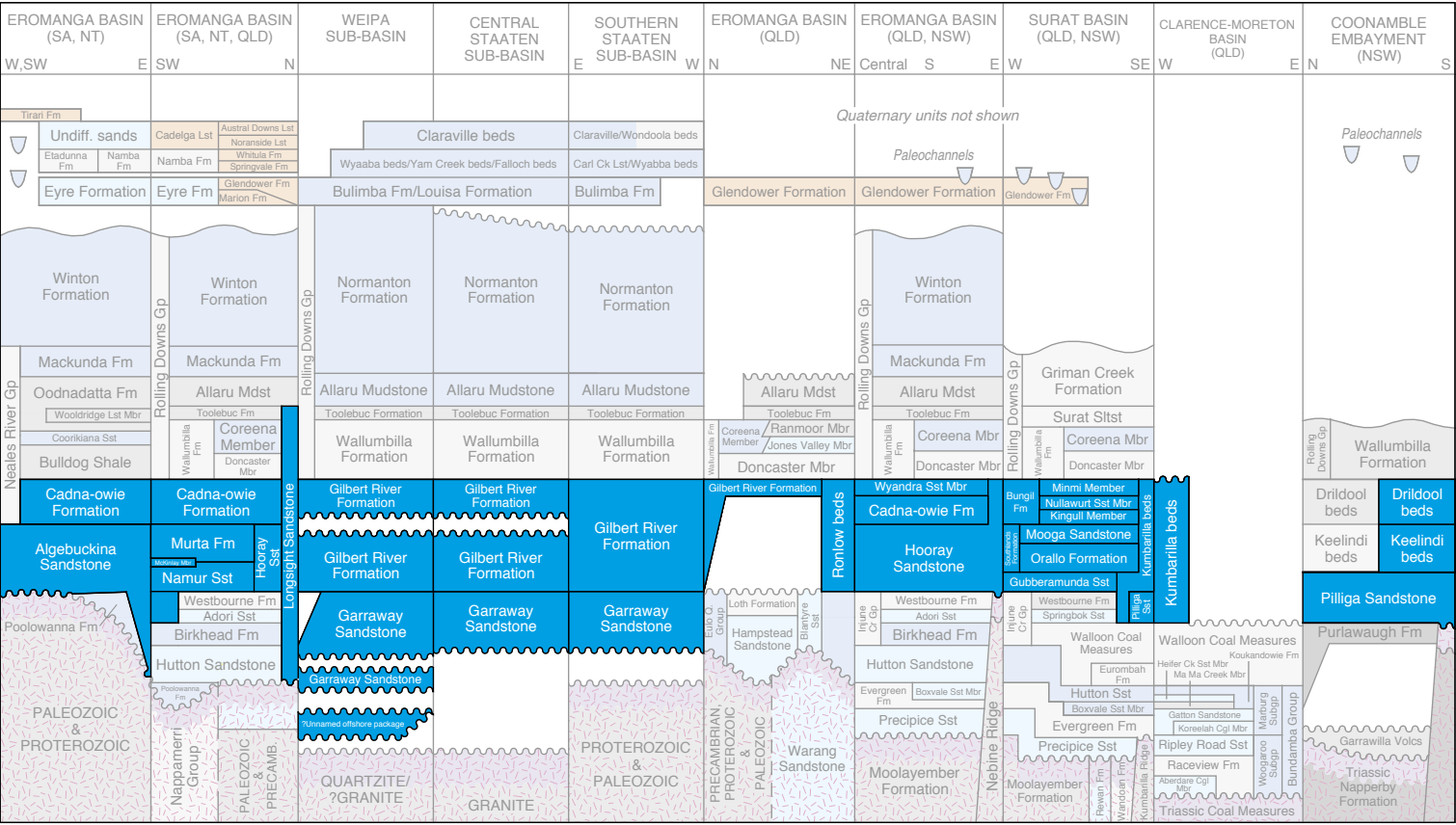
—³⁶Cl/Cl Ratio

Chlorine-36 (³⁶Cl) is a naturally-occurring radioisotope useful for understanding regional flow paths and can be used to determine flow rate and the age of groundwater. With a half-life of 300 000 years, chlorine-36 is an ideal tool for extensive groundwater systems such as the GAB.

High chlorine-36 values are present in all the major recharge zones: the northern Eromanga Sub-basin; the northern Eulo-Nebine Ridge region; eastern Surat Sub-basin/Coonamble Embayment; and the western Eromanga Sub-basin. These recharge zones identified by a high chlorine-36 signature are mirrored by low alkalinity concentrations (see Map 35).

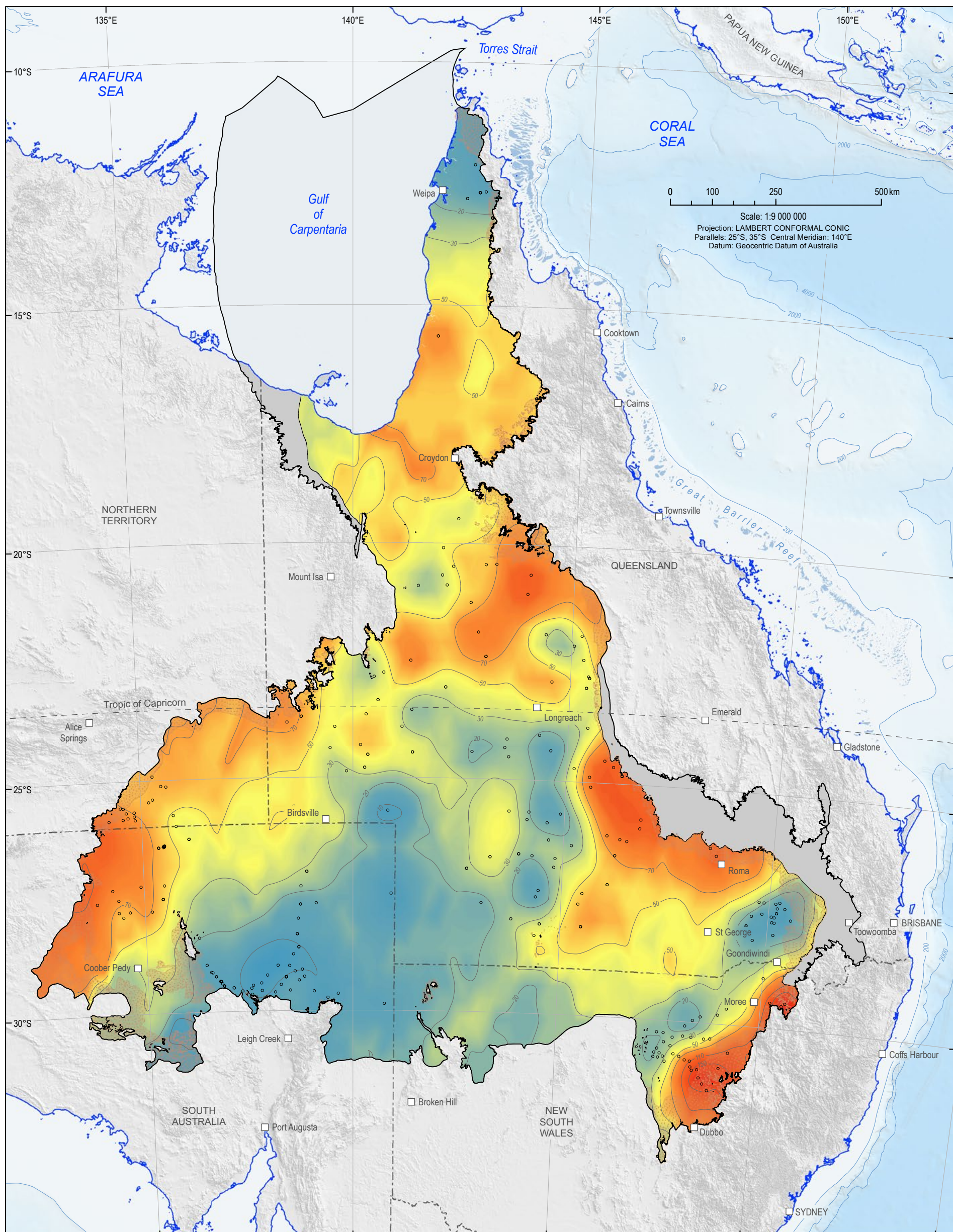
Low chlorine-36 values are found within the Mimosa Syncline of the Surat Sub-basin, the northern end of Cape York, and the central and southern parts of the Eromanga Sub-basin. The presence of highly-depleted chlorine-36 values adjacent to the recharge zone in the northeastern Surat Sub-basin suggest that groundwater flow rates in this region are very slow.

Data density for chlorine-36 analysis is much lower than all other chemistry parameters mapped in this Atlas and there are a number of significant data gaps. One critical data gap is in the northeastern recharge zone of the Surat Sub-basin across the Kumbarilla Ridge. There is considerable uncertainty around the groundwater flow paths for this part of the Basin and further chlorine-36 measurements would assist with determining recharge zones and the flow regime in this region.



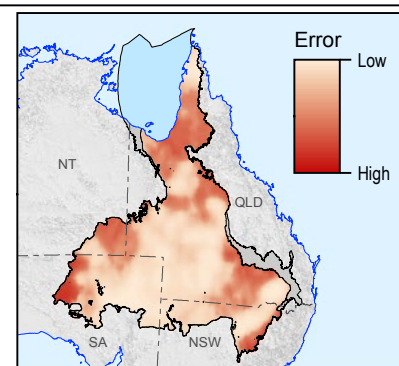
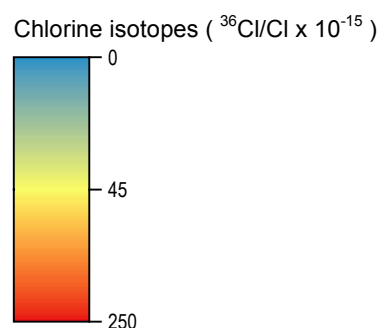
14-8061-31

 Cadna-owie – Hooray Aquifer and Equivalents



- Great Artesian Basin
- Cadna-owie – Hooray Aquifer and Equivalents
- Recharge zone
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Chlorine isotope contour ($^{36}\text{Cl}/\text{Cl} \times 10^{-15}$)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Groundwater sample location
- City/town



Predicted value error map

14-8061-57

Map 46

Cadna-owie – Hooray Aquifer

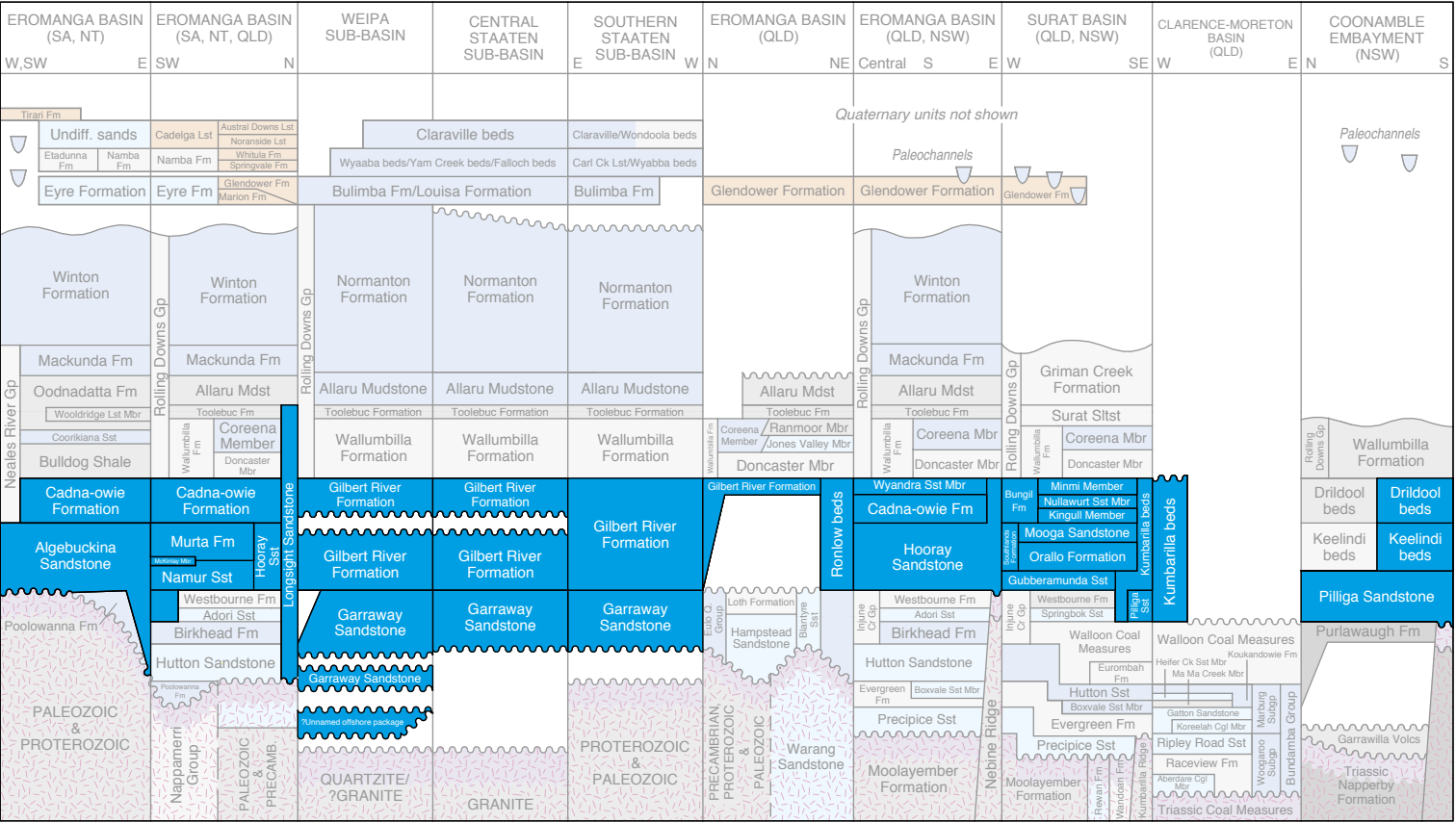
—Deuterium (²H Hydrogen)

Deuterium is the most conservative species in groundwater and indicates recharge phenomena and flow in the aquifer.

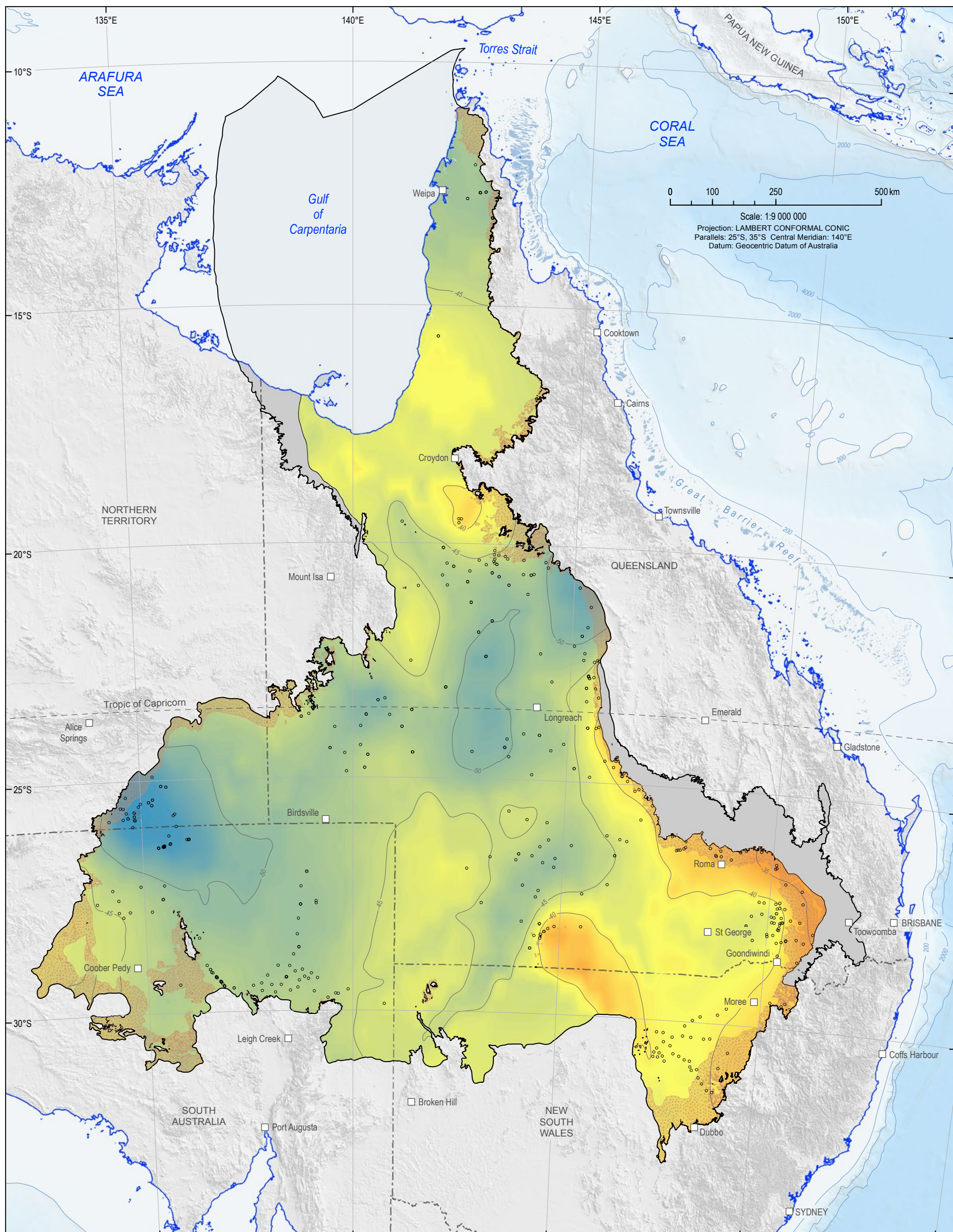
Recharge zones in the northeastern regions of the Eromanga Sub-basin have signatures typically less than -45 per mil (SMOW) and this is largely retained along basin-wide flowpaths through the Central Eromanga Depocentre or through the Poolowana Trough to discharge zones at the southern margins and western margins of the Eromanga Sub-basin. The Finke River groundwater recharge plume in the western Eromanga Sub-basin is an exception and has the lightest deuterium signature within the GAB. Recharge from the Finke River would only occur occasionally and the light signature suggests recharge primarily from monsoonal rainfall events and flooding with minimal evaporation¹⁴. Deuterium values in the Surat Sub-basin are enriched (> -45 per mil (SMOW)) in the eastern

recharge zone of the Coonamble Embayment. In contrast, the northeastern part of the Surat Sub-basin there is a rapid transition from >-35 per mil (SMOW) in the outcrop areas to less the < -40 per mil (SMOW) in the depocentre of the basin. In this part of the basin, there is a strong signature of methanogenesis found in the $\delta^{13}\text{C}$ of the dissolved inorganic carbon and reflected in the isotopic carbon-13 signature of the methane gas¹⁷.

A region of higher deuterium values is located on the central part of the Eulo-Nebine Ridge, coinciding with lower salinity. The Westbourne and Birkhead-Walloon aquitards thin or are absent in this region and the variation in deuterium is a likely response from mixing with groundwater from the deeper aquifers.



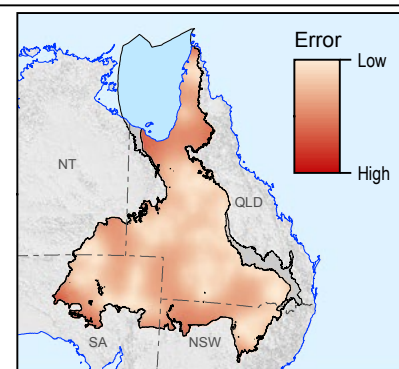
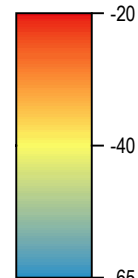
Cadna-owie – Hooray Aquifer and Equivalents



- Great Artesian Basin
- Cadna-owie – Hooray Aquifer and Equivalents
- Recharge zone
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Deuterium contour ($\delta^2\text{D}$ ‰ SMOW)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Groundwater sample location
- City/town

Deuterium ($\delta^2\text{D}$ ‰ SMOW)



Predicted value error map

14-8061-58

Map 47

Cadna-owie – Hooray Aquifer

—Oxygen-18 (¹⁸O)

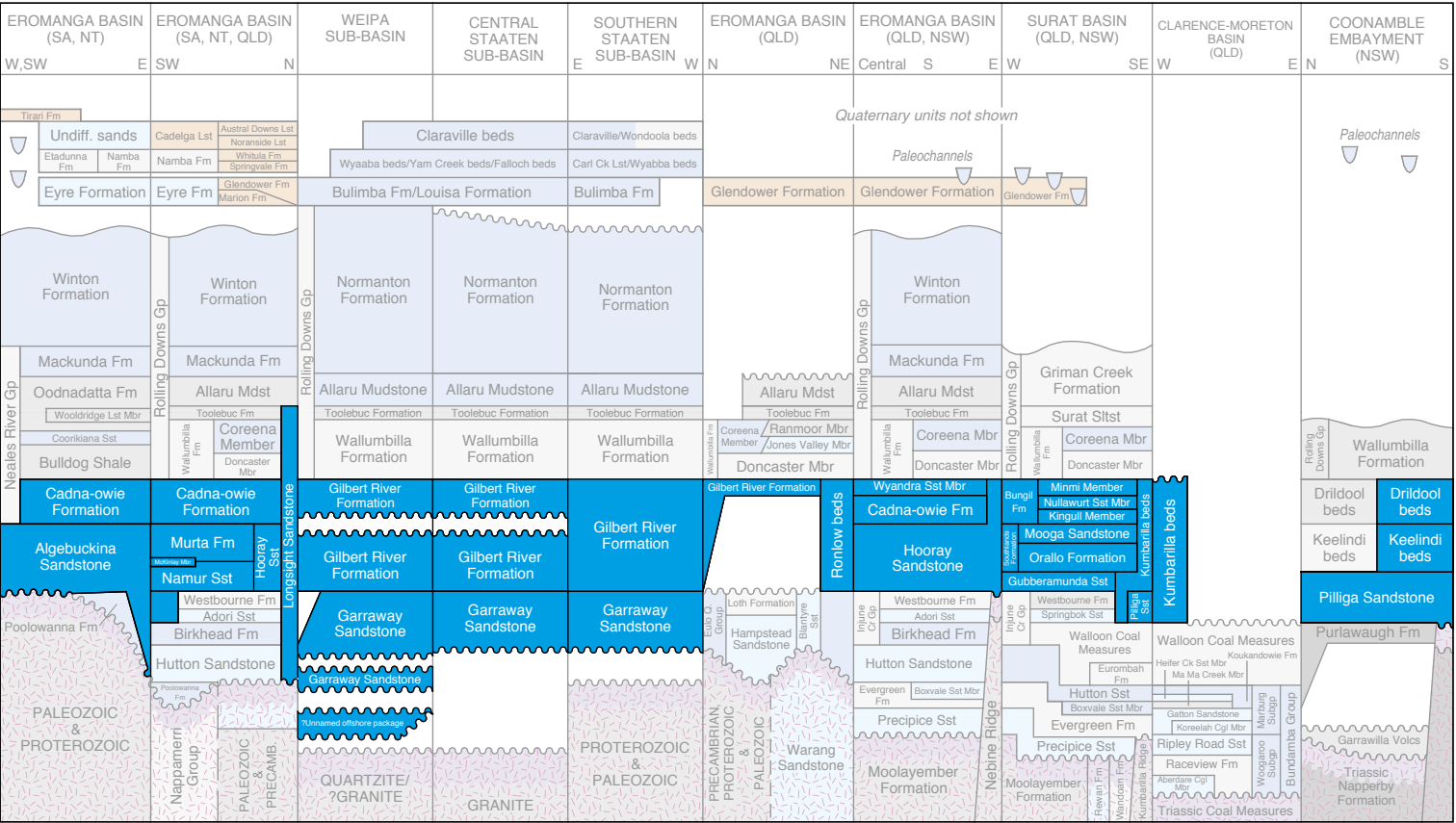
The oxygen-18 values broadly mirror corresponding deuterium values and ratios between the two parameters generally indicate a groundwater signature consistent with a slightly-evaporated rainfall signal.

Recharge zones in the northern and northeastern regions of the Eromanga Sub-basin have signatures typically less than -7 per mil (SMOW) and this is largely retained along basin-wide flow paths through to the Poolowana Trough to discharge zones at the southern margins. Unlike the pattern for deuterium, the consistency of the signature is not maintained from the eastern recharge zones, across the Eromanga Depocentre towards the southern margin. This could be potentially due to prolonged periods of water-rock interaction, due to very low groundwater flow rates in this deeper region.

In the low-alkalinity, high-salinity region of the southwestern Eromanga Basin, the oxygen-18 has a significantly less-depleted signature. The deuterium and oxygen-18 ratios in this region exhibit a strongly evaporative signal, which is consistent with the accumulation of saline groundwater. The Finke River groundwater recharge plume in the western Eromanga Sub-basin is overprinted in this region and has the effect of depleting the groundwater oxygen-18. Recharge from the Finke River

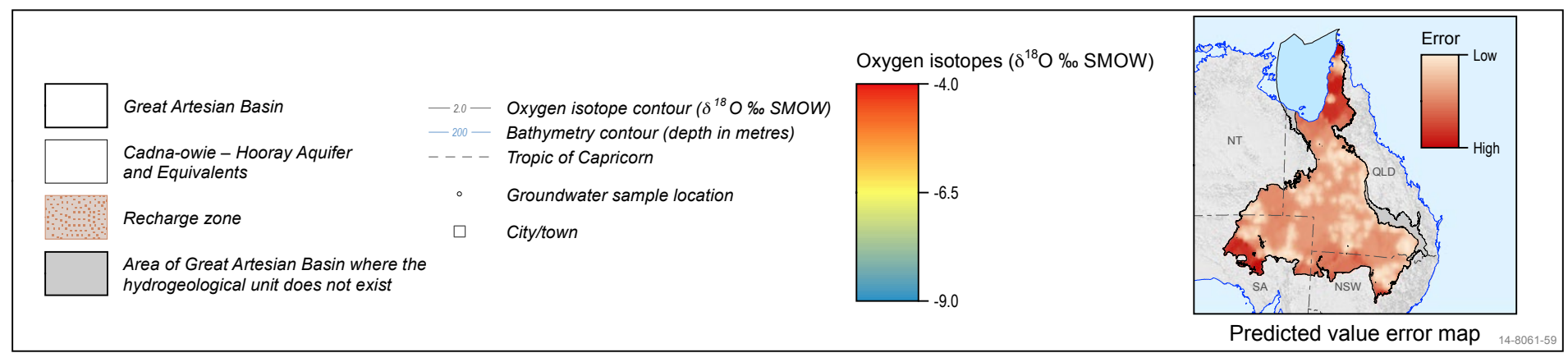
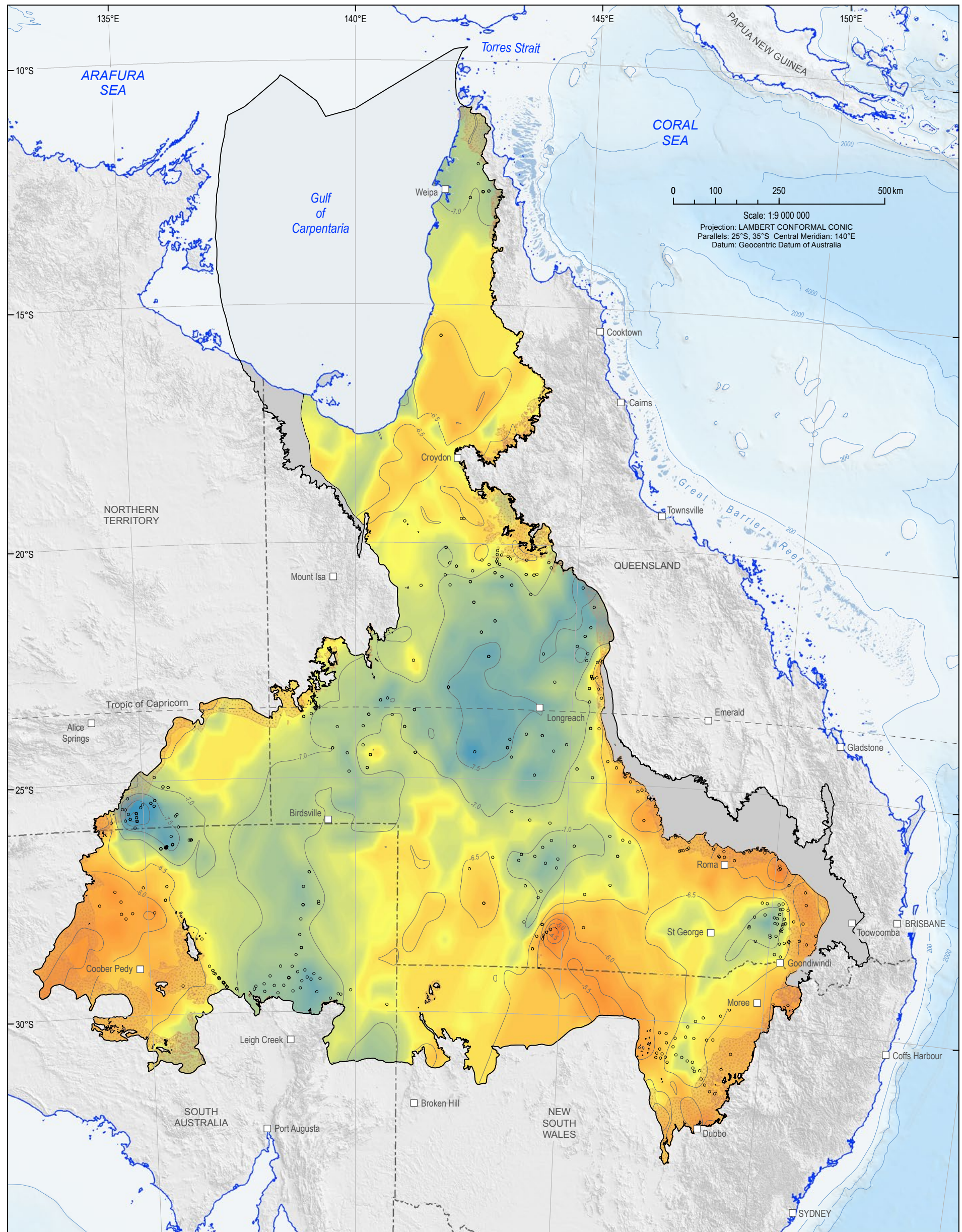
would only occur occasionally and the depleted signature suggests recharge primarily from monsoonal rainfall events and flooding with minimal evaporation.

An inverse of the typical relationship is observed in the northeastern corner of the Surat Sub-basin. Here the groundwater has an isotopically depleted signature compared to the adjacent outcrop areas to the north and east. Water isotope ratios are unusual in this deeper, low-flow region and plot to the left of Local and Global Meteoric Water Lines. The isotopic signature is consistent with microbial CO₂ reduction to methane (methanogenesis), which is reflected by the presence of methane gas in the groundwater with a carbonate reduction isotopic signature. Methanogenesis preferentially uses hydrogen from water molecules and this enriches the residual water in deuterium¹⁸. An additional contributor could be the formation of clays by hydrolysis of feldspars and lithic fragments in the host sandstone, which would leave the residual fluid depleted in oxygen-18 and enriched in deuterium¹⁹.



14-8061-31

Cadna-owie – Hooray Aquifer and Equivalents



Map 48

Cadna-owie – Hooray Aquifer

—Carbon-13 (¹³C)

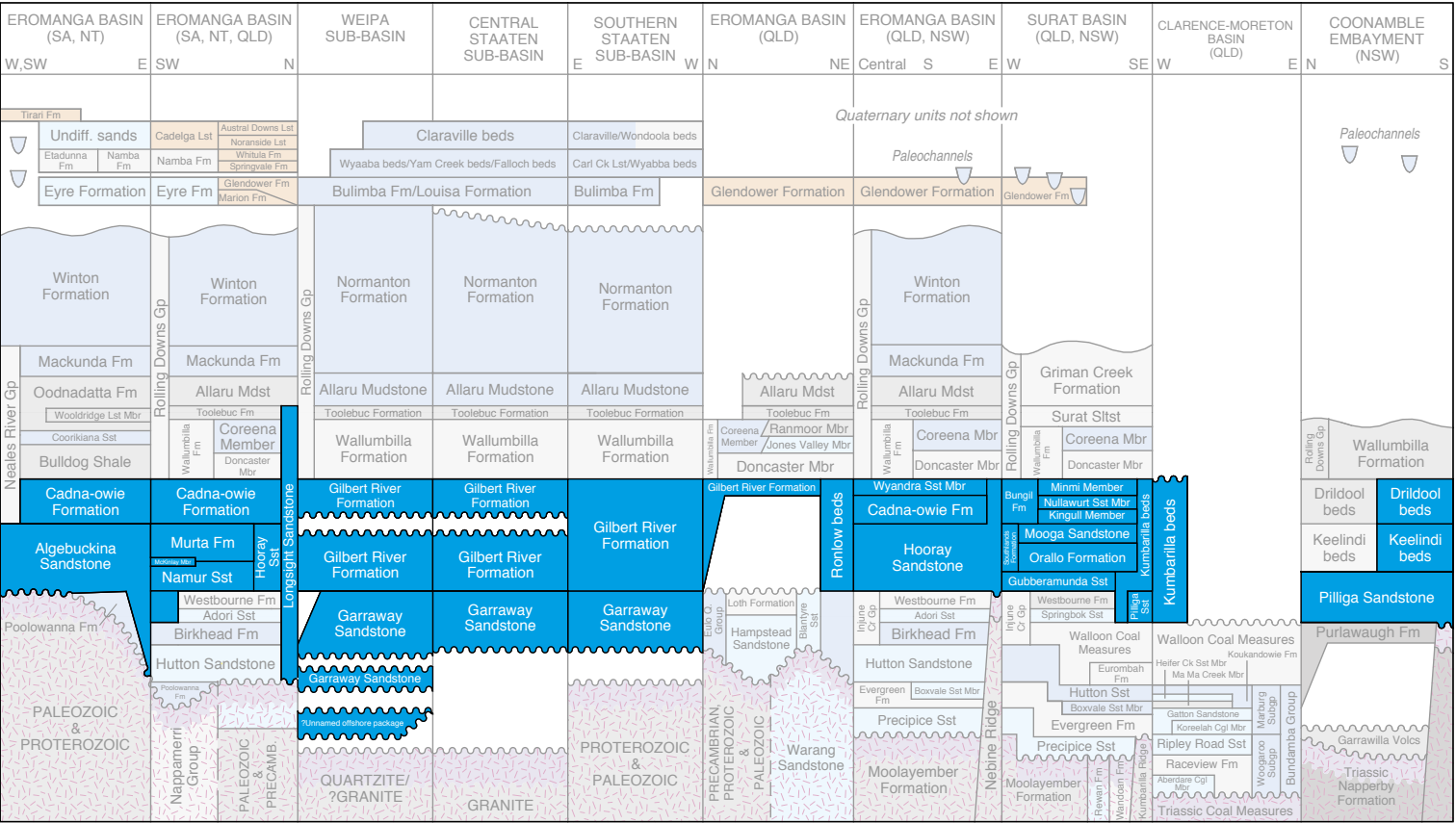
More negative $\delta^{13}\text{C}$ values are found in the recharge zones, increasing to less negative values along regional groundwater flow paths. Weakly negative to positive values are found in regions where biological reduction of carbonate to methane is prevalent.

There is considerable regional variation in $\delta^{13}\text{C}$ values with depleted isotopic values in the recharge zones (< -15 ‰ Pee Dee belemnite (PDB)) of the eastern Eromanga Sub-basin progressing to more enriched values along groundwater flow paths. Isotopically very light values are found in the recharge beds around Tambo and Torrens Creek on the eastern margin and in Cape York in the northernmost extent of the GAB. The highly negative values suggest there is little dissolution of carbonate minerals in these regions and $\delta^{13}\text{C}$ values are dominated by the influence of soil CO_2 .

In the central and western margins of the Eromanga Sub-basin the $\delta^{13}\text{C}$ values typically range from -5 to -10 ‰ PDB. Enriched values are observed adjacent to the northwestern recharge zones of the Eromanga Sub-basin where the Longsight Sandstone outcrops against Cambro-Ordovician rocks, dominantly carbonate, of the Georgina Basin. Enriched values are also found at the western margin against the Mt Isa basement terrain.

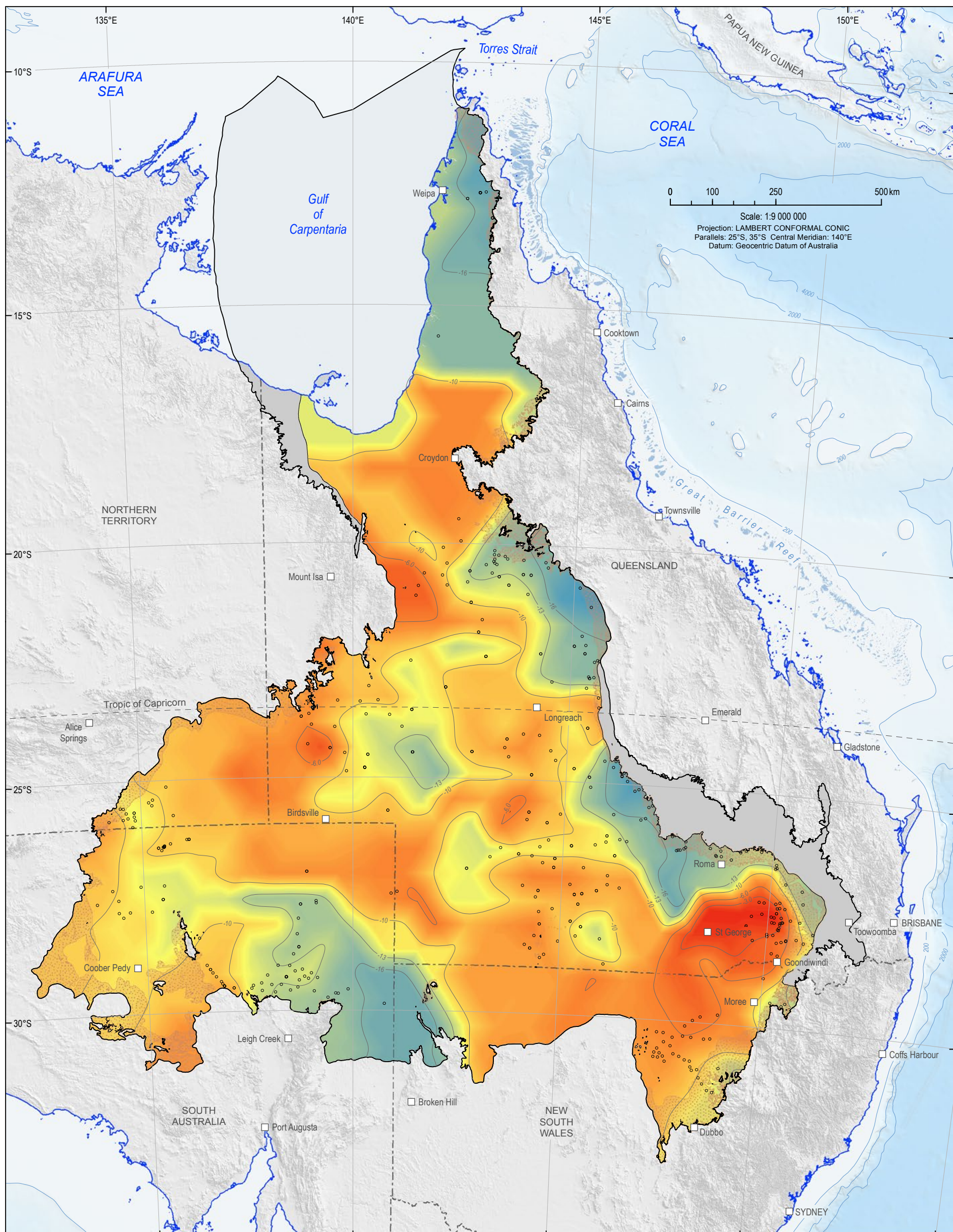
A large region of isotopically depleted $\delta^{13}\text{C}$ is found on the southern margin of the aquifer from Lake Frome Embayment to Lake Eyre. This is unexpected given the regional flow patterns and the general enrichment of $\delta^{13}\text{C}$ down groundwater flow paths. Typically, isotopically depleted $\delta^{13}\text{C}$ is found in recharge zones. It suggests there is significant mixing in this region with very old groundwater (based on the chlorine-36) with a more depleted $\delta^{13}\text{C}$ signature.

A region of highly enriched $\delta^{13}\text{C}$ is found in the deeper, central part of the Surat Sub-basin. Values here range from -3 to +2 ‰ and are due to bacterial CO_2 reduction, where $^{12}\text{CO}_2$ is preferentially used over $^{13}\text{CO}_2$ resulting in an enrichment of $^{13}\text{CO}_2$ in the dissolved inorganic carbon. The higher $\delta^{13}\text{C}$ signal in the groundwater is supported by the unusual shift in water isotope ratios (see Maps 46 and 47) and the presence of methane gas with a carbonate reduction signature. Consistent with the low alkalinity measurements, the presence of groundwater with a $\delta^{13}\text{C}$ signature typical of recharge, in the northeastern corner of the Surat Sub-basin, suggests that the elevated level of salinity in the region is due to low aquifer permeability and low recharge rates, rather than vertical leakage from deeper formations.



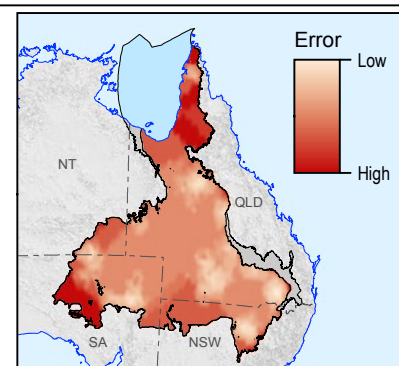
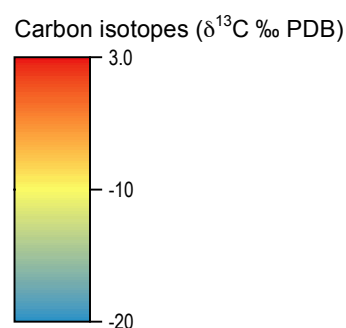
14-8061-31

Cadna-owie – Hooray Aquifer and Equivalents



- Great Artesian Basin
- Cadna-owie – Hooray Aquifer and Equivalents
- Recharge zone
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- Carbon isotope contour ($\delta^{13}\text{C}$ ‰ PDB)
- Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Groundwater sample location
- City/town



Predicted value error map

14-8061-60

Map 49

Adori-Springbok Aquifer—Alkalinity

The Adori-Springbok Aquifer generally shows low to moderate alkalinity levels except for the Central Eromanga Depocentre.

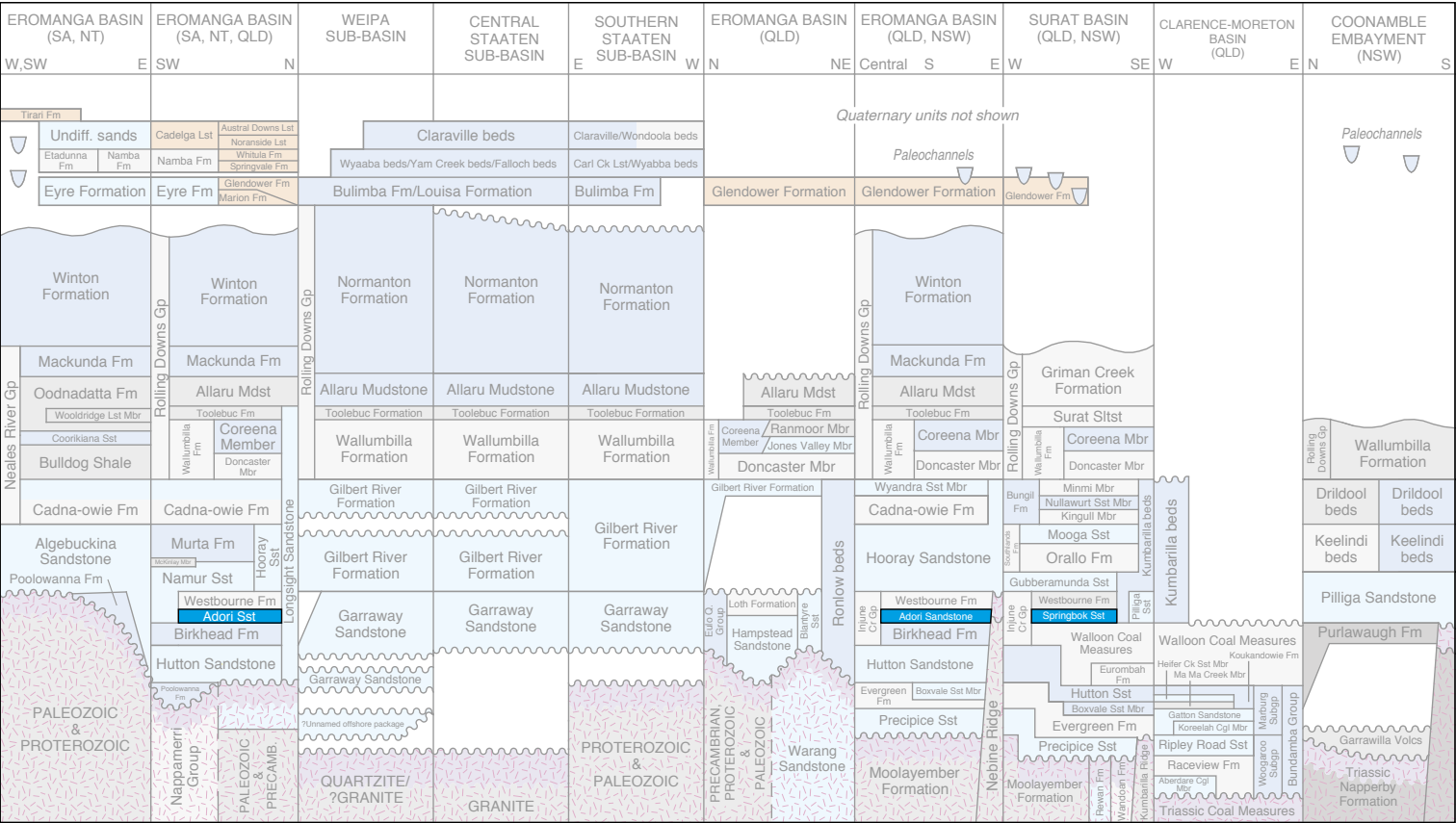
Areas of low alkalinity (<300 mg/L) are restricted to the recharge zones along the eastern margins of the Eromanga Sub-basin, the northeastern margin of the Surat Sub-basin, across the Eulo-Nebine Ridge area and the northern Eromanga Sub-basin.

Within the Eromanga Sub-basin, the groundwater is characterised by low alkalinity in the east, and increasing alkalinity down flow paths towards the Central Eromanga Depocentre. The low alkalinity centred on the Eulo-Nebine Ridge is likely due to enhanced recharge and greater throughflow of groundwater from the eastern margin of the basin.

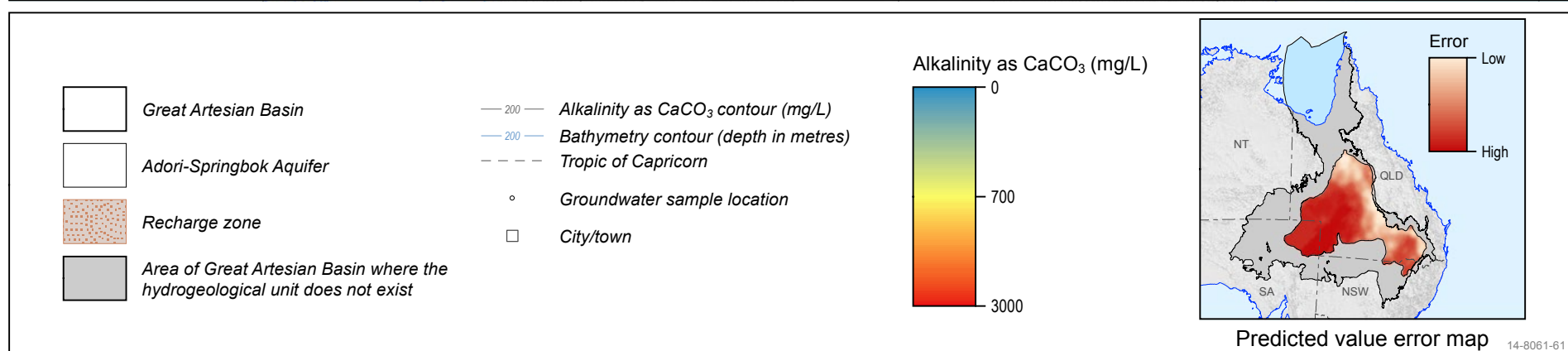
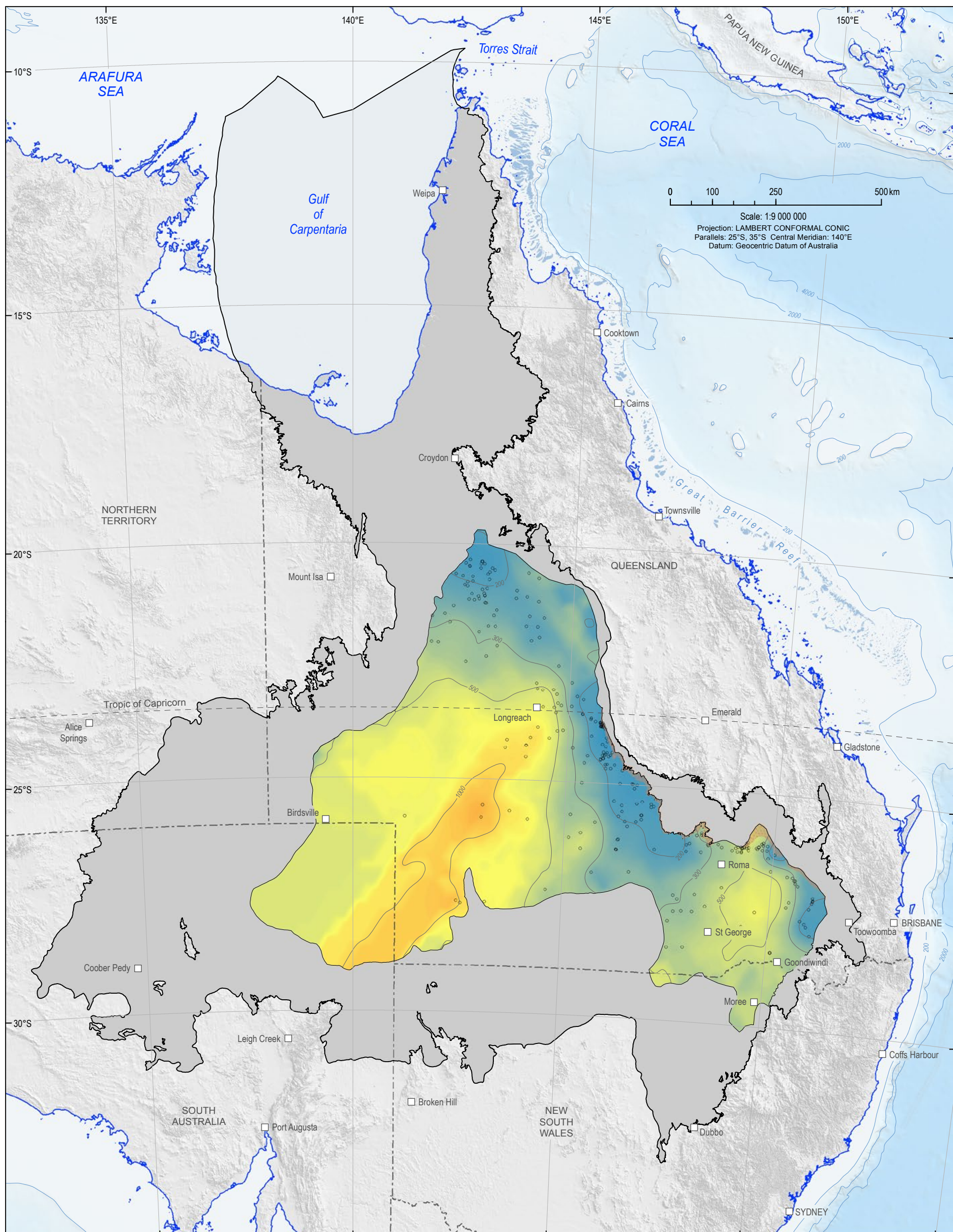
Low alkalinity at the northern extent of the Adori-Springbok Aquifer may be explained by vertical flow from the underlying Hutton Aquifer along the Cork Fault or mixing with the overlying Cadna-owie – Hooray Aquifer. The Cadna-owie – Hooray and Adori aquifers merge northward of this region.

Elevated alkalinity values are observed proximal to a portion of the northern recharge zone in the Surat Sub-basin, which may be attributed to either low aquifer permeability and recharge rates, or potential mixing with the deeper higher-alkalinity groundwater from the underlying Walloon Coal Measures.

In contrast to the Hutton Aquifer, recharge to the Adori-Springbok Aquifer on the eastern margin of the Surat Sub-basin is significant, based on the low alkalinity values.



 Adori-Springbok Aquifer



Map 50

Adori-Springbok Aquifer—Total Dissolved Solids

The salinity of the Adori-Springbok Aquifer shows significant regional variability. Measured values range from 150 mg/L to over 2 500 mg/L.

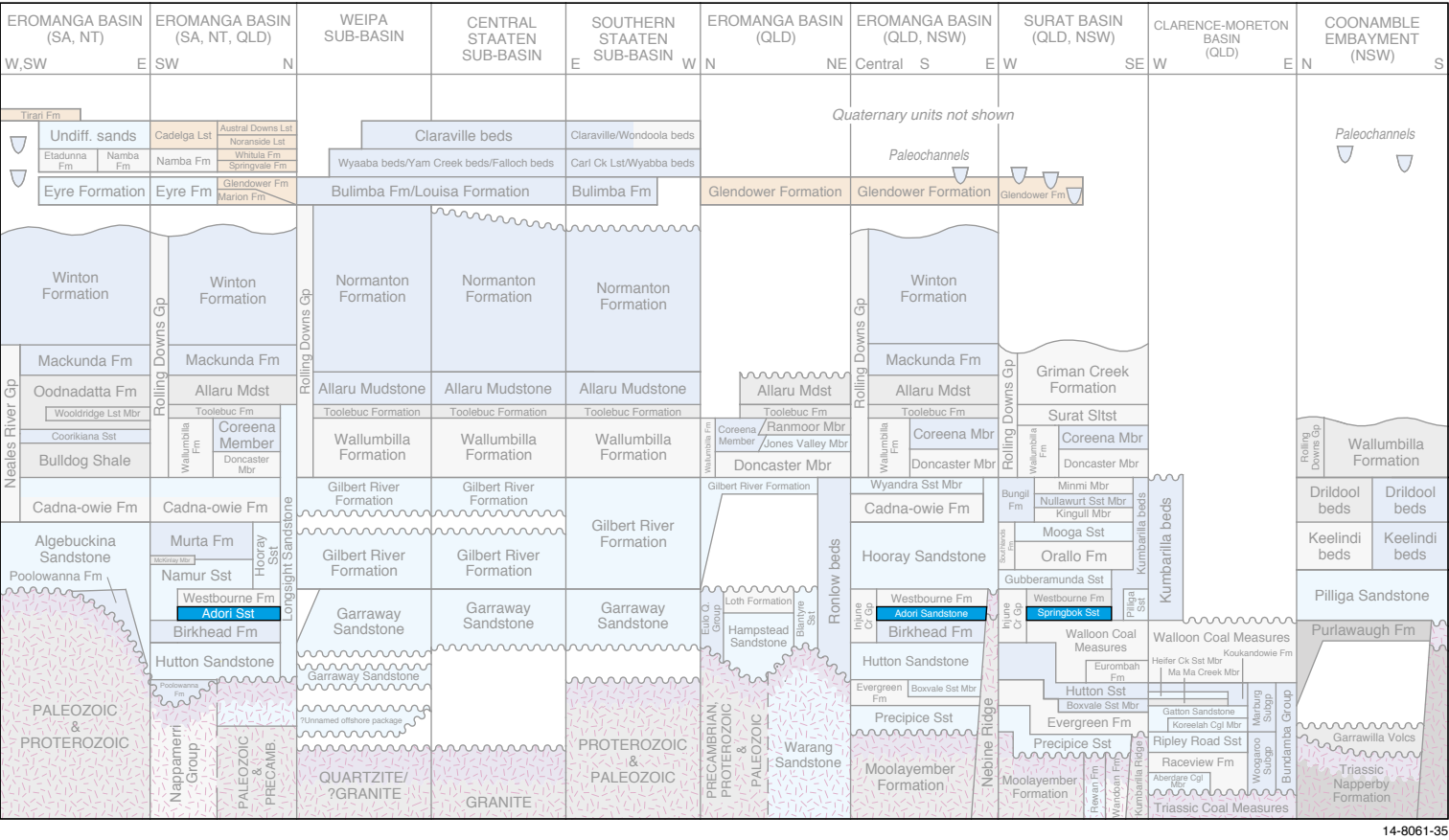
Within the Eromanga basin, the groundwater is characterised by low salinity in the east, and increasing salinity down flowpaths towards the Central Eromanga Depocentre. The low salinity centred on the Eulo-Nebine Ridge is likely due to enhanced through flow of recharge waters from the eastern margin of the basin.

Large portions of fresh groundwater occur to the north and along the eastern margin of the Eromanga Sub-basin. Brackish regions are dominant in the northeast of the Surat Sub-basin and to the west toward the Central Eromanga Depocentre.

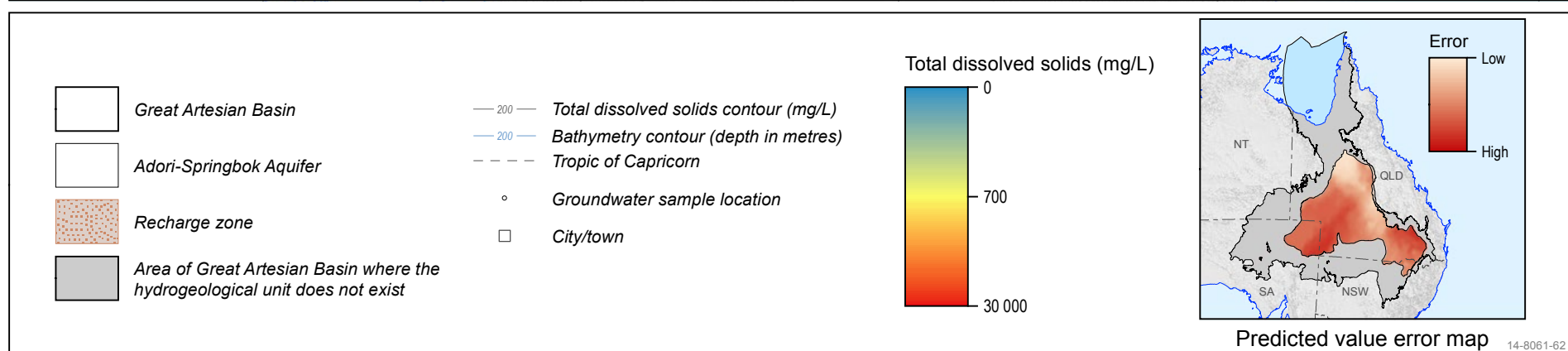
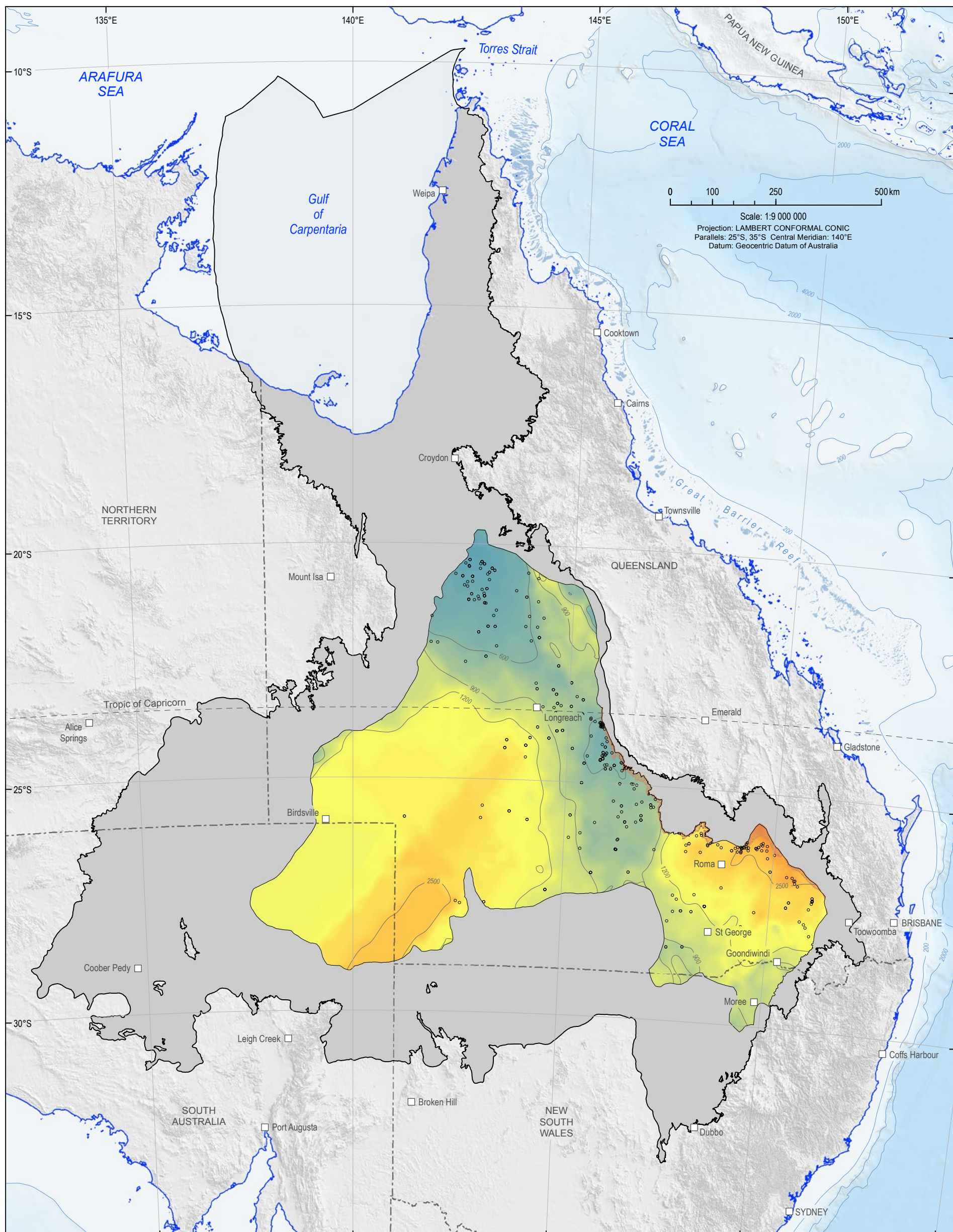
The fresh groundwater in the northern portion of the Adori-Springbok Aquifer may be explained by vertical flow from the underlying Hutton Aquifer along the Cork Fault or recharge from the overlying Cadna-owie – Hooray Aquifer. The Cadna-owie – Hooray and Adori aquifers merge northward of this region.

The Springbok Sandstone is the equivalent of the Adori Sandstone in the Surat Sub-basin. Similar to other aquifers in the Surat Sub-basin, brackish salinity values are observed proximal to the northern recharge zones. In this region of the Surat Sub-basin, groundwater from the Springbok Sandstone is often indistinguishable from the overlying Westbourne Formation. Groundwater for this region has a strong chloride signal, which is absent from the Walloon Coal Measures for this part of the Basin, suggesting a strong influence from mixing or ion diffusion from the Westbourne Formation.

Higher salinity along the northeastern margin of the Surat Sub-basin is possibly a consequence of mixing with more saline groundwater from the underlying Walloon Subgroup (particularly the upper Jundah Coal Measures) and the overlying Westbourne Formation. Apart from the upper Rolling Downs Aquitard, the Jundah Coal Measures contain some of the most saline groundwater within the Surat Sub-basin.



Adori-Springbok Aquifer



Map 51

Hutton Aquifer and Equivalents—Alkalinity

To the southwest in the Eromanga Sub-basin, the Hutton Sandstone transitions laterally into the Algebuckina Sandstone. The Algebuckina Sandstone extends to the western margin and has a common lateral connection with both the Hutton and Cadna-owie – Hooray aquifers. Water chemistry associated with the Algebuckina Sandstone has been assigned to the Cadna-owie – Hooray Aquifer.

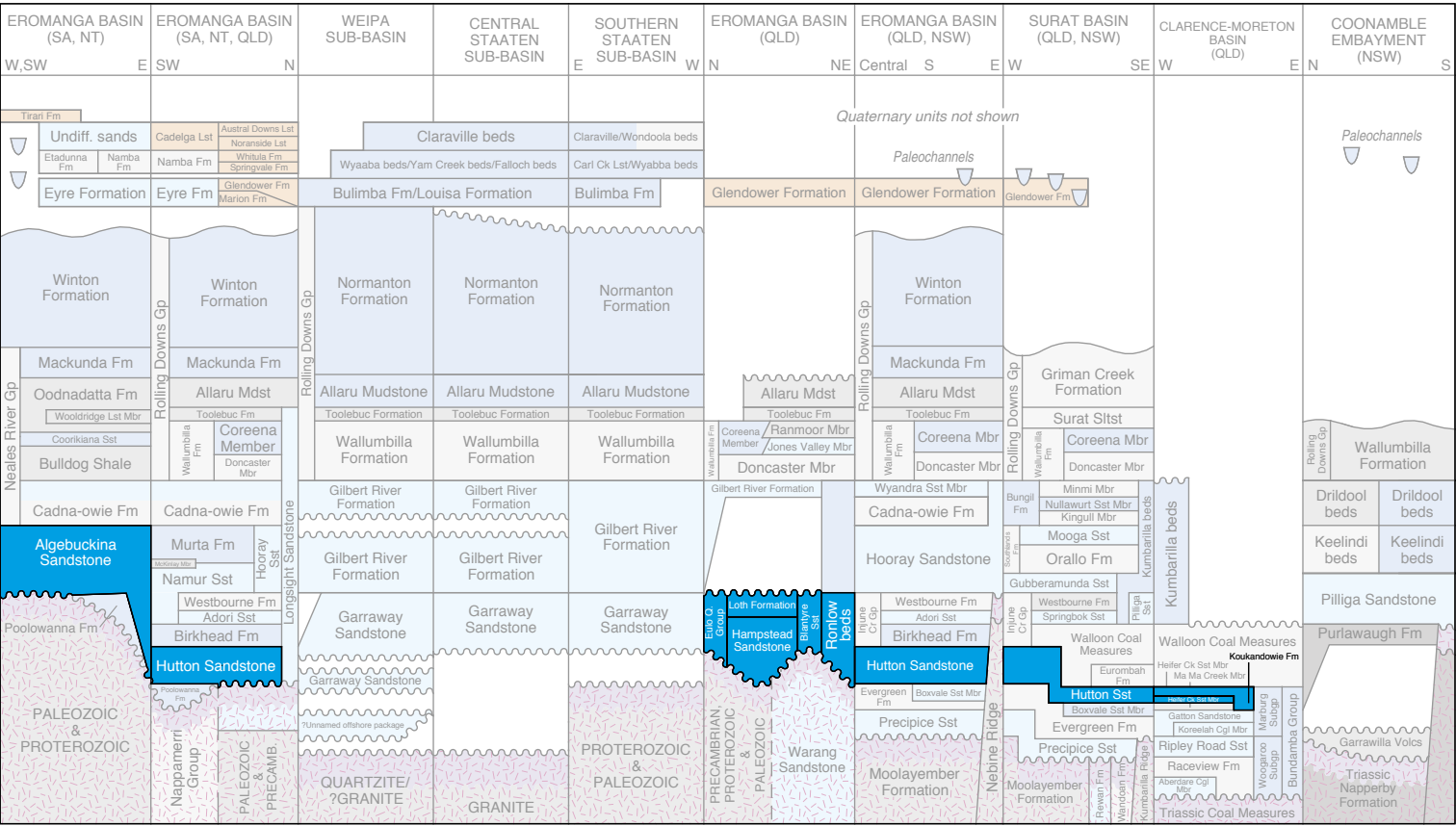
Large regions of the Hutton Aquifer, away from the eastern recharge zone, show elevated alkalinity levels.

Areas of low alkalinity (<300 mg/L) are restricted to the recharge zones along the eastern margins of the Eromanga Sub-basin, the northern extent of the Surat Sub-basin, across the Eulo-Nebine Ridge area and the northern Eromanga Sub-basin. The low alkalinity centred on the Eulo-Nebine Ridge is likely due to enhanced through flow of recharge waters from the eastern margin of the basin. The Warrego River is thought to be a prominent source of localised recharge to the outcropping Hutton Aquifer in this region.

The majority of the Surat Sub-basin has alkalinity values greater than 500 mg/L with a large portion in the central part of the sub-basin greater than 1000 mg/L. The central and western parts of the Eromanga Sub-basin have alkalinity values greater than 500 mg/L. The progressive increase of alkalinity from the north to the south in the Surat Basin and from the eastern

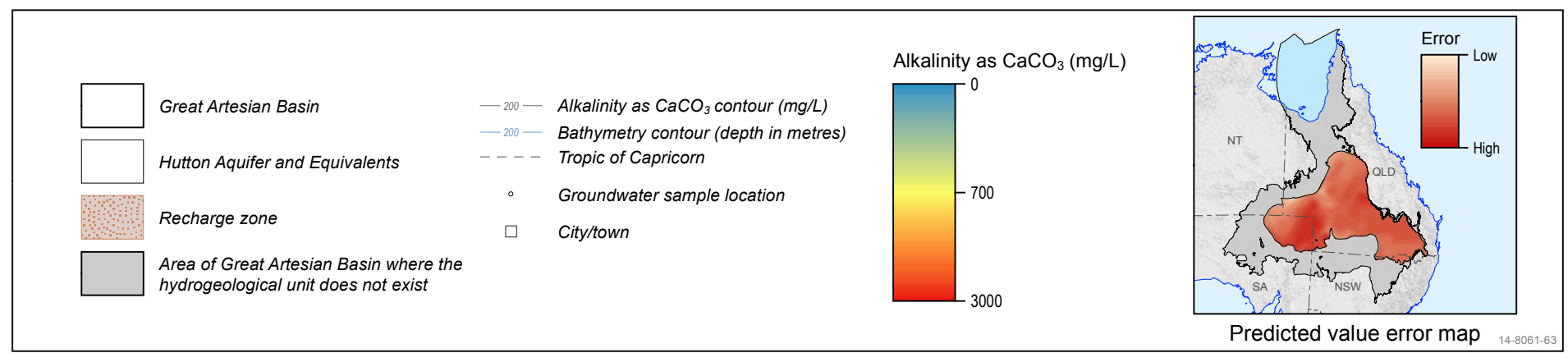
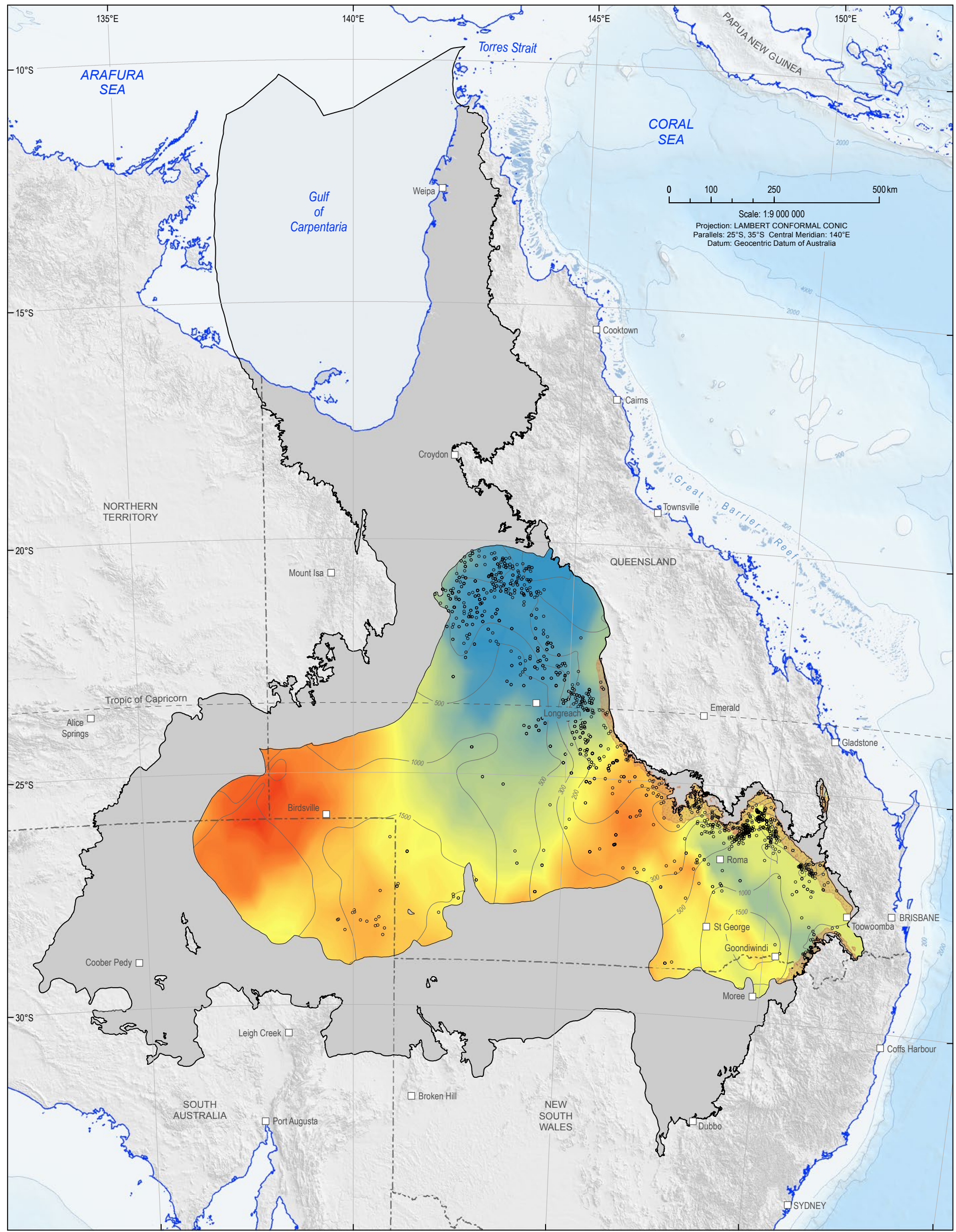
recharge zones to the southwest in the Eromanga Sub-basin suggests hydrochemical evolution along regional flow paths. An additional contribution to the high alkalinity accumulated in the Central Eromanga Depocentre is the decomposition of organic matter (oil and conventional gas accumulations are present within the Hutton Aquifer in this region). High alkalinity (>1000 mg/L) is observed in the vicinity of the Mimosa Syncline which coincides with a strongly depleted chlorine-36 isotope signature (see Map 53), suggesting that this may be a region of low flow, verging on stagnation. High levels of biogenic methane are found in this part of the sub-basin due to the reduction of dissolved inorganic carbon¹⁷.

Northwards toward the Euroka Arch (see Map 5), there is direct hydraulic connection between the Hutton Aquifer and the overlying Cadna-owie – Hooray Aquifer as both Birkhead-Walloon and Westbourne aquitards wedge out and are absent over this basement high. This is a region of relatively high rainfall and recharge resulting in low alkalinity.



14-8061-67

 Hutton Aquifer and Equivalents



Map 52

Hutton Aquifer and Equivalents—Total Dissolved Solids

The Hutton Aquifer contains a large amount of fresh groundwater in the eastern Eromanga Sub-basin. Brackish groundwater regions dominate the Central Eromanga Depocentre and almost the entire Surat Sub-basin.

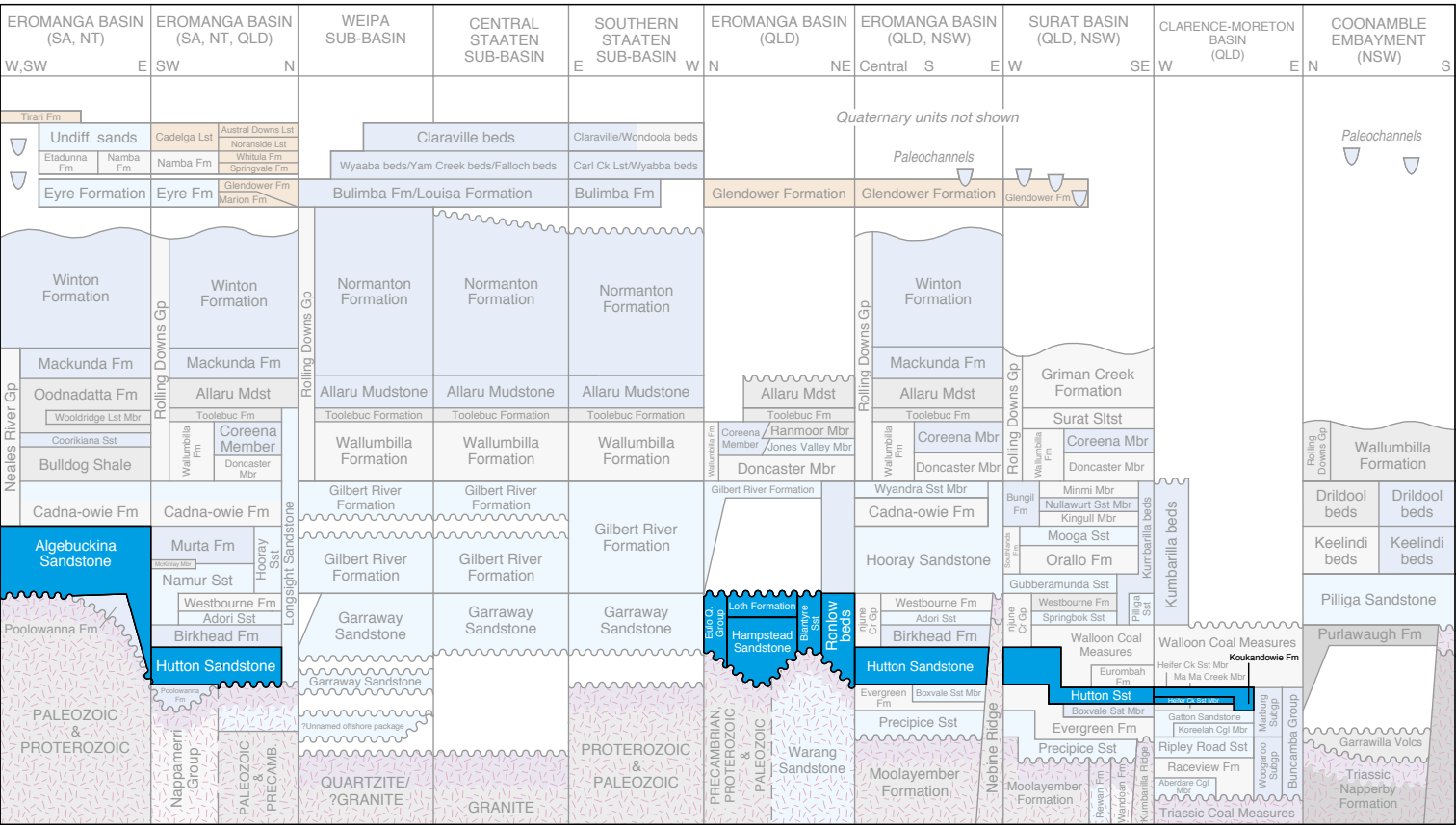
The salinity values show significant regional variability. Measured TDS values range from less than 100 mg/L to more than 2500 mg/L.

Within the Eromanga Sub-basin, groundwater is characterised by low salinity in the east, increasing in salinity down flowpaths towards the Central Eromanga Depocentre. The low salinity centred on the Eulo-Nebine Ridge is likely due to enhanced through flow of recharge waters from the eastern margin of the basin. The Warrego River is thought to be a prominent source of localised recharge to the outcropping Hutton Aquifer in this region²⁰.

In the Surat Sub-basin, brackish groundwater is observed in and proximal to the northern recharge zones, except for outcrop areas near Taroom and further west of Injune. High recharge rates have been measured near Injune but low rates of recharge extend further east towards the north of Dalby. Similar to the Cadna-owie – Hooray Aquifer, the Hutton Aquifer in this region has low permeability and contains clays and interbedding of siltstones and mudstones²⁰. Interestingly a one metre thick band of halite has been recorded in the Hutton Sandstone in

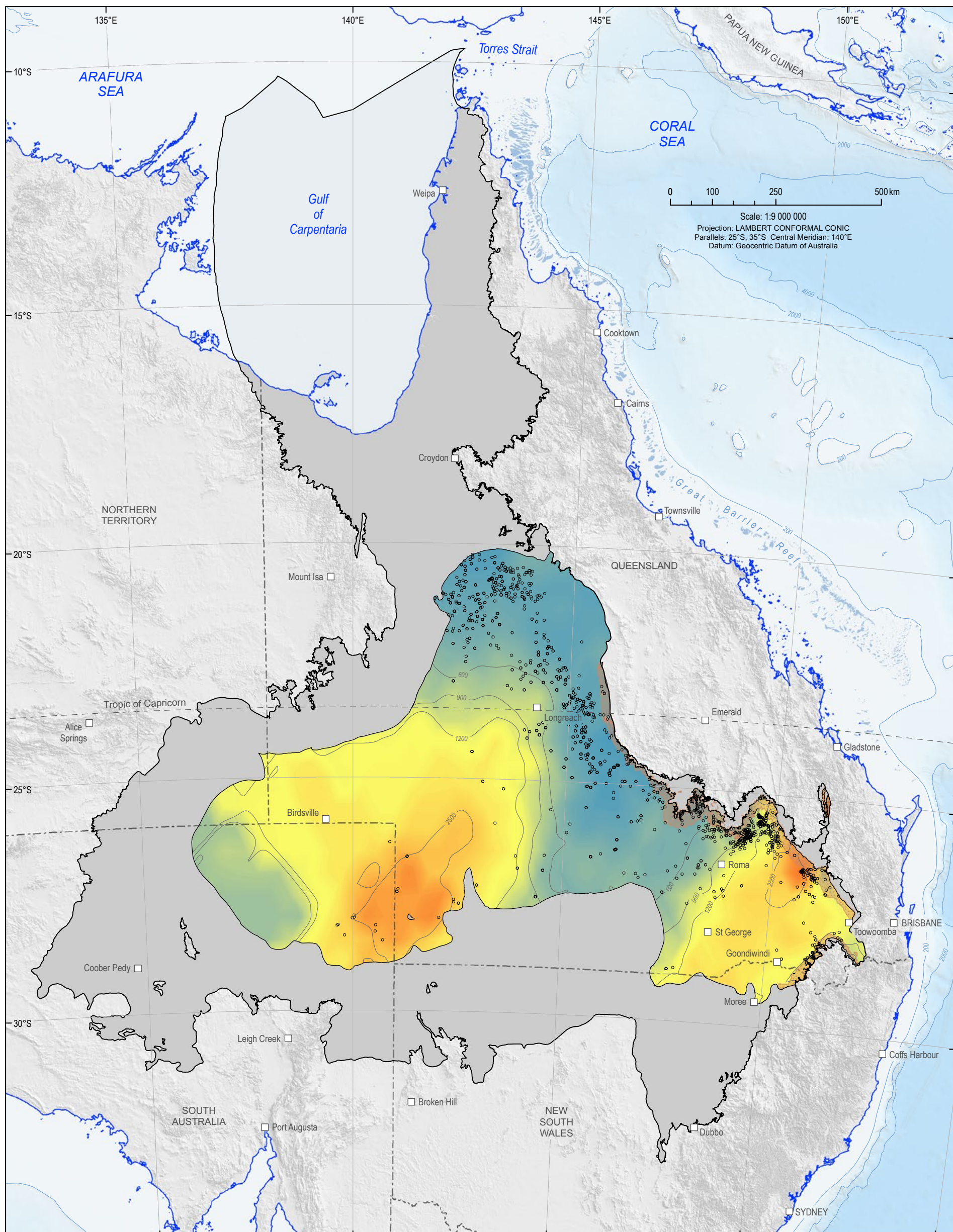
a cave near Jandowae in this near eastern corner. It is unknown how laterally extensive the halite is and whether it contributes significantly to the elevated Na-Cl signature in the region²¹. Regional flow dynamics are not well understood within the Hutton Aquifer and this northern region may be subject to stagnant flow conditions.

Salinity is highest near the northeastern Surat Sub-basin recharge zone (~150 km east of Roma), possibly due to a combination of the low recharge rates, presence of halite, and infiltration of more saline groundwater from overlying units (e.g. Walloon Coal Measures) in areas where the overlying Eurombah Formation (aquitard) is thin or absent. Additionally, diffusion of chloride ions is possible from the underlying Evergreen Formation, which is characterised by a fluvial and marginal to shallow-marine depositional environment. Sodium and chloride against bromide ratios tend towards seawater ratios at greater salinity levels within the Hutton Sandstone. This potential Evergreen Formation overprint on the Hutton Aquifer recharge water chemistry (i.e. low alkalinity and presence of elevated calcium, magnesium and sulphate) occurs in the northeastern region of the Surat Basin.



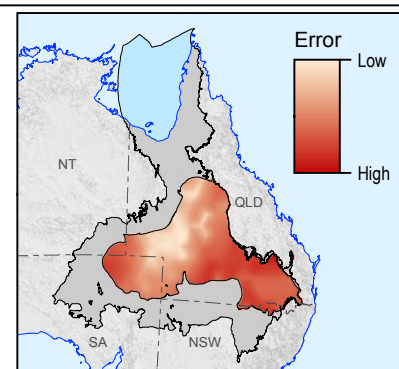
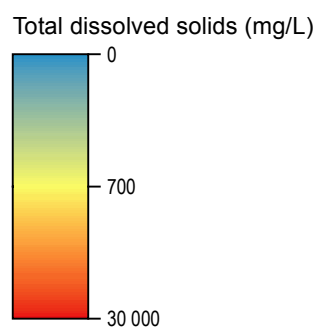
14-8061-67

Hutton Aquifer and Equivalents



- Great Artesian Basin
- Hutton Aquifer and Equivalents
- Recharge zone
- Area of Great Artesian Basin where the hydrogeological unit does not exist

- 200 Total dissolved solids contour (mg/L)
- 200 Bathymetry contour (depth in metres)
- Tropic of Capricorn
- Groundwater sample location
- City/town



Predicted value error map

14-8061-64

Map 53

Hutton Aquifer and Equivalents

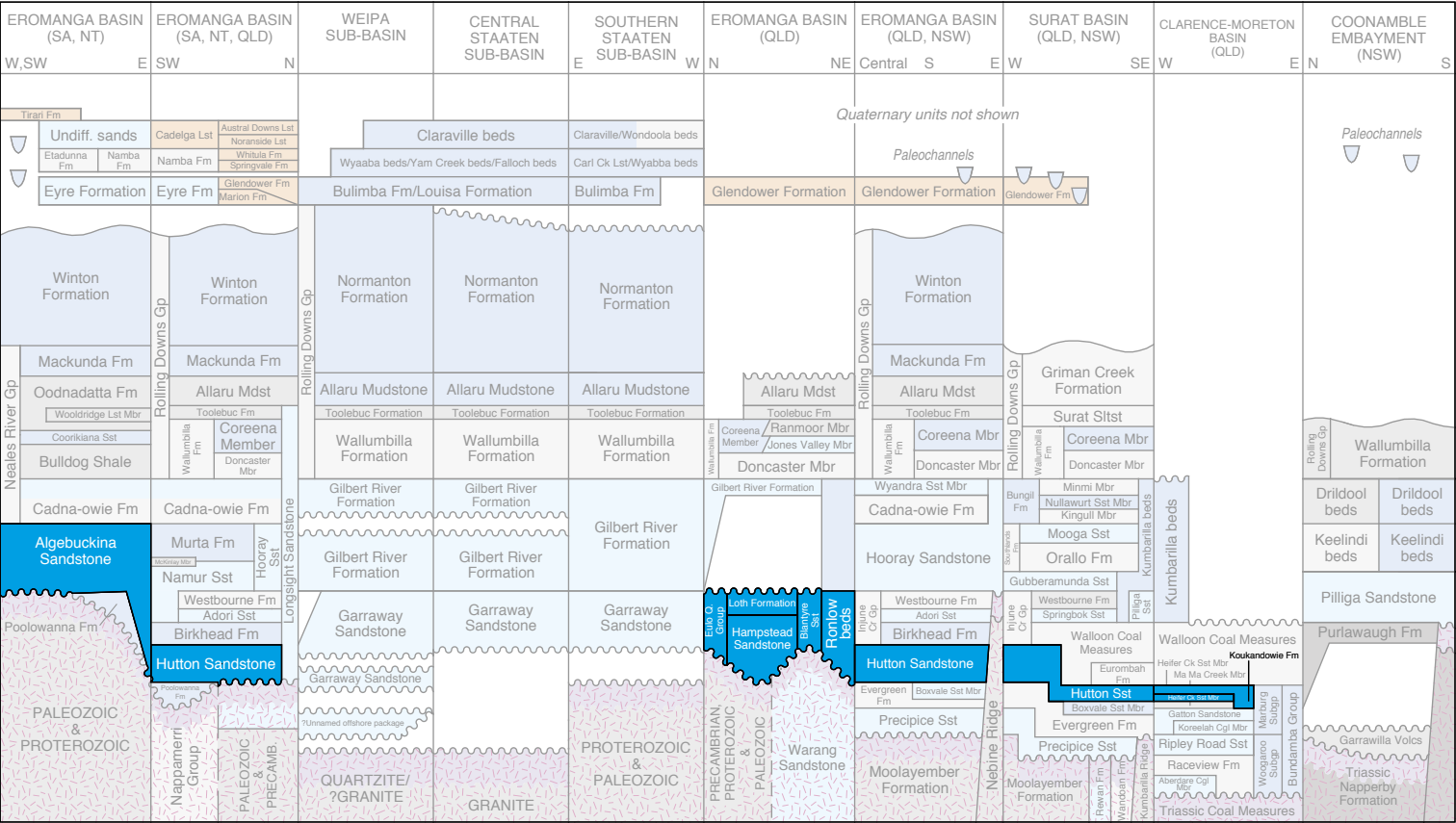
—³⁶Cl/Cl ratio

There is limited chlorine-36 data for the Hutton Aquifer but it does provide insight into recharge mechanisms and possible flow paths.

High chlorine-36 values are restricted to the northern extent of the Mimosa Syncline-Roma Shelf and eastern margin of the Surat Sub-basin, across the Kumbarilla Ridge into the Clarence-Moreton Sub-basin. There are anomalously low chlorine-36 values in the northeastern corner of the Surat Sub-Basin, suggesting this is a region of stagnant flow or that it is strongly influenced by the presence of very old salts.

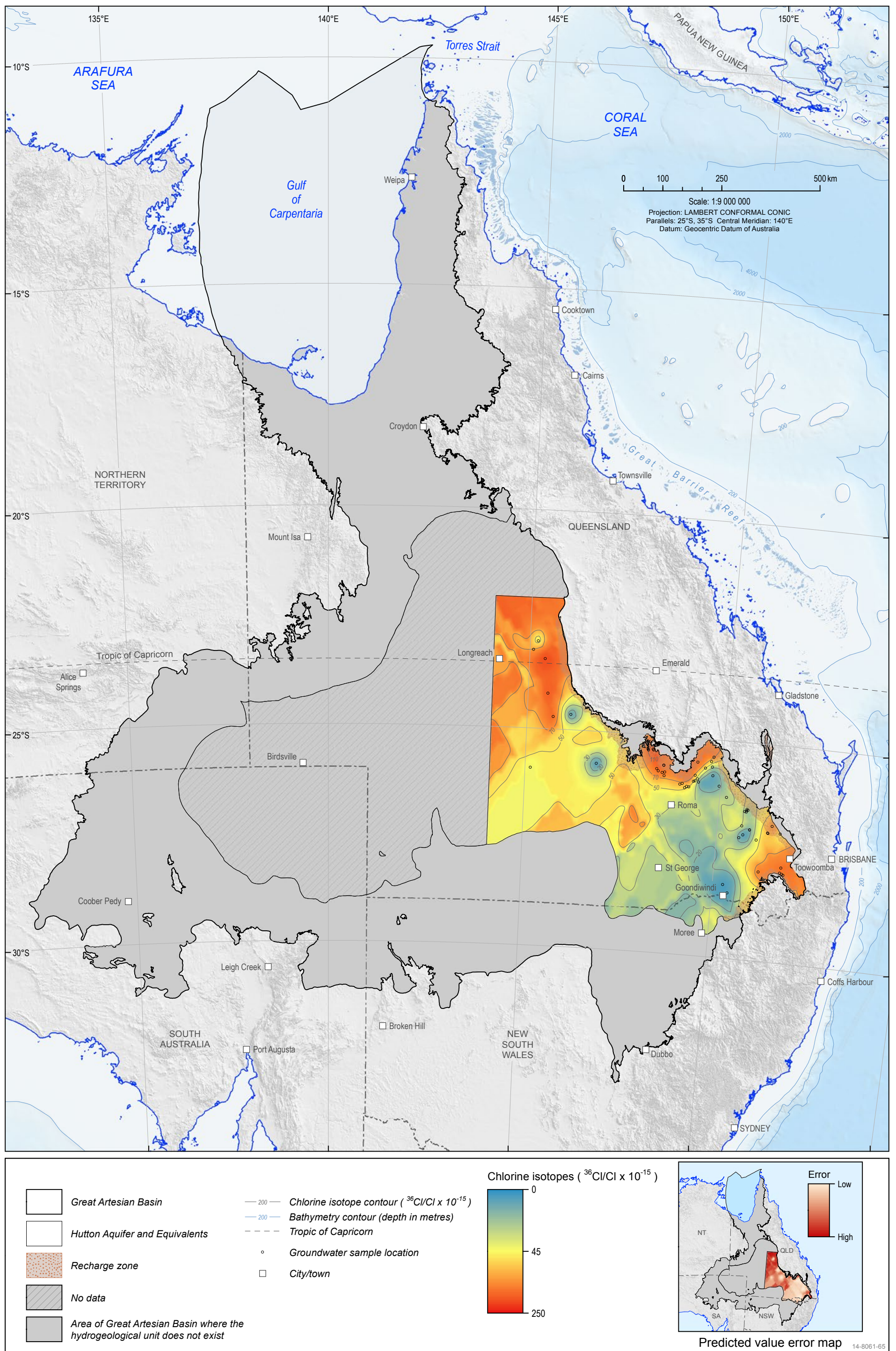
Away from the margins of the aquifer, there are few measurements, and predicted values shown on the map are associated with considerable error. The predictions reflect the alkalinity map (see Map 51), with low values throughout most

of the Surat Sub-basin, particularly in the Mimosa Syncline, and elevated levels across the Eulo-Nebine Ridge and in the eastern part of the Eromanga Basin. There are two low chlorine-36 values found on the Eulo-Nebine Ridge and their location is coincident with the so called TACEM anomalies¹⁴ in the shallower Cadna-owie – Hooray Aquifer, which are two unusual, discontinuous areas of high chloride that occur within a region of low chloride concentration, located approximately 75 km west and 200 km northwest of Roma (see Map 37). These have been attributed to recharge events immediately following sustained periods of aridity and the leaching of salts from overlying aquifers.



 Hutton Aquifer and Equivalents

14-8061-67



Map 54

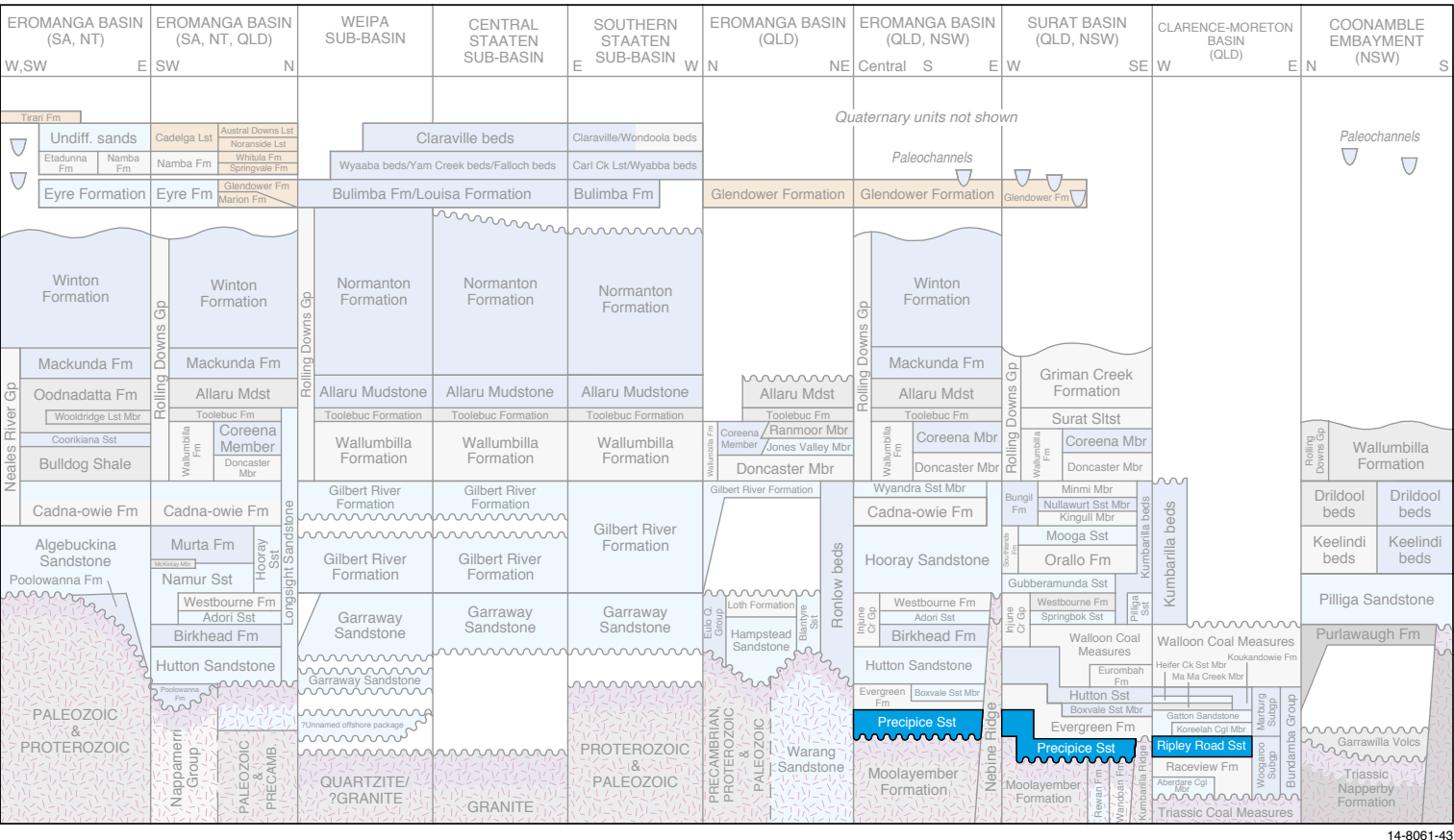
Precipice Aquifer and Equivalents—Alkalinity

Northern regions of the Precipice Aquifer display low alkalinity but alkalinity increases markedly southwards within the Mimosa Syncline and across the Roma Shelf.

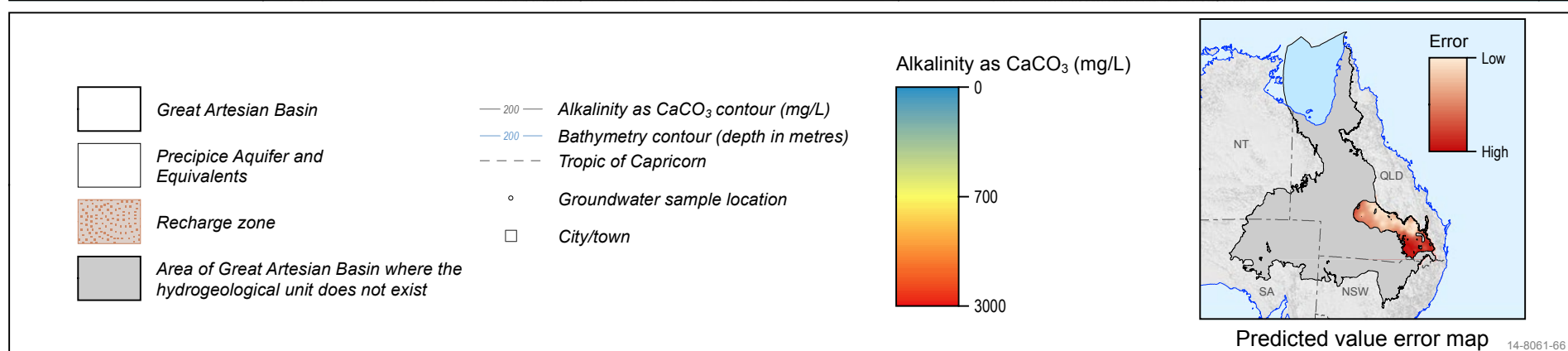
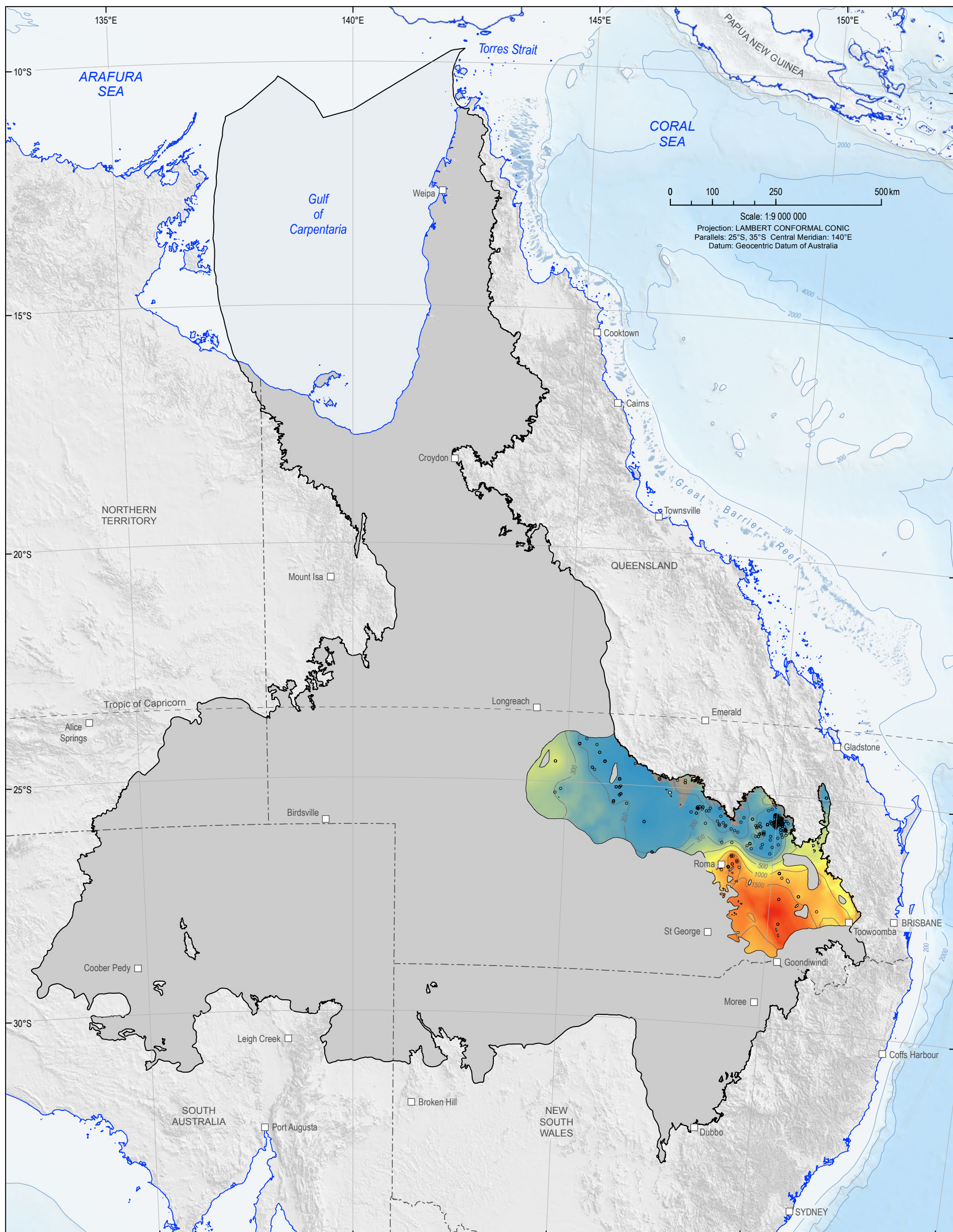
The areas of low alkalinity (<300 mg/L) mirror the low salinity regions (see Map 55) and include recharge zones along the eastern margin of the Eromanga sub-basin and the northern margin the Surat Basin, the majority of the western region and a large section in the northern part of the Surat Sub-basin. Low alkalinity groundwater persists along the Nebine Ridge and is associated with anticipated higher flowrates due to the increased horizontal permeability in this region.

The large area of low alkalinity groundwater in the northern part of the Surat Sub-basin is coincident with increased thickness of the aquifer in the northern section (see Map 32) and that parts of the aquifer are in direct contact with the Clematis Aquifer

from the underlying Bowen Basin (see Maps 8 and 14). Higher alkalinity values are observed with increasing depth within the Mimosa Syncline. Parts of the Precipice Aquifer within the Mimosa Syncline are in direct contact with the underlying high alkalinity waters of the Blackwater Group in the Bowen Basin. There is evidence that the Goondiwindi and Moonie faults in this region extend into the Precipice Sandstone, which could provide a conduit for vertical groundwater flow up from the Bowen Basin into the Surat Sub-basin¹⁶. In addition, the very high alkalinity is co-located with production of oil and the presence of thermogenic gases in the region around Moonie. The decomposition of organic matter would provide an additional source of alkalinity.



 Precipice Aquifer and Equivalents



Map 55

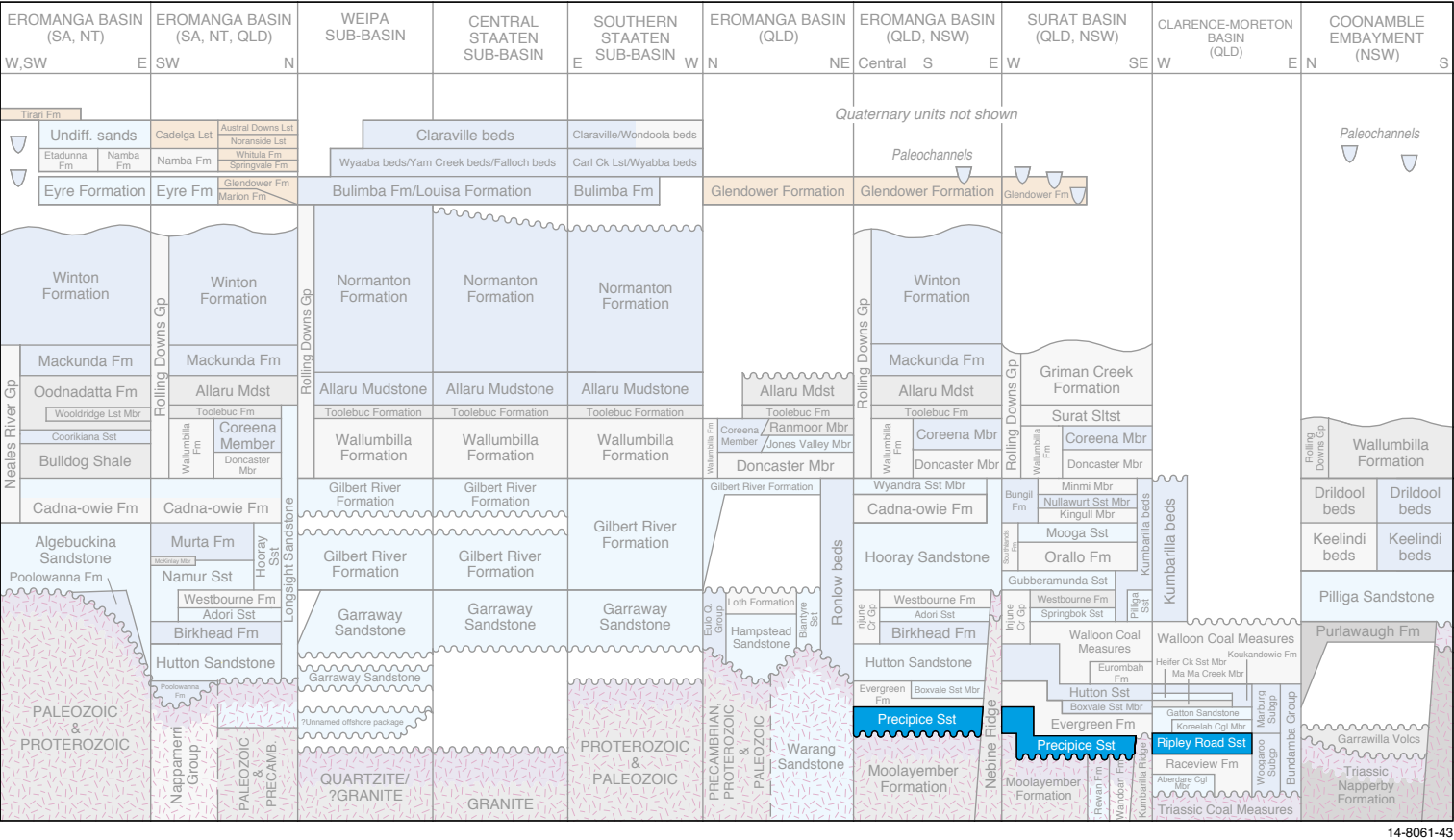
Precipice Aquifer and Equivalents—Total Dissolved Solids

Groundwater in the Precipice Aquifer is fresh to brackish and the salinity shows significant regional variability. Measured TDS values range from less than 100 mg/L to 6000 mg/L.

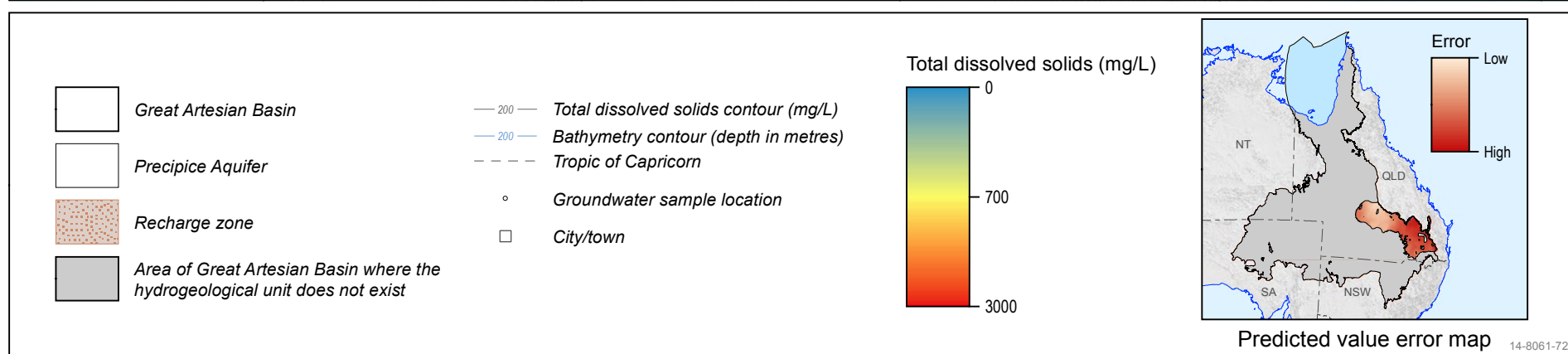
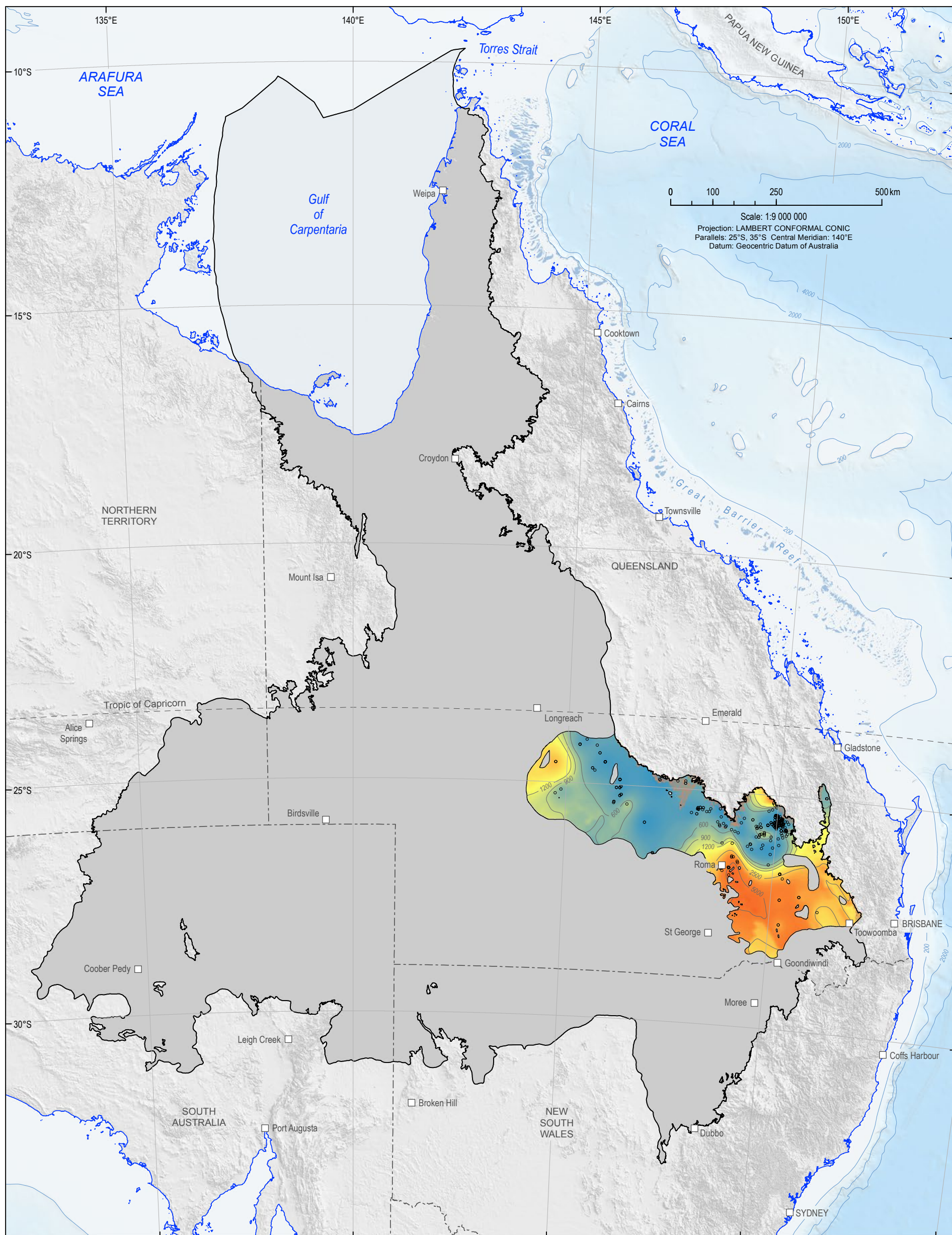
Fresh groundwater coincides with recharge along the eastern margin of the Eromanga Sub-basin and the northern margin the Surat Sub-basin. Low salinity groundwater persists along the Nebine Ridge and is associated with anticipated higher flow rates due to the increased horizontal permeability in this region.

In contrast to the other aquifers in the Surat Sub-basin, a large portion of low salinity groundwater is found in the northern part of the Mimosa Syncline, which then transitions to brackish groundwater in the southern and eastern parts of the sub-basin. The northern low-salinity groundwater is coincident with a thicker portion of the Precipice Aquifer (see Map 32).

In this area, a portion of the Clematis Aquifer, of the underlying Bowen Basin, is in direct contact with the Precipice Aquifer (see Map 14). The Clematis Aquifer contains relatively fresh groundwater²² and any upward leakage may influence salinity concentrations in the Precipice Aquifer. Similarly, the rapid increase in salinity to the south coincides with an area of direct contact between the Precipice Aquifer and the Blackwater Group partial aquifers from the underlying Bowen Basin. In this case the Blackwater Group contains more saline groundwater and upward leakage into the Precipice Aquifer may explain the relatively rapid transition from low salinity to more saline conditions exhibited.



 Precipice Aquifer and Equivalents



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Glossary

AEM. See Airborne electromagnetics

Aeolian. Term applied to landforms or sedimentary materials which are formed or transported by the action of wind, or to environments dominated by atmospheric geomorphic processes.

AHD. See Australian Height Datum

Airborne electromagnetics (AEM). A geophysical survey method that measures the electromagnetic properties of a geological profile using an airborne platform. Electrical conductivity and magnetic susceptibility are derived, and because these properties vary depending on the nature of the rock, water saturation, salinity and other parameters, the resultant maps are used for estimation of the nature of underground rock formations, groundwater, contamination and other geological and environmental changes.

Airborne radiometrics. See radiometrics

Alluvial, alluvium. Materials deposited from transport by flowing water confined to a channel or valley floor.

Anoxic. Conditions where oxygen is absent or present in very low concentrations.

Anticline. An arch-shaped fold of originally flat lying sedimentary layers.

Aquiclude. A geological unit with very low hydraulic conductivity that obstructs groundwater flow to or from an adjacent aquifer.

Aquifer. A geological unit, group of units or part of a unit which is saturated and sufficiently porous and permeable to store and allow the movement of groundwater. Aquifers may yield quantities of groundwater for consumptive use or discharge to springs.

Aquitard. A saturated geological unit that can store groundwater but cannot transmit significant quantities of groundwater. Also termed a 'leaky' confining layer as it retards, but does not completely prevent, water flow to or from an adjacent aquifer.

Architecture. The relationship of different geological units to each other in space. For example, regolith architecture, sedimentary architecture etc.

Arkose. A sandstone containing abundant feldspar.

Artesian. Situation where the piezometric surface of a confined aquifer is above the land surface.

Artesian bore. A bore which intersects artesian conditions in an aquifer, so that the groundwater level in the bore rises above the natural ground level.

Australian Height Datum (AHD). The datum that sets mean sea level as zero elevation. Mean sea level was determined from observations recorded by 30 tide gauges around the coast of the Australian continent for the period 1966–1968.

Bank storage. The water in an alluvial system that was recharged by the adjacent stream during rising stream levels.

Basalt. A mafic volcanic rock rich in iron and magnesium and low in silica.

Base flow. The discharge into a stream from natural storages, such as groundwater discharge from connected aquifers, particularly sustaining stream flow between rainfall events.

Basement. Bedrock that underlies the geological materials of interest.

Basin. A large depression in the Earth's crust filled by sedimentary or volcanic rocks.

Basin inversion. The uplift of a sedimentary basin relative to surrounding low lying areas due to a variety of tectonic processes.

Bed, bedding. Layers or layering of sediments or sedimentary rocks that reflect differences in size, composition or colour of constituent grains.

Bedrock. Loose term given to any geological material that underlies the stratum of interest. Bedrock is often composed of crystalline rocks such as granite or metasediments.

Berriasian. The oldest stage of the Lower Cretaceous. It occurred between 145.5 and 140.2 million years ago.

Biogenic carbonate. Calcium carbonate (CaCO₃) directly precipitated by biological processes, such as shells or corals.

Bioturbation. The displacement and mixing of sediment particles by plants and animals.

Bore. A narrow constructed hole used to intercept groundwater from an aquifer. Also known as a borehole, well or piezometer.

Bore yield. The volume of water that can be abstracted from a bore (either by pumping or natural artesian flow) over a specific time interval. Bore yields are typically reported in units like litres per second (L/s) or megalitres per year (ML/yr).

Bounding surface. A surface within a sedimentary succession that marks the upper or lower limits of a major mappable unit.

Calcrete. Calcium carbonate (CaCO₃) formed in soil or sediments in a semi-arid region under conditions of sparse rainfall and warm temperatures, normally by precipitation of calcium. Calcrete is common in low-lying areas in arid to semi-arid regions, particularly palaeovalleys ('valley calcrete'), and may form aureoles around salt lakes. It is commonly a significant near-surface aquifer in the arid zone.

Cambrian. A period of geological time, between 545 and 490 million years ago.

Carbonate. CO₃ ions that can be carried in solution in surface water or groundwater and precipitated with Ca, Mg, or Fe ions to form carbonate minerals and rocks.

Carboniferous. A period of geological time between 359 and 300 million years ago.

Catchment. The area of land from which rainwater drains into a river, stream or lake. Catchments are separated from each other by topographic divides.

Cemented. The cementation of sedimentary grains by later minerals precipitated from groundwater. Sometimes 'consolidated' is used as an approximate synonym.

Cenozoic. The geological era extending from 65.5 million years ago to the present.

Clay. A term that refers to either grain size or mineralogy; (a) an earthy sediment composed of rock or mineral fragments or detrital particles smaller than a very fine silt grain; (b) clay minerals that are hydrous aluminium silicates derived largely from feldspars, micas and carbonate by weathering.

Colluvial. Gravity depositional processes found in slope depositional environments forming colluvium.

Colluvium. The deposits associated with colluvial processes.

Cone of depression. The area around a well where the hydraulic head (or potentiometric surface) in the aquifer has been lowered by groundwater extraction.

Confined aquifer. An aquifer that is overlain and underlain by impervious layers (aquitards). The groundwater level in a borehole intercepting a confined aquifer will be above the top of the aquifer.

Consolidated. See cemented.

Core, coring. A drilling method that recovers intact samples of subsurface materials.

Cretaceous. The geologic period from 145 ± 4 to 66 million years ago. It follows the Jurassic and precedes the Cenozoic.

Deltaic. Pertaining to a delta, e.g. deltaic sediments.

DEM. See Digital Elevation Model.

Depocentre. The centre of deposition within a sedimentary basin. This is usually the deepest point within a sedimentary basin.

Devonian. The geological period extending from 416 to 359 million years.

Diagenesis. The changes that occur to sediments after they are deposited, including cementation and weathering.

Diffusion. The movement of ions or molecules from zones of high solute concentrations to zones of low solute concentration.

Diffusivity. The ratio of conductivity to storage capacity (with units of L^2/t). For example, hydraulic diffusivity is the ratio of hydraulic conductivity to specific storage.

Digital elevation model (DEM). Digital representation of the topography of the earth. DEMs are obtained by many systems, including ground surveying, airborne radar and laser surveys, or from satellite radar.

Discharge, groundwater. The volumetric flow rate of groundwater from the saturated zone to the earth surface.

Discharge, stream. The volumetric flow rate of water in the stream.

Discharge zone. An area in which subsurface water is discharged to the land surface. In the arid zone, evaporite minerals (salts) precipitate as the water evaporates to the atmosphere. See also spring.

Dissected. A term applied to landscapes which have been extensively eroded to form valleys and gullies.

Dolomite. Calcium-magnesium carbonate, $CaMg(CO_3)_2$

Drawdown. Lowering of the groundwater level due to loss of groundwater from the aquifer.

Duricrust. A hardened layer formed in the regolith by cementation of soil or sediment, generally by minerals rich in iron, sulphate, silica, or carbonate.

EC. See Electrical conductivity

Electrical conductivity (EC). The ability of an electrical current to pass through a substance. EC is commonly used to estimate the amount of soluble salt in solution. EC measurements can be made with a range of devices on water, soils, and soil-paste extracts. Units of electrical conductivity are commonly given in mS/m, dS/m or $\mu S/cm$; $100 \text{ mS/m} = 1 \text{ dS/m} = 1000 \mu S/cm$. Here, S is the symbol for siemens, and the prefixes d is deci (10^{-1}), c is centi (10^{-2}), m is milli (10^{-3}) and μ is micro (10^{-6}).

Eocene. Geological epoch extending from 55.8 to 33.9 million years ago. Preceded by the Paleocene and followed by the Oligocene.

Ephemeral. A short-lived transitory event. Ephemeral wetlands are only inundated and ephemeral streams only flow for relatively short periods of time.

Evaporation. The process by which water changes its physical state from a liquid to a gas, so that vapour is lost from soil or water directly into the atmosphere, due to increased temperature.

Evaporative concentration. Concentration of solutes in groundwater due to evaporation. The chemical constituents may remain fairly constant although the volume of water in which they are dissolved decreases owing to evaporation.

Evapotranspiration. The total water loss from the land surface to the atmosphere, through the combined effects of evaporation and transpiration.

Fault. Fracture in a rock body along which displacement has occurred.

Floodplain. A low-lying area adjacent to a river or stream that is subject to inundation when the waterway floods. Floodplains are often sites of deposition of fine-grained sediments.

Fluvial. River depositional environment.

Fracture. Cracks in indurated rocks formed by stress and strain. Fractures along which significant movement has occurred are called faults.

Fractured rock aquifer. Aquifers which store and transmit groundwater in the fractures, joints, bedding planes and cavities of the rock mass.

Gaining stream. A stream or river-reach into which groundwater flows via the stream bed and/or banks.

GDE. See groundwater dependent ecosystem

Geomorphology. The study of landforms.

Gigalitre (GL). 1000 megalitres or 1 billion litres.

GL. See Gigalitre

Glacial-interglacial cycles. Earth ice-age climate cycles where ice-sheets advance (glacial) and contract (interglacial) on timescales of up to 100 thousand years, over the past 2.5 million years.

Global meteoric water line. The worldwide average relationship between hydrogen and oxygen isotope ratios in natural precipitation samples.

Graben. A depressed or down-thrown block bounded on at least two sides by faults. See also half graben

Groundwater. Water stored below ground in the saturated zone, within the pore spaces or fractures of a rock mass.

Groundwater dependent ecosystem (GDE). Ecosystems that rely on groundwater systems for their existence and health.

Groundwater divide. A divide that is defined by groundwater flow directions that flow in opposite directions perpendicular to the location of the divide.

Groundwater mounding. Outward and upward expansion of the watertable caused by enhanced recharge.

Head. A measurement of water pressure representing the total energy at the entrance of a piezometer. Usually measured as a water surface elevation. Differences in head between two or more points can be used to determine hydraulic gradient and direction of groundwater flow. Synonymous with hydraulic head.

Holocene. The most recent geological epoch extending from 12,000 years ago to the present.

Hydraulic conductivity (K). The volume of water flowing through a 1 m² cross-sectional area of an aquifer under a hydraulic gradient of 1 m/1 m (100%) in a given time (usually 1 day). The property of the geological material that describes the capacity for water to move through pore spaces or fractures.

Hydraulic gradient. With regard to an aquifer, the rate of change of hydraulic head per unit of distance of flow at a given point and in a given direction.

Hydraulic head. The height of the groundwater level above a given datum at a given point in an aquifer.

Hydrochemistry. Study of the chemical characteristics of water to interpret hydrological processes.

Hydrodynamics. Study of the motion of fluids.

Hydrogeology. The branch of geology concerned with the occurrence, distribution and effects of groundwater.

Hydrograph (Bore). The variation in time in the groundwater level within a bore.

Hydrograph (Stream). The variation in time of the water level and/or flow in a surface water body.

Hydrostratigraphy. The identification of mappable stratigraphic units on the basis of hydraulic properties (such as the distribution of aquifers and aquitards).

Infrabasins. Bedrock sedimentary basins underlying the geological sequence of interest.

Isotope. A variant of a chemical element with a different atomic mass. Used in hydrogeologic applications to date and understand the origin and evolution of groundwater.

Jurassic. The geologic period from 200 to 145 million years ago. It follows the Triassic and precedes the Cretaceous.

Kilolitre (kL). 1000 litres, equivalent to one cubic metre (1 m³).

Lacustrine. Depositional environments or sediments associated with lakes.

LANDSAT. A polar-orbit satellite launched by NASA to collect multispectral imagery of the Earth surface. Seven satellites have been launched in the series. Commonly written as Landsat.

Local meteoric water line. Average relationship between hydrogen and oxygen isotope ratios in natural precipitation a given area.

Losing stream. A stream or river reach which leaks surface water to an underlying aquifer.

Lunette. Elongated, crescent-moon shaped dune built up by wind on the downwind margin of a lake.

Ma. Abbreviation for million ages ago. See My.

Megalitre (ML). 1 million litres.

Mesozoic. The geological era extending from 251 to 65.5 million years ago. It is followed by the Cenozoic.

Miocene. Geological epoch extending from 23 to 5.3 million years ago. Preceded by the Oligocene and followed by the Pliocene.

Mudstone. A fine-grained sedimentary rock composed of particles smaller than silt.

My. Abbreviation meaning a duration of one or more million years. See Ma.

National-scale. A synoptic view across the nation that crosses jurisdictional boundaries. For mapping in Australia, typically refers to scales of between 1:1 000 000 and 1:2 000 000.

Normal Fault. In normal faults the hanging wall (rock above the fault plane) has moved downward relative to the footwall (rock below the fault plane).

Oligocene. Geological epoch extending from 33.9 to 23 million years ago. It is part of the Cenozoic era, and is preceded by the Eocene and followed by the Pliocene.

Outcrop. An area over which a particular rock units occurs at the surface.

Palaeo-. Prefix meaning old or ancient.

Palaeochannels. Former river channels that are recognised in the surface (from aerial or satellite images) or subsurface (typically in AEM surveys or drilling).

Palaeosol. A buried soil profile representing a former land surface.

Palaeovalley. Ancient valley filling sediments including (but not restricted to) those of palaeochannels. Typically palaeovalley sediments are not associated with currently active river processes.

Paleocene. A geologic epoch from about 66 to 56 million years ago. It follows on from the Cretaceous and marks the start of the Cenozoic. The Paleocene is followed by the Eocene.

Paleozoic. Geological era extending from 542 to 251 million years ago. It is followed by the Mesozoic.

Permeability. The ability of a material, such as rock or sediment, to allow the passage of a liquid, such as water. Permeable gravel and sand, allow free movement, whereas impermeable clays are barriers.

Piezometer. A non-pumping bore, generally of small diameter, used specifically to monitor groundwater levels or hydraulic head within an aquifer.

Pleistocene. Geological epoch extending from 2.5 million to 12 thousand years ago.

Pliocene. Geological epoch extending from 5.3 to 2.5 million years ago. It is part of the Cenozoic era, and is preceded by the Miocene and followed by the Pleistocene.

Porosity. The proportion of the rock volume consisting of open spaces or pores that can hold water. Primary porosity formed when the sediments were laid down; these spaces may be variably infilled by cement, leaving remnant primary porosity. Secondary porosity forms through modification of rocks, such as by dissolution of soluble grains, formation of fractures, or solution-forming karst.

Potentiometric head. See hydraulic head

Potentiometric surface. A surface which represents the level that groundwater under pressure, within a confined aquifer, would rise to, if intercepted by a bore.

Proterozoic. The geological era between 2500 and 545 million years ago. The Proterozoic is formally divided into the Paleoproterozoic (2500 and 1600 million years), Mesoproterozoic (1600-1000 million years), and Neoproterozoic (1000-545 million years).

Quaternary. Geological period extending from 2.5 million years ago to the present.

Recharge. Replenishment of groundwater by natural infiltration of surface water (precipitation, runoff) or artificially via managed aquifer recharge operations.

Redox. Variations in chemical state between oxidation and reduction.

Riparian. Of, on, or relating to the banks of a natural stream.

Salinity. The measure of salt in water, geological material or the landscape.

Sandstone. A sedimentary rock composed of sand-sized particles.

Saprolite. Weathered rock in which more than 20% of the weatherable minerals in the original rock have been altered *in situ*, with interstitial grain relationships being undisturbed. Saprolite is altered from the original rock by mainly chemical alteration and loss without any change in volume. This is sometimes referred to as constant volume alteration. Saprolite can be highly porous and permeable and may be an important aquifer, or may be impermeable and act as an aquitard.

Saturated zone. Part of the geological profile where the voids are filled with water at a pressure greater than atmospheric. The watertable is the top of the saturated zone in an unconfined aquifer.

Sedimentary. Pertaining to sediments, the deposits formed by water, ice or wind.

Seismics, seismic survey. The study of vibrations of the earth and their propagation through the ground. A seismic survey is the acquisition of seismic data using artificial sources to induce vibrations in the earth. This provides information on the lateral extent and depth of geological layers.

Semi-confined aquifer. An aquifer which is partly confined by layers of lower-permeability material, through which water movement can still occur.

Shale. A sedimentary rock composed of clay particles.

Siltstone. A sedimentary rock composed of silt-sized particles (<62 microns but >3 microns).

Specific yield. Ratio of the volume of water obtained by draining a volume of saturated rock or soil, relative to the bulk volume of the rock or soil. Also known as the drainable porosity.

Spring. A naturally-occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool.

Storativity. The volume of water released from storage per unit decline in the hydraulic head in the aquifer, per unit area of the aquifer. Also known as the storage coefficient.

Stratigraphy. The study of how different layers of sediments can be related to each other.

Sub-artesian aquifer. An aquifer containing groundwater under pressure that rises to a level greater than that at which it is first encountered, when tapped by a bore, but does not reach the surface.

Subcrop. An area over which a geological unit is close to surface but not outcropping. Usually an area of subcrop is covered by a thin veneer of soil or alluvial sediments.

Transmissivity. A measure of the ability of groundwater to pass through soil, sediment or rock. The capacity of a rock to transmit water under pressure. Expressed as the volume of water flowing through a cross-sectional area of an aquifer that is 1m x the aquifer thickness under a hydraulic gradient of 100% in a given amount of time (usually 1 day). Transmissivity is equal to the hydraulic conductivity (K) times the aquifer thickness.

Transpiration. Water given off by plants via pores in the surface tissues. See also evapotranspiration

Trans-tensional region. An area that experiences both extensive and transtensive shear and is characterised by both extensional structures (normal faults, grabens) and strike-slip faults.

Triassic. The geologic period that extends from 251 to 201 million years ago. It is preceded by the Permian and followed by the Jurassic. It is oldest period in the Mesozoic era.

Unconfined aquifer. A type of aquifer in which the upper boundary is defined by the watertable. Unconfined aquifers can be recharged directly from the ground surface as there are no overlying confining beds.

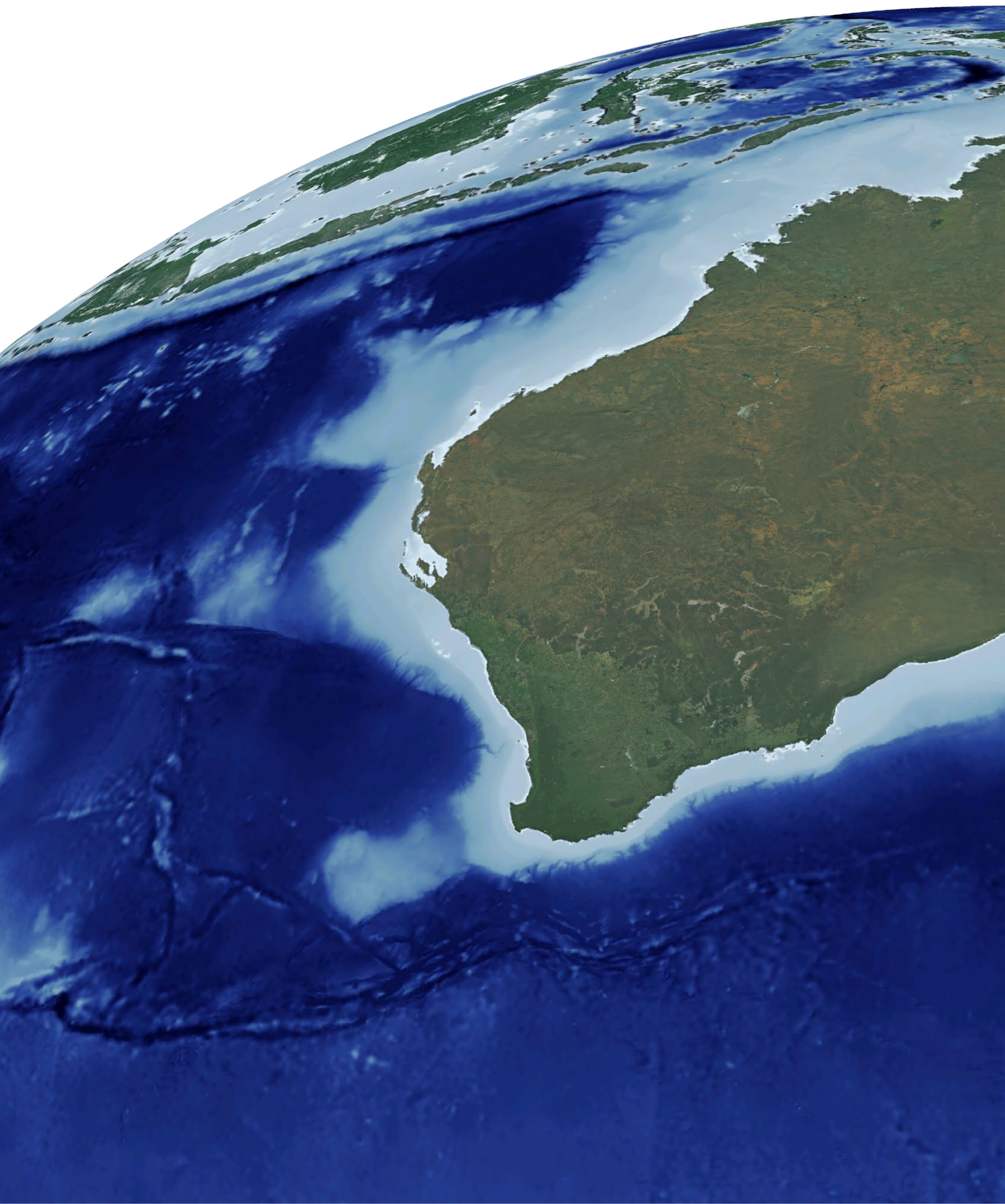
Volcanic. Processes and materials (such as ash and lava) produced by volcanic activity.

Volcanogenic. Processes and products pertaining to volcanic activity.

Watertable. The surface below which an unconfined aquifer is saturated with water. At the watertable, pore water pressure equals atmospheric pressure. See also potentiometric surface.

Weathered, weathering. The physical and chemical changes that a rock undergoes when it is exposed to the atmosphere and shallow groundwater.

Well. A constructed hole in the ground to access groundwater. See also bore.



Statements



Minor release of water

🕒 Posted on February 2, 2015

There has been a very minor operational release of produced water from Santos' Dewhurst pilot.

A maximum of 2 to 3 litres of water was released from a high point vent, which would have the contained approximately 2-3 teaspoons of salt.

There was no equipment malfunction, these types of vents are designed to release small amounts of gas that can sometimes gather in water flowlines.

During the course of normal operations, water droplets can also be released with the gas.

The small scale of the release did not trigger a reporting process. The affected area was cleaned up to ensure the surrounding environment was not impacted.

The EPA is aware of the release.

Santos adheres to strict environmental and reporting guidelines at all times to ensure natural gas is extracted safely.

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March 2015

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The irrigation system design and operations would treat these as different management zones, as outlined in the irrigation concept design report (Appendix 3). Therefore irrigation infrastructure, cropping and irrigation scheduling would vary according to the irrigation management class of the soil to minimise potential impacts.

As outlined in Section 4.3.2, the soil on-site has a number of inherent limitations due to its sodic nature. Without chemical dosing, the addition of irrigation water to the sodic soil could present the following issues:

- limiting of leaching, which could cause salt to accumulate over time and the development of saline subsoils, as sodicity reduces flow of water through soil
- crusting and sealing of the soil, which could impede water infiltration leading to potential increased runoff, as sodicity causes dispersion in the soil surface
- acceleration of erosion, which could cause the appearance of gullies and tunnels, as sodicity increases dispersion in the subsoil
- a dense, cloddy and structureless soil as it destroys aggregation.

However, as discussed in Section 2.6.3.2, prior to being used for irrigation purposes, water from the WBTP will be treated to a level that conforms with the *Environmental Guidelines: Use of Effluent by Irrigation* (DEC, 2004). The addition of chemicals to the treated water will make the water suitable for the intended soils and will serve to maintain or improve soil structure stability. This will be closely monitored as outlined in 2.7.1.2.

As outlined in Table 2-10 of Section 2.6.2.1, the following soil preparation activities will be undertaken during construction:

- application of gypsum – displaces the sodium within the soil, reducing its sodicity and dispersivity
- application of lime – neutralises soil acidity, and additional calcium would also ameliorate sodium
- deep ripping – breaks up the hard, coarse subsoil to assist in water infiltration
- application of fertiliser (during soil preparation, and continuing on throughout operation) – increases the nitrogen levels in soils, a limiting nutrient onsite.

The salinity of the treated water to be applied to the irrigation area would be rated as 'low' according to the DEC Guidelines (2004), as described in Section 2.6.3.4. Most irrigation waters carry a salt load that presents a risk of accumulation in the rootzone, particularly in arid regions or where high water tables exist. The annual rainfall of approximately 650 millimetres onsite will assist in offsetting salt deposition by irrigation water.

The expected EC of the treated water is 1.0 mS/cm. The estimated salt load of the treated water (using the calculation method described in DECC's *Load Calculation Protocol* (June 2009)) is 0.7004 mg/L. The total annual salt load to the soils over the irrigation area, based on an irrigation application rate of 372 millimetres per hectare or 3.7 ML/ha, is expected to be 1,859 kg/ha. Around 876 kg/ha of this is predicted to comprise sodium chloride salts. The remainder is attributed from calcium sulphate salts which have a positive effect on soil quality.

At an annual irrigation application rate of 372 millimetres or 3.7 megalitres per hectare, the annual salt input from irrigation is shown in Table 6-2.

Table 6-2 Annual salt loading from application of treated irrigation water

Salt added	Annual salt load (kg/ha)
Sodium	434
Calcium	242
Chloride	442
Sulphate	741
Total salts	1,859

The calcium sulphate salts typically have a positive effect on soil quality. Sodium chloride can impact soil stability (i.e. increased dispersibility), so the proposed irrigation system would provide control sensitivity such as deep drainage. Regular soil sampling and monitoring of salt accumulation in and beneath the rootzone would also be implemented.

The proposed irrigation area within the site is also prone to becoming waterlogged in the surface soil and would be untrafficable following extended rainfall periods, i.e. periods where continuous rainfall events exceed 50 millimetres. Land preparation and operational activities would be restricted during these periods. The irrigation schedule (application of the treated water) would be managed to minimise waterlogging and runoff. Traffic would also be kept to a minimum in the irrigation area to reduce soil compaction.

To gain a better understanding of the potential effects of irrigation of this site, three irrigation management schemes were modelled for comparison to the current rain-fed pasture setting. Details of this modelling are provided in the concept irrigation design report, provided in Appendix 3.

The four irrigation scenarios that were modelled using the HowLeaky modelling program were:

- Scenario 1 (baseline) – current dryland pasture under natural rainfall. This was simulated to compare the natural erosion, deep drainage and runoff from the site
- Scenario 2 – even irrigation of all 97.8 hectares, simulation based on an average year with one megalitre per day treated irrigation water
- Scenario 3 – even irrigation of all 97.8 hectares, simulation based on an average year with unlimited treated irrigation water
- Scenario 4 (likely management approach for the proposed activity) – irrigation split between Class A (68 ha) and B soils (30 ha), with priority given to watering Class B soils from October to May, and no irrigation of Class B soils from June to September. One megalitre per day treated irrigation water supply.

Irrigation events were set at 12 millimetres per application. An irrigation event was triggered once the soil water deficit reached 50 millimetres or 36 per cent of the 140 millimetre plant available water capacity (PAWC).

Three parameters having potential environmental impacts were modelled – runoff, deep drainage, and erosion and site sediment loss. The results of the modelling for these parameters are provided in Table 6-3.

Table 6-3 Water losses from system with potential environmental impacts = HowLeaky model output

Water loss mechanism	Scenario 1	Scenario 2	Scenario 3	Scenario 4 – Class A soils	Scenario 4 – Class B soils
Deep drainage (mm/yr)	4.0	3.9	16.9	4.3	5.7
Runoff (mm/yr)	14.2	13.5	39.6	14.6	17.6
Erosion and site sediment loss (t/ha-yr)	0.22	0.22	0.70	0.24	0.30



Leewood Produced Water Treatment and Beneficial Reuse Project

Review of Environmental Factors

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Document status

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Rev A	Draft for technical review	KB	RS	21 March 2014
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Approval for issue

Name	Signature	Date
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Executive summary

Overview

Santos NSW (Eastern) Pty Limited (Santos) on behalf of the titleholders of Petroleum Assessment Lease (PAL) 2 is proposing to construct and operate a Water and Brine Treatment Plant (WBTP) and associated infrastructure at a property known as "Leewood" located within PAL 2 (the proposed activity).

The proposed activity is permissible without development consent and requires assessment and determination under Part 5 of the *Environmental Planning and Assessment Act 1979* (EP&A Act). The Office of Coal Seam Gas within NSW Trade and Investment is the determining authority for the proposed activity.

RPS Australia East Pty Ltd has prepared this Review of Environmental Factors (REF) to assess the potential environmental impacts of the proposed activity. The REF addresses the requirements of section 111 of the EP&A Act, clause 228 of the *Environmental Planning and Assessment Regulation 2000* and *ESG2: Environmental Impact Assessment Guidelines; For exploration, mining and petroleum production activities subject to Part 5 of the Environmental Planning and Assessment Act 1979* (DTIRIS, 2012). The REF concludes that the proposed activity is unlikely to have a significant impact on the community and environment, including threatened species, populations or ecological communities, and that an environmental impact statement is not required.

Proposed activity

The primary objective of the proposed activity is to construct and operate a purpose built, centralised water treatment facility outside of the Pilliga State Forest, to treat, manage and beneficially reuse produced water and brine from coal seam gas (CSG) exploration and appraisal activities.

Produced water and brine management ponds have been constructed at Leewood (approved 19 March 2013). These ponds store produced water and brine from previous and future exploration and appraisal activities within Petroleum Exploration Licence (PEL) 238, PAL 2 and Petroleum Production Lease 3 (PPL3).

The scope of the proposed activity includes:

- a water treatment plant, including pre-treatment and reverse osmosis plant
- a brine treatment plant
- a brine distribution manifold and associated piping, to allow water distribution into the water treatment plant and associated return flows to brine storage ponds
- a treated water storage tank (five megalitre capacity)
- irrigation of treated water at the Leewood property through a managed irrigation system (including a centre pivot and sub-surface irrigation system)
- the construction of (and the ability to operate) a treated water pipeline extending to the Leewood property boundary to transfer water to another location for irrigation by a third party (if required)
- a small potable water treatment system for water extracted from the licensed bore
- other associated infrastructure, including a gas pipeline to fuel the generators
- amelioration of soils within the Leewood irrigation area by deep tillage, fertiliser, lime and gypsum in preparation for irrigation.

In addition, the treated water is to be used for other uses both on and off the site including dust suppression, drilling and construction and fire fighting. Santos is investigating the option of providing treated water to third parties for agricultural irrigation, although this potential use of treated water does not form part of the activity for the purposes of this REF and will be subject to separate assessment and approvals.

The water and brine treatment plant will have a capacity of 1.5 megalitres per day.

During operation, water from the produced water and brine management ponds will be pumped to the water treatment plant where it will undergo the removal of solids, reverse osmosis to separate the water and brine streams, and chemical and pH adjustment. The treated water will then be available for beneficial use with the treated water storage tank providing a water balance buffer. The brine will be transferred to the brine treatment plant for concentration and further recovery of treated water. Concentrated brine will be stored in the Leewood ponds.

Potential environmental impacts

Potential environmental impacts mostly relate to:

- construction activities – clearing of land, erosion and sediment control, traffic, noise and air emissions or other hazards and risks generally present during construction
- operational activities – irrigation practices to ensure soil structure and stability is maintained, management of waste streams (including concentrated brine) or other hazards and risks such as chemical spills or tank failure.

A range of mitigation measures will be put in place to avoid, mitigate or manage impacts. This includes infrastructure responses such as leak detection systems and bunding of areas where chemicals are stored, and management responses such as incident management plans.

The proposed activity will remove approximately 99.6 hectares of the Derived Grassland vegetation community. This includes approximately 97.8 hectares for the managed irrigation area and approximately 1.8 hectares for the WBTP. This vegetation community is currently in poor condition. No *Threatened Species Conservation Act 1995* or *Environment Protection and Biodiversity Conservation Act 1999* listed threatened species, populations, ecological communities, or their habitats are likely to be impacted. Appropriate erosion and sediment control measures will be put in place to manage any other impacts associated with clearing.

Two non-Aboriginal heritage items (pits associated with the Sydney University Giant Air-shower Recorder) and four Aboriginal heritage items (two quartz flake artefacts and two scar trees) have been identified at the Leewood property. The layout of the proposed activity and the protection measures that are already in place around each of these items ensures that these items will not be impacted. Management protocols will be implemented during site preparation works in the event that any further items are uncovered.

Noise, air and traffic studies concluded that impacts during operation and generally during construction will be minimal.

During some stages of construction, the nearest sensitive receivers could experience noise levels in excess of 40 dBA during standard construction hours. Appropriate construction noise management techniques will be implemented accordingly. Ongoing consultation with affected landowners prior to and during construction will ensure impacts are managed appropriately.

During operation, treated water will be used mostly for irrigation. An irrigation and water balance model has been developed to test a range of weather operating conditions and resultant impacts such as runoff, topsoil loss or changes to deep drainage. Under all scenarios surface water runoff will not increase significantly,

there will be minimal changes to deep drainage with no impact to groundwater quality, while topsoil losses and soil salinity will be within acceptable limits. An Irrigation Management Plan, including a soil monitoring program, will be implemented as part of the proposed activity.

Conclusion

A range of potential impacts to the environment and community may be associated with the proposed activity. These have been considered in detail in the REF. The proposed activity has been located and designed to avoid significant environmental and heritage constraints and to reduce impacts to the surrounding community.

There would be economic benefits to Narrabri and the surrounding region to be realised through the expenditure associated with the construction workforce required and the purchase of materials, fuels and consumables. In addition, indirect benefits will occur through associated service provision as well as the use of the site as productive irrigated agricultural land. During operation, there will be opportunities for employment of local people.

On balance, with the implementation of the mitigation measures identified in the Statement of Commitments outlined in the REF, the proposed activity will have a low adverse impact on the environment.

The proposed activity is not likely to significantly affect the community, environment or any threatened species, populations or ecological communities, their habitats or critical habitat and does not require preparation of an environmental impact statement or species impact statement.

1.0 Introduction

1.1 Background

Santos NSW (Eastern) Pty Limited (Santos) (or its assigned contractor) proposes to construct and operate a Water and Brine Treatment Plant (WBTP) and associated infrastructure, including a managed irrigation system, at a property known as "Leewood" (the proposed activity). This will be done for and on behalf of the titleholders of Petroleum Assessment Lease (PAL) 2.

Leewood is located within PAL 2, on the Newell Highway approximately 24 kilometres south-west of Narrabri, NSW. Santos has constructed two double lined 300 megalitre ponds and associated infrastructure at Leewood. These ponds are designed to store produced water and brine from Santos' past and ongoing coal seam gas (CSG) exploration and appraisal activities within PAL 2, Petroleum Exploration Licence (PEL) 238 and Petroleum Production Lease 3 (PPL 3). The construction and operation of this infrastructure at Leewood was assessed under the *Leewood – Produced Water and Brine Management Ponds REF* (RPS, 2012) and approved by the NSW Division of Resources & Energy (DRE) on 19 March 2013.

The proposed activity is designed to treat produced water stored at Leewood from Santos' CSG exploration and appraisal activities, and beneficially reuse the treated water for irrigation at Leewood, dust suppression, construction and drilling uses in Santos' activities. The treated water may also be used for firefighting if required. Santos is investigating the potential to provide treated water to third parties for use in off-site agricultural irrigation. The off-site use of any treated water by third parties for irrigation does not form part of the proposed activity and any such use would be subject to separate assessment and approvals.

The primary purpose of the proposed activity is to enable Santos to continue its CSG exploration and appraisal activities within PAL 2, PEL 238 and PPL 3. The WBTP will operate for up to five years. The further development of the CSG field will necessitate a larger water treatment facility and this will be subject to further assessment and regulatory approvals as part of the Narrabri Gas Project. The EIS for the Narrabri Gas Project is currently being prepared.

The proposed activity is permissible without consent and requires assessment and determination under Part 5 of the *Environmental Planning and Assessment Act 1979* (EP&A Act). The Office of Coal Seam Gas (OCSG) within the Department of Trade and Investment is the determining authority for the proposed activity because approval is required for a Petroleum Operations Plan and in turn the proposed activity under the conditions of PAL 2.

RPS Australia East Pty Ltd (RPS) has prepared this Review of Environmental Factors (REF) to assess the potential environmental impacts of the proposed activity. The REF addresses the requirements of section 111 of the EP&A Act, clause 228 of the *Environmental Planning and Assessment Regulation 2000* and the *ESG2: Environmental Impact Assessment Guidelines; For exploration, mining and petroleum production activities subject to Part 5 of the Environmental Planning and Assessment Act 1979* (DTIRIS, 2012) (ESG2 Guidelines).

The REF demonstrates that the proposed activity is unlikely to have a significant impact on threatened species, populations or communities or their habitats, or the environment and community. It is considered that the potential impacts of the proposed activity are adequately addressed through the REF, proposed consultation and mitigation measures, and that an EIS is not required.

1.2 Structure of REF

This REF has been prepared having consideration of the NSW Government's ESG2: Environmental Impact Assessment Guidelines.

This REF comprises the following:

- **Section 1** Introduces the proposed activity and provides an overview of the REF
- **Section 2** Provides an overview of the proposed activity, including consultation activities
- **Section 3** Provides an overview of the site
- **Section 4** Discusses the existing environment in detail
- **Section 5** Discusses the relevant legislation associated with the proposed activity
- **Section 6** Considers the potential environmental impacts of the proposed activity and recommends mitigation measures to ensure these impacts are appropriately managed
- **Section 7** Provides a summary of the potential impacts
- **Section 8** Concludes the impact assessment
- **Section 9** Provides the Statement of Commitments for the proposed activity.

The following technical investigations and inputs have been prepared to assist in the preparation of this REF, and are appended:

- Ecological Assessment, prepared by Eco Logical Australia
- Aboriginal Cultural Heritage Due Diligence Report, prepared by Central Queensland Cultural Heritage Management
- Agricultural Impact Assessment (AIS), prepared by RPS
- Transport Assessment, prepared by GTA Consultants
- Noise and Vibration Impact Assessment, prepared by Pacific Environment
- Air Quality Impact Assessment, prepared by Pacific Environment
- SEPP 33 Hazard Assessment, prepared by Sherpa Consulting.

2.0 The proposed activity

2.1 Summary of the activity

Santos NSW (Eastern) Pty Limited is the proponent for the proposed activity on behalf of the titleholders of PAL 2. The proposed activity will include:

- construction and operation of:
 - a water treatment plant, including pre-treatment and reverse osmosis plant
 - a brine treatment plant
 - a brine distribution manifold and associated piping at Leewood, to allow water distribution into the water treatment plant and associated return flows to brine storage ponds
 - a treated water storage tank (five megalitre capacity)
 - a managed irrigation system including a centre pivot and sub-surface drip irrigation system
 - other associated infrastructure, including a gas pipeline to fuel the generators
 - a small potable water treatment system for water extracted from the licensed bore
- the construction of (and the ability to operate) a treated water pipeline extending to the Leewood property boundary to transfer water to another location for irrigation by a third party (if required)
- re-use of treated water for irrigation at the Leewood property and other uses both on and off site including dust suppression, drilling and construction and firefighting. Santos is investigating the option of providing treated water to third parties for agricultural irrigation, although this potential use of treated water does not form part of the proposed activity for the purposes of this REF and will be subject to separate assessment and approvals
- amelioration of soils within irrigation area by deep tillage, fertiliser, lime and gypsum in preparation for irrigation
- decommissioning and rehabilitation of the site, if the Narrabri Gas Project does not proceed.

Santos (or its assigned operator) will operate the proposed activity for up to five years. The WBTP will treat up to 1.5 megalitres per day of produced water from Santos' CSG exploration and appraisal activities within PEL 238, PAL 2 and PPL 3. The operational process is expected to involve, but is not limited to:

- pumping of produced water from the produced water pond to the water treatment plant
- treatment of produced water within the water treatment plant, including removal of solids by filter (pre-treatment), reverse osmosis to separate the water and brine streams (treatment), and chemical and pH dosing (post-treatment) to make the treated water appropriate for irrigation
- transfer of treated water to the treated water storage tank or directly to the on-site managed irrigation system for beneficial re-use
- beneficial re-use of treated water for irrigation, or other uses both on and off-site such as dust suppression, drilling and construction and firefighting
- transfer of brine to the brine treatment plant for concentration and further recovery of treated water
- storage of brine in the existing Leewood ponds.

The location of the proposed activity in relation to the storage ponds currently on site at Leewood are shown in Figure 2-1. An overview of the operational phase of the proposed activity is outlined in Figure 2-2.

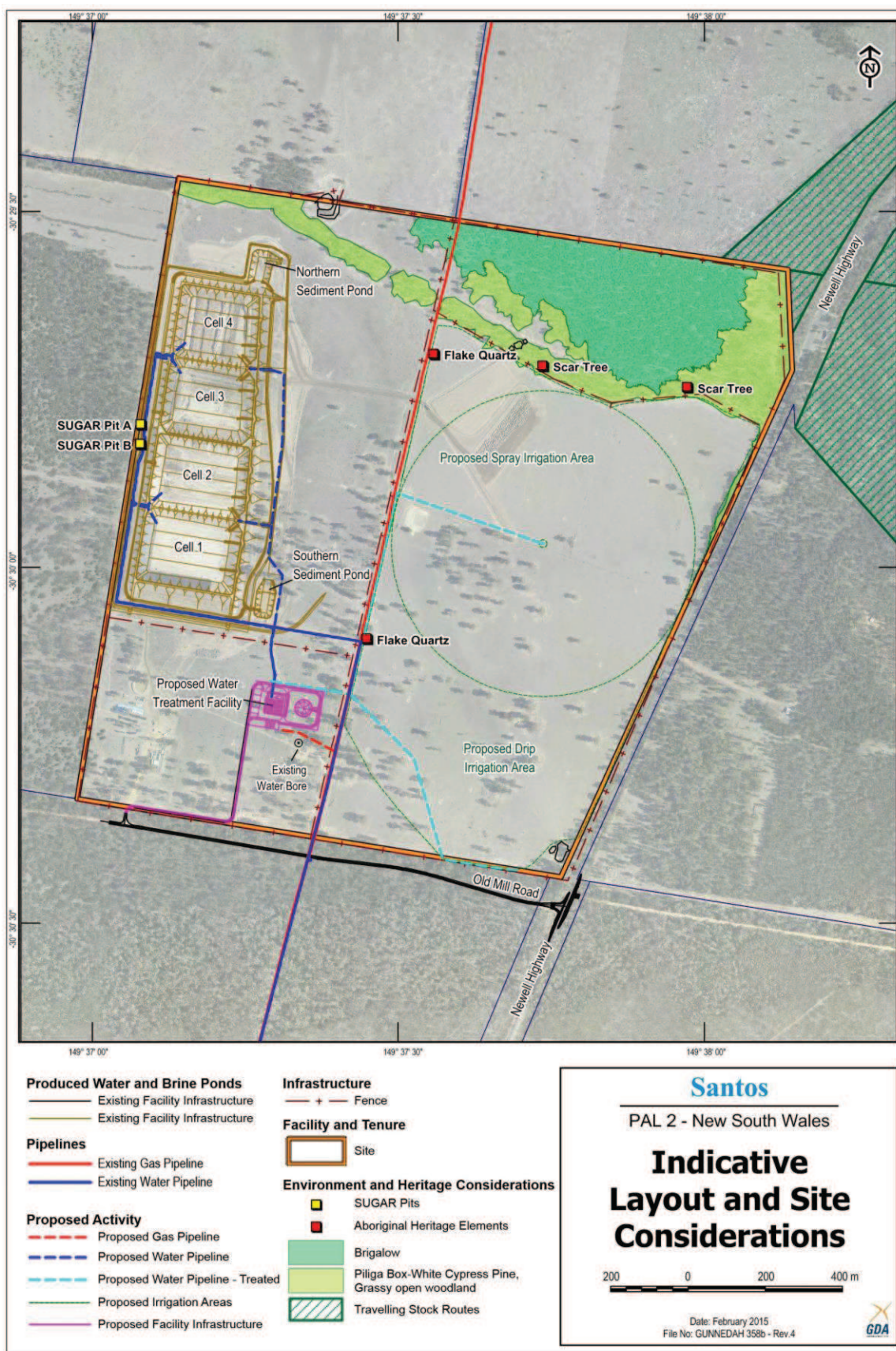


Figure 2-1 Indicative layout of produced water and brine ponds and site considerations

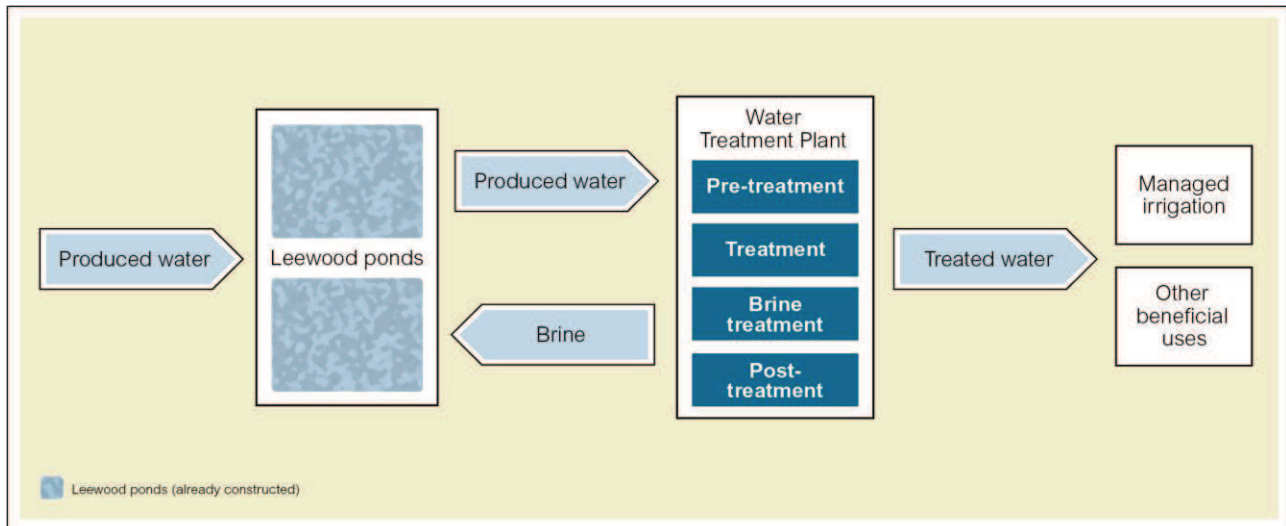


Figure 2-2 Overview of treatment process

The total area of potential disturbance from the proposed activity is approximately 99.6 hectares. This includes the:

- Irrigation area – 97.8 hectares
- WBTP, treated water storage tank and associated infrastructure – 1.8 hectares

References to 'the site' throughout this REF refer to the Leewood property. A detailed description of the construction and operation phases of the proposed activity is provided at Section 2.6.

2.2 Regional location and context

Figure 2-3 shows the regional location and context of the site.

No mineral or coal titles overlie or adjoin the site.

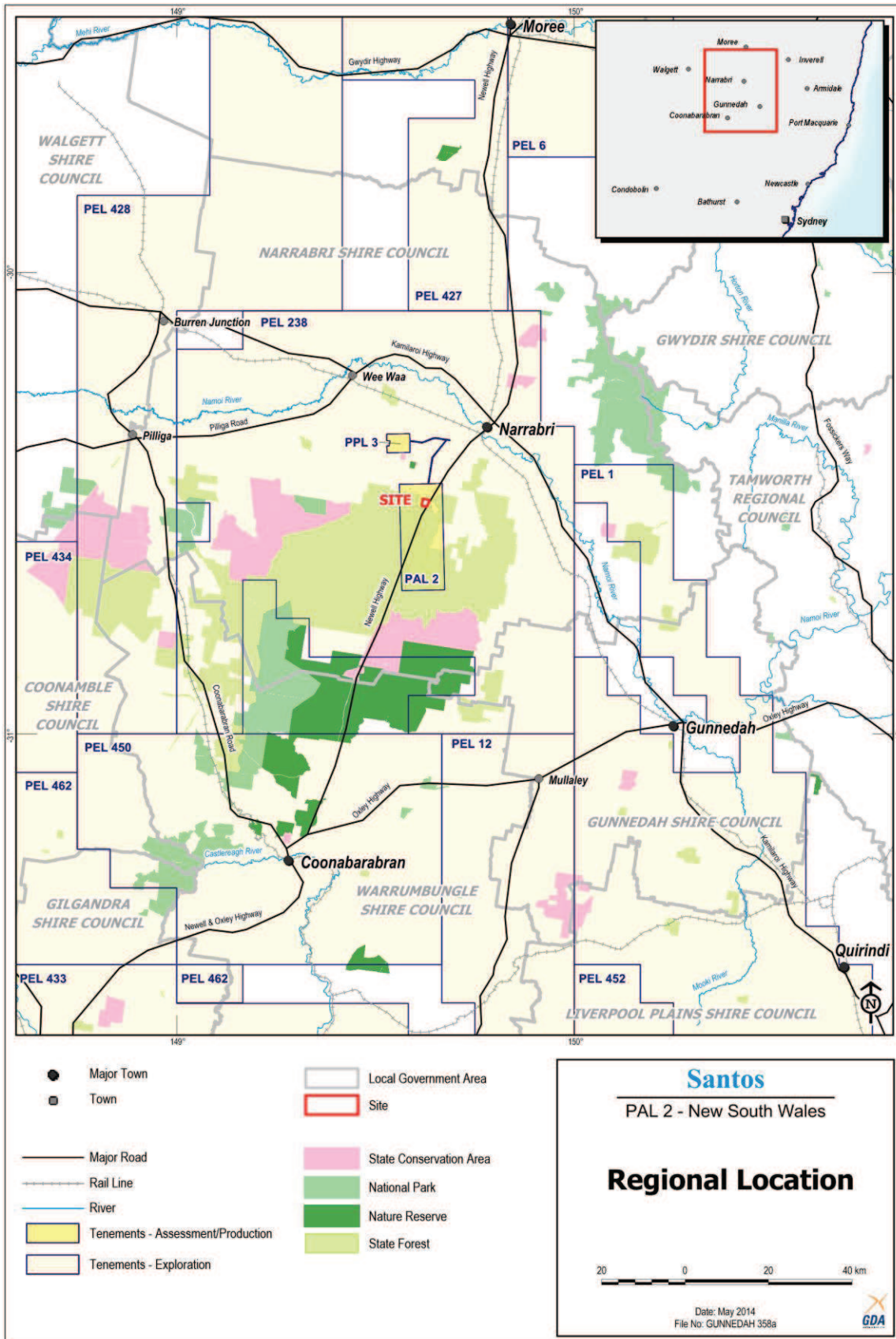


Figure 2-3 Regional location

2.3 Stakeholder consultation

2.3.1 Approach and objectives

Santos understands the importance of proactive and effective engagement with communities and stakeholders and undertakes general consultation in the area of its activities.

In addition, Santos has also developed a specific stakeholder engagement plan for the proposed activity. The objectives of the stakeholder engagement plan are to:

- increase overall awareness and understanding of the CSG industry and the proposed activity in particular
- keep landholders, neighbours, residents, local council and relevant government agencies informed of the proposed activity and progress
- consider the interests of stakeholders in the project design and implementation
- identify key issues or concerns for stakeholders and the community and address these through the environmental assessment process
- provide timely, accurate and credible information to stakeholders and the broader community
- stakeholders.

The following stakeholders have been identified for the proposed activity:

- state government:
 - Minister for Resources and Energy
 - State Member
 - OCSG
 - NSW Environment Protection Authority (EPA)
 - NSW Office of Water (NOW)
 - Forestry Corporation of NSW (FCNSW, neighbouring landholder)
 - Roads and Maritime Services (neighbouring landholder)
 - NSW Crown Lands Division (neighbouring landholder)
 - NSW Department of Health
 - Local Land Services (North West)
- local government – Narrabri Shire Council
- neighbouring private landowners
- Crown and Castle, an entity with a telecommunications tower lease on a neighbouring property
- Narrabri Gas Project Community Consultative Committee (Narrabri CCC)
- NSW Farmers
- Namoi Water
- Narrabri Local Aboriginal Land Council (Narrabri LALC)
- The Gomeroi People (Native Title claimants)
- Narrabri Chamber of Commerce.

- local contractors/service providers
- general community

2.3.2 Broad consultation activities

Santos uses a wide range of consultation tools to engage with various stakeholders as part of its overall community engagement program for its activities within PEL 238 and PAL 2. This includes providing general information through the Santos website, media announcements and shopfront at Narrabri, monthly activity updates in the local newspaper, a monthly activity update newsletter emailed to key stakeholders, operation of a 1800 information line and enquiry email address, monthly community site tours, information stands at local agricultural shows and community events. Santos continue to host community engagement activities on site at Leewood.

Santos participates in the independently chaired Narrabri Gas Project Community Consultative Committee (Narrabri CCC) that meets monthly in Narrabri and comprises a cross-section of representative bodies within the community. Topics discussed include detailed project and impact assessment briefings, activity updates and project planning. Communiques from these meetings are uploaded to the Santos website and also distributed by participants across their networks for broader community dissemination.

Neighbouring landholders receive regular neighbour advices and monthly activity updates for works undertaken on the Leewood property.

The types of broad consultation activities Santos carries out and the targeted stakeholders are summarised in Table 2-1.

Table 2-1 Broad consultation and targeted stakeholders

Stakeholder	Consultation tools							
	Website	1800 number	One on one meetings	Project information centre	Agency workshop	Formal correspondence	Information sessions and community tours	Community consultation committee
Government agencies	•		•		•	•	•	•
Landowners	•		•		•	•	•	•
Adjacent landowners	•	•	•			•	•	
Indigenous community	•	•	•			•	•	•
Special interest groups (e.g. environment and conservation groups)	•	•	•				•	•
Local business and contractors	•	•	•	•	•		•	•
Broader community	•	•	•	•			•	•

2.3.3 Activities under stakeholder engagement plan

Table 2-2 identifies specific engagement that has occurred under the stakeholder engagement plan for the proposed activity.

Table 2-2 Activities under stakeholder engagement plan

Stakeholder	Details of engagement
OCSG	A meeting with the EPA and OCSG was held on 20 March 2014 to discuss the proposed activity. A letter advising of the activity and an Activity Overview will be sent to the relevant regional agency staff member; updates are included in the monthly Activity Update; and project progress will be discussed at Government Information Forums. OCSG is represented on the Narrabri Gas Project CCC.
EPA	A meeting with the EPA and OCSG was held on 20 March 2014 to discuss the proposed activity. A more detailed discussion of the proposed irrigation system and the water balance was held with the EPA on 2 April 2014. A letter advising of the activity and an Activity Overview will be sent to the relevant regional agency staff member; updates are included in the monthly Activity Update; and project progress will be discussed at Government Information Forums. EPA is represented on the Narrabri Gas Project CCC.
NOW	A meeting with NOW was held on 5 August 2014 to discuss the proposed activity. A letter advising of the activity and an Activity Overview will be sent to the relevant regional agency staff member; updates are included in the monthly Activity Update; and project progress will be discussed at Government Information Forums. NOW is represented on the Narrabri Gas Project CCC.
FCNSW	A letter advising of the activity and an Activity Overview will be sent to the District Manager. Updates are included in the weekly report and progress updates will be discussed at monthly face to face meetings and Government Information Forums.
Roads and Maritime Services	A letter advising of the activity and an Activity Overview will be sent to the District Manager; updates are included in the monthly Activity Update; and project progress will be discussed at Government Information Forums.
NSW Crown Lands Division	A letter advising of the activity and an Activity Overview will be sent to the relevant regional agency staff member; updates are included in the monthly Activity Update; and project progress will be discussed at quarterly Government Information Forums.
NSW Department of Health	A letter advising of the activity and an Activity Overview will be sent to the District Manager; updates are included in the monthly Activity Update; and project progress will be discussed at Government Information Forums.
Local Land Services	A letter advising of the activity and an Activity Overview will be sent to the District Manager; updates are included in the monthly Activity Update; and project progress will be discussed at Government Information Forums. Local Land Services (North West) is represented on the Narrabri Gas Project CCC.
Narrabri Shire Council	A letter advising of the activity and an Activity Overview was sent to the Mayor and General Manager on 28 July 2014. A letter advising of the activity and an Activity Overview will be sent to the District Manager; updates are included in the monthly Activity Update; and project progress will be discussed at Government Information Forums. Narrabri Shire Council is represented on the Narrabri Gas Project CCC.
Neighbouring private landowners	A letter advising of the activity and an Activity Overview was sent to neighbouring landholders on 28 July 2014. An on-site visit of the Leewood facility was held for neighbouring landholders on 1 July 2014 and the proposed activity was discussed. Leewood neighbours meetings will be held quarterly and updates are included in the monthly Activity Update.
Narrabri Gas Project CCC	An overview of the proposed activity was presented at the (previous) Santos Narrabri CCC on 23 July 2014. A Santos representative answered questions during the meeting and provided follow up responses to technical questions, through the Chair, on 6 August 2014. An overview of the proposed activity was provided to the Narrabri Gas Project CCC in March 2015. Updates are included in the monthly Activity Update that goes to CCC members; and project progress will be discussed as required at CCC meetings.
NSW Farmers	A letter advising of the activity and an Activity Overview was sent to the Regional

Stakeholder	Details of engagement
	Manager Zone 1 and the Mining and Coal Seam Gas Officer on 28 July 2014. Updates are included in the monthly Activity Update and NSW Farmers is represented on the Narrabri Gas Project CCC.
Namoi Water	A letter advising of the activity and an Activity Overview was sent to the Executive Officer on 28 July 2014. Updates are included in the monthly Activity Update and Namoi Water is represented on the Narrabri Gas Project CCC.
Narrabri LALC and the Gomeroi People	Representatives of the Narrabri LALC and Gomeroi People inspected the eastern portion of the Leewood property (including the area to be impacted by the proposed managed irrigation system and the area of Brigalow and Pilliga Box/White Cypress Pine grassy open woodland in the north) on 11 April 2014. Four Aboriginal heritage sites were identified during the inspection including two scar trees within the area of vegetation in the northern part of the site and two quartz flakes in the proposed irrigation area. These finds are discussed further in Sections 4.13 and 6.5 of the REF. The representatives were consulted regarding adequate buffer distances and protection measures (refer to Section 6.5 of the REF). Updates are included in the monthly Activity Update and Narrabri LALC is represented on the Narrabri Gas Project CCC.
Narrabri Chamber of Commerce	A letter advising of the activity and an Activity Overview was sent to the President on 28 July 2014. Updates are included in the monthly Activity Update and the Narrabri Chamber of Commerce is represented on the Narrabri Gas Project CCC.
Local contractors/service providers	An email advising of the activity and an Activity Overview was emailed to contractors on 4 August 2014. Updates are included in the monthly Activity Update.
General community	Information and progress updates are included in the monthly Activity Update in advertisements in The Narrabri Courier. The monthly site tours to Leewood for the community are advertised locally.

2.3.4 Engagement outcomes

Table 2-3 identifies the issues raised and outcomes of engagement under the stakeholder engagement plan.

Table 2-3 Outcomes of engagement under stakeholder engagement plan

Stakeholder	Issues rated	How/where issue is addressed
EPA	The REF must cover load-based licensing requirements for salt loads in the irrigation water.	Addressed in Section 5.2.3 of the REF.
	The REF must consider the Department of Environment and Conservation (DEC) Environmental Guidelines: Use of Effluent by Irrigation.	Addressed in Section 2.6.3.4 of the REF, and Appendix 3 (Concept Irrigation Design Report) considered these guidelines.
	The REF must describe an appropriate soil and groundwater monitoring program for the proposed activity.	Addressed in Sections 2.7.1 of the REF.
	The REF must describe the proposed brine disposal method.	Addressed in Sections 2.6.3 and 2.6.4 of the REF.
	The REF must assess potential impacts of permeate salts on soil quality.	Addressed in Section 6.1.1 of the REF, and Appendix 3 (Concept Irrigation Design Report) considered these guidelines.
	The REF must assess the potential for, and any impact of, salt passing through the irrigation zone.	Addressed in Section 6.1.2.1 of the REF, and Appendix 3 (Concept Irrigation Design Report) considered these guidelines.
	The REF must provide information on local groundwater systems.	Addressed in Section 4.10 of the REF.
	The REF must identify distances from the irrigation area to surface water bodies including Mollee and Bohena creeks.	Addressed in Section 4.9 of the REF.

Stakeholder	Issues rated	How/where issue is addressed
OCSG	The REF must describe the proposed brine disposal method.	Addressed in Sections 2.6.3 and 2.6.4 of the REF.
	The REF must identify planning for incident and plant failure management.	Addressed in Section 2.7.4 of the REF.
	The REF must identify waste streams of the proposed activity and how these are proposed to be managed.	Addressed in Sections 2.7.3 and 6.1.7 of the REF.
NOW	No issues were raised at the meeting on 5 August 2014 between representatives of the NOW and Santos. No subsequent queries were raised by the NOW.	N/A
FCNSW, RFS	The REF must identify if there is opportunity to use treated water for fire suppression activities.	Addressed in Section 2.6.3.5 of the REF.
Narrabri LALC and the Gomerioi People	- The two scarred tree locations were requested to be avoided. - The two isolated artefacts were requested to be avoided or relocated to avoid impact.	Addressed in Section 6.5.2 of the REF.
Other stakeholders and general public	The REF must identify how the treated water will be used.	Addressed in Sections 2.6.3.4 and 2.6.3.5 of the REF.
	The REF must identify indicative timing for the project.	Addressed in Sections 2.1 and 2.6.2.1 of the REF.
	The REF must identify how the facility is constructed to manage risks associated with plant failure.	Addressed in Sections 2.6.1 and 2.7.4 of the REF.
	The REF must identify what power source will be used for the facility	Addressed in Section 2.6.1.8 of the REF.
	The REF must assess how the reverse osmosis process deals with bacteria in the water.	Reverse Osmosis (RO) is very effective at removing bacteria from water. RO removes salt at an ion level which has a particle size generally between 0.0001 and 0.001 microns. Bacteria particle size is generally 0.5 to 10 microns. This particle size is easily removed during the RO process.
	The REF must assess how the treated water is assessed as being suitable for irrigation and pH levels are balanced to soil conditions.	Addressed in Section 2.6.1.1 of the REF and Appendix 3 (Concept Irrigation Design Report).

Issues relevant to the Leewood property and/or the proposed activity that have been raised by stakeholders during broader consultation activities are identified in Table 2-4 below.

Table 2-4 Issues raised during broader engagement

Stakeholder	Issues raised	How/where issue is addressed
FCNSW	- Requested that information on bushfire risk management and mitigation be provided. - Requested adequate notification of works undertaken on Old Mill Road, for which FCNSW is the road authority, and other activities undertaken on the site relevant to FCNSW.	- Regular meetings are held with FCNSW and feedback is incorporated into planning activities. - Mitigation measures relating to fire management and preparedness are outlined in Section 6.3.1.2. - Old Mill Road is not proposed to be upgraded as part of the proposed activity. The Newell Highway intersection was upgraded prior to construction of the

Stakeholder	Issues raised	How/where issue is addressed
		produced water and brine storage ponds. FCNSW will be notified prior to the works occurring.
Neighbouring private landowners	- Emphasised the importance of keeping neighbours informed of activities. - Identified site security and boundary fencing as an important issue. - Requested adequate notification of work activities that may impact on access along Old Mill Road.	- Monthly Activity Updates are provided to neighbouring landholders. - Individual telephone calls to neighbours about activities directly relevant to their property. - Neighbour on-site meetings will be held regularly to provide information and answer questions about the activities at Leewood. - Old Mill Road is not proposed to be upgraded as part of the proposed activity. The Newell Highway intersection was upgraded prior to construction of the produced water and brine storage ponds. Neighbouring landowners will be notified prior to the works occurring.
Santos Narrabri CCC	- Enquiries have previously been made about: - how produced formation water is proposed to be managed - how salt by-products from water treatment are proposed to be managed - Santos' preparedness for fire management in State forest.	- The main objective of the proposed activity is to manage and treat produced water, as outlined in Section 2.6. - The resulting concentrated brine from the brine treatment plant will be stored in the brine storage ponds on site and/or disposed of to landfill, as discussed in Sections 2.6.1.2 and 2.6.3.3. - Santos has a fire response procedure developed in liaison with NSW Rural Fire Service (RFS) to address wildfire concerns in the local area. - Santos will continue to participate in RFS and FCNSW fire management and preparedness planning. - Mitigation measures relating to fire management and preparedness are outlined in Section 6.3.1.2.

2.3.5 Future and ongoing consultation activities

Santos will continue the broad consultation program described in Section 2.3.3 prior to and during construction and operation of the proposed activity. Further specific consultation for the proposed activity will occur prior to construction commencing. These activities are identified in Table 2-5.

Table 2-5 Proposed engagement prior to construction commencing

Stakeholder	Engagement activity
NOW	- Face to face briefing. - Government Information Forum and field visit. - Information for assessment officers. - Representative is a member of Narrabri Gas Project CCC that will receive regular updates.
FCNSW	- Face to face briefing. - Government Information Forum and field visit. - Information for local officers. - Updates in monthly Activity Update newsletter.

Stakeholder	Engagement activity
Roads and Maritime Services	- Government Information Forum and field visit. - Information for local officers. - Updates in monthlyActivity Update newsletter.
NSW Crown Lands Division	- Government Information Forum and field visit. - Information for local officers. - Updates in monthlyActivity Update newsletter.
NSW Department of Health	- Government Information Forum and field visit. - Information for local officers.
Local Land Services	- Government Information Forum and field visit. - Information for local officers. - Updates in monthlyActivity Update newsletter. - Representative is a member of Narrabri Gas Project CCC that will receive regular updates.
Narrabri Shire Council	- Government Information Forum and field visit. - Information for Council officers. - Updates in monthlyActivity Update newsletter. - Representative is a member of Narrabri Gas Project CCC that will receive regular updates.
Immediate neighbours adjoining Leewood	- On-site neighbours meeting quarterly. - Regular updates in monthlyActivity Update Newsletter.
Landholders in immediate area	- Information. - CommunitySite Tours.
Narrabri Gas Project CCC	- Face to face briefing. - Information for members. - Field visit. - Updates in monthlyActivity Update newsletter.
NSW Farmers (Narrabri Branch)	- Information. - CommunitySite Tours. - Representative is a member of Narrabri Gas Project CCC that will receive regular updates.
Namoi Water	- Information. - CommunitySite Tours. - Representative is a member of Narrabri Gas Project CCC that will receive regular updates.
Narrabri Chamber of Commerce	- Information for members. - CommunitySite Tours. - Representative is a member of Narrabri Gas Project CCC that will receive regular updates.
Contractors	- Contractor Forum. - Information for existing contractors. - CommunitySite Tours.
General community	- Monthly CommunitySite Tours. - Updates in The Narrabri Courier, including monthlyActivities Update advertisements. - Pro-active articles in local media. - Santos shopfront in Narrabri. 1800 freecall information number. - Energy NSW information email.

Stakeholder	Engagement activity
	▪ Santos ENSW Website. ▪ Displays at local agricultural shows and field days. ▪ Staff briefings on project and key messages.

2.3.6 Stakeholder complaint and conflict management

Santos' primary approach to conflict management is open and proactive communications with all stakeholders.

The 1800 information line is available 24 hours per day, seven days per week and is provided on all project communication materials including community updates, fact sheets and stakeholder and community letters. Santos aims to respond to all enquiries or complaints received via the information line within two business days.

To manage enquiries or complaints received, Santos maintains a complaint register of:

- all project related concerns or complaints received from individual members of the community or representative bodies
- the response provided or action taken
- a system to track notes on progress to resolution.

Santos has a documented complaint management procedure which is communicated to relevant staff members. This procedure involves the following steps:

- capture enquiry or complaint and record details, including time and date the call/email is received, contact name, phone number, and nature of enquiry/complaint and any response provided
- assess and investigate enquiry/complaint by the relevant business unit and escalate if unable to be resolved
- where a complaint involves a reportable incident, notify OCSG and/or EPA as required by the relevant petroleum lease/licence or environmental protection licence and relevant legislation
- where possible, provide the enquirer/complainant a timeframe for responding to them or resolving the issue, and keep them updated on progress
- close out complaint/enquiry and record all communication actions and responses
- report all issues weekly to the Santos management team.

2.4 Justification of activity

2.4.1 Objectives

The overall objectives of the proposed activity are to:

- establish a purpose-built WBTP to treat and beneficially reuse produced water from Santos' exploration and appraisal activities.

The design objectives for the WBTP include:

- ensuring produced water can be treated to a quality suitable for managed irrigation
- incorporating plant/processes to reduce the overall volume of brine to be managed.

2.4.2 Method and scale

The WBTP will enable the treatment of the produced water via reverse osmosis technology, discussed in further detail in Section 2.6.3.2. The treated water will be of such quality to enable its reuse for irrigation and other beneficial uses. The proposed activity will also allow the study of brine reduction technology, which will in turn allow the overall volume of waste to be reduced.

The proposed activity has been designed to adequately cater for Santos' existing and proposed exploration and appraisal activities.

The appraisal program is estimated to produce a total approximate volume of 1.4 gigalitres of produced water from 2014 to 2018 with an average daily production of one megalitre and a peak daily production of 1.5 megalitres over the operational period.

The treated water will be used in the irrigation system at Leewood and other beneficial uses for CSG activities undertaken in PEL238, PAL 2 and PPL 3 such as construction, drilling, dust suppression and for fire fighting, if required.

2.4.3 Location

The proposed activity will be located on the Leewood property adjacent to Leewood produced water and brine storage ponds. The Leewood property was selected during early planning for the facility as it:

- was able to be acquired by Santos, thus allowing Santos flexibility to operate as needed and thereby avoiding disruption to another landowner's operations
- is outside the Pilliga forest and would minimise impacts on ecological values associated with the Pilliga forest
- has minimal other ecological values (refer to Section 4.11)
- does not represent high quality agricultural land (refer to Section 4.4) and is not within mapped Biophysical Strategic Agricultural Land (BSAL).

The property's proximity to Santos' existing infrastructure was also a key consideration during selection of the site. Leewood is located between Santos' existing facilities at Bibblewindi (including a gas compressor and produced water storage ponds) and Wilga Park Power Station. The buried pipeline which conveys gas from Bibblewindi to Wilga Park Power Station also crosses the property. This allowed the Leewood produced water flow line (approved by the DRE on 19 March 2013) to be constructed within the existing gas pipeline easement, avoiding significant vegetation removal. It will also allow the offtake of gas from the pipeline to provide gas-fired power generation at Leewood.

The proposed site is suitable for cropping and managed irrigation as it is relatively flat, will require removal of only low quality vegetation and is free of surface rock outcrops. Cropping and irrigation will also be consistent with surrounding land uses. While there are some limitations to irrigating the site, including the relatively low quality soils and potential partial flooding of the lower (central) part of the site during rain events up to twice a year on average, these can be overcome by soil amelioration, use of a sub-surface drip irrigation system in the flood affected area and appropriate site management.

2.4.4 Consistency with ecologically sustainable development

The proposed activity is considered to be justified in terms of its consistency with the principles of ecologically sustainable development. Ecologically sustainable development is a primary object of the EP&A

Act and is defined under section 4 of the EP&A Act as having the same meaning as section 6(2) of the *Protection of the Environment Administration Act 1991*, being:

...ecologically sustainable development requires the effective integration of economic and environmental considerations in decision-making processes. Ecologically sustainable development can be achieved through the implementation of the following principles and programs:

- (a) *the precautionary principle—namely, that if there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation,*
- (b) *inter-generational equity—namely, that the present generation should ensure that the health, diversity and productivity of the environment are maintained or enhanced for the benefit of future generations,*
- (c) *conservation of biological diversity and ecological integrity—namely, that conservation of biological diversity and ecological integrity should be a fundamental consideration,*
- (d) *improved valuation, pricing and incentive mechanisms—namely, that environmental factors should be included in the valuation of assets and services.*

The proposed activity's consistency with these principles is outlined in Table 2-6.

Table 2-6 Consistency of proposed activity with ecologically sustainable development principles

Principle	Proposed activity's consistency
Precautionary principle	Measures to prevent the environmental degradation of the site will be implemented during all phases of the proposed activity. The soil and water monitoring program referred to in Section 2.7.1 will allow changes to the environment to be monitored and corrective action to be implemented if required. A precautionary approach was taken during the design phases of the proposed activity, which aimed to avoid significant environmental constraints, thereby minimising the risk of serious or irreversible harm to the environment as a result of the proposed activity. The site is located outside the Pilliga forest, to minimise impacts on ecological values associated with this area. During the environmental assessment process, investigation into a range of issues was carried out to determine the full potential impacts of the proposed activity. This included commissioning air quality, noise, greenhouse gas, transport, hazard assessment, agricultural and groundwater studies, and drawing on information from technical specialists including heritage consultants, ecologists, engineers, geologists and hydrogeologists.
Intergenerational equity	The proposed activity has been designed in accordance with sustainable management principles. It will assist in providing a comprehensive water management process for Santos' exploration and appraisal activities in the area, to ensure that potential impacts of the activities are not left to be addressed by future generations. Whilst the proposed activity will have limited impact on the local economy, the future development of a commercial gas project would have wider economic benefits both to the local and NSW economy. The proposed activity will consume minor quantities of non-renewable resources; concentrated brine will be disposed of to landfill.
Conservation of biological diversity and ecological integrity	The proposed activity has been located and designed to avoid potential impacts to biodiversity and ecological integrity. The proposed activity has been situated such that the sensitive vegetation will not be impacted by the proposed activity. Some areas of non-significant vegetation will be removed to facilitate the proposed activity; however this will not result in significant impacts to any threatened species, population or ecological community, or their habitat.
Improved valuation, pricing and incentive mechanisms	While clear and widely accepted standards have not yet been established for the application of this principle, Santos acknowledges and accepts the financial costs associated with all the measures required to avoid, minimise, mitigate and manage potential impacts of the proposed activity.

2.5 Alternatives

2.5.1 Water treatment plant processes

The produced water requires desalination prior to the proposed beneficial use for irrigation and other beneficial uses due to its salinity.

The following desalination technologies were considered as potential options:

- reverse osmosis (RO)
- forward osmosis
- ion exchange
- Higgins loop
- electrodialysis/electrodialysis reversal
- vibratory shear enhanced process
- capacitive deionization
- thermal processes.

Table 2-7 outlines the relative advantages and disadvantages for the technologies considered.

Table 2-7 Advantages and disadvantages of water treatment plant technology options

Technology	Advantages	Disadvantages
Reverse osmosis	▪ Proven technology for removing dissolved compounds from water. ▪ Capable of treating a wide range of TDS (1,000-35,000 mg/L). ▪ Commercially available from multiple vendors.	▪ Membranes require regular cleaning. ▪ Increased energy requirements (however, lower than thermal desalination). ▪ Pre-treatment processes are required.
Forward osmosis	▪ Capable of treating wide range of TDS, from brackish waters with TDS of 500 mg/L to seawater with TDS of 35,000 mg/L. ▪ High recovery. ▪ Low energy requirement.	▪ Currently in the development stage and not a commercial scale product ▪ Not a proven technology for treating produced water or similar.
Ion exchange	▪ High recovery. ▪ Low energy requirement.	▪ Large chemical usage to regenerate resins and therefore large waste stream produced. ▪ Significant resin cost associated with the size of plant required for use as sole treatment process.
Higgins loop	▪ High recovery. ▪ No pre-treatment process required.	▪ High chemical consumption for resin regeneration. ▪ Carbon dioxide by-product produced and vented. ▪ Large number of process valves required. ▪ High volumes of resin and ongoing resin loss.
Electrodialysis/electrodialysis reversal	▪ Limited pre-treatment required. ▪ Low scaling potential.	▪ Typically used on high hardness, lower salinity waters (TDS 200-500 mg/L).

Technology	Advantages	Disadvantages
		- Not cost effective at higher TDS due to high energy use. - Not a proven technology for treating produced water or similar. - Only available from one vendor in Australia.
Vibratory shear enhanced process	- High flux. - High recovery.	- Many moving parts. - Limited performance track record. - Not a proven technology for treating produced water or similar.
Capacitive deionization	- High recovery. - Low energy requirement.	- Not commercially supported in Australia nor available at the application size required. - Influent TDS limited to 2,500 mg/L. - Not a proven technology for treating produced water or similar.
Thermal processes: - Multi-stage flash distillation. - Multiple effect distillation with either mechanical vapour compression or thermal vapour compression. - Membrane distillation. - Brine concentrator with either mechanical vapour compression or thermal vapour compression.	High recovery – each process uses heat to evaporate water, leaving a highly concentrated waste stream (TDS > 20,000 mg/L).	- High energy requirement. - High capital cost.

Of the technologies reviewed, only RO and thermal technologies were considered proven and capable of treating the produced water. RO was considered the most appropriate technology as it:

- is a proven technology that is widely available and used on a wide variety of applications, including all major CSG projects currently in operation or development
- has lower specific energy consumption than thermal treatment
- is highly modular, enabling relatively simple increases in plant capacity to allow for increases in produced water volume
- is more cost effective than thermal treatment.

2.5.2 Brine treatment plant processes

To reduce the overall volume of brine to be managed, it is necessary to further concentrate brine beyond the limit of conventional RO technology. A range of treatment technologies were considered for further processing the brine produced from the RO process.

Table 2-8 outlines the relative advantages and disadvantages for the technologies considered.

Table 2-8 Advantages and disadvantages of brine treatment plant technology options

Technology	Advantages	Disadvantages
Membrane Brine Concentrator (high pressure RO)	- Lower energy consumption. - Utilised existing technology. - Limited exotic materials required. - Operates at ambient temperatures.	- Membranes require regular cleaning. - Plant availability may be low.
Multi-stage flash distillation	- Longest track record. - Low fouling propensity.	- Older technology that consumes 50% more energy than multi-effect distillation. - Low concentration ratios.
Multiple-effect distillation	- Operates at low temperatures (<70°C). - More efficient compared with multi-stage flash distillation. - Less capital intensive compared with brine concentrator (mechanical vapour compression/ thermal vapour compression) and multi-stage flash distillation - Utilises waste heat.	- Greater number of packages as not supplied with an integrated crystalliser. - Issues with foam. - Reliance on waste heat, therefore dependent on other infrastructure being in place before commissioning.
Brine concentration utilising mechanical vapour compression	- More efficient compared with multi-stage flash distillation. - Foam is not an issue compared with multi-effect distillation. - Less dependent on other infrastructure being in place prior to commissioning (mechanical vapour compression is an electrically driven process, rather than driven by waste heat). - Less potential for noise issues compared with steam ejectors. - No supplementary cooling required.	- High energy requirements. - Tall units may result in increased visual impact. - High capital expenditure compared to multi-effect distillation.
Brine concentration utilising thermal vapour compression	- More efficient compared with multi-stage flash distillation. - Foam is not an issue compared with multi-effect distillation. - Utilises waste heat.	- Higher capital expenditure compared with multi-effect distillation. - Brine concentrators (mechanical vapour compression or thermal vapour compression) are tall units which in some circumstances can have a visual amenity impact. - Reliance on waste heat, hence dependent upon other infrastructure being in place before commissioning. - Noise from the thermo-compressor is a challenge. - Requires supplementary cooling.
Membrane distillation	- Utilises a low-grade heat source. - Maintains process performance almost independently of feed solution TDS concentration.	Unproven technology in the industry.

Thermal concentration technologies typically employ thermal vapour compression or mechanical vapour compression to enhance the efficiency of the process. Thermal vapour compression processes require the addition of a heat source (typically steam) and also require supplementary cooling (usually provided by cooling towers), whereas the only energy input into mechanical vapour compression plants is electrical energy. Using semi-quantitative assessment criteria it was determined that for the relatively short term appraisal program the membrane concentrator technology is appropriate due to lower energy consumption and low environmental impacts of the process. The assessment included technical and non-technical parameters such as ease of delivery, operational requirements, cost and health and safety considerations.

2.6 Description of the activity

2.6.1 Design overview

Major water treatment process units within the WBTP will be enclosed within containers. Details of the proposed WBTP location are shown in the site layout drawing in Appendix 1.

2.6.1.1 Water treatment plant

The design layout and location of the water treatment plant (refer to site layout drawing in Appendix 1) shows the units will be housed within approximately 12, 12 metre long shipping containers. The footprint of the water treatment plant containerised-infrastructure will be approximately 50 by 50 metres within a bunded area situated within a platform of 110 by 180 metres to accommodate a five megalitre treated water storage tank and access roads.

The water treatment plant will treat up to 1.5 megalitres of produced water per day, converting 65-70 per cent of this volume to treated water and 30-35 per cent to brine. The ponds at Leewood currently hold about 150 megalitres of brine that was produced at the Bibblewindi Water Treatment Plant during previous exploration and appraisal activities. This brine will be processed through the produced water and brine treatment plant at Leewood as part of the proposed activity. The expected water quality of the produced water and brine that will enter the water treatment plant is provided in Appendix 2.

The water treatment plant is designed to treat produced water and brine in three stages, comprising of pre-treatment, treatment and post-treatment. The three process stages are shown in Figure 2-4, while further details of these processes are provided in Section 2.6.3.2.

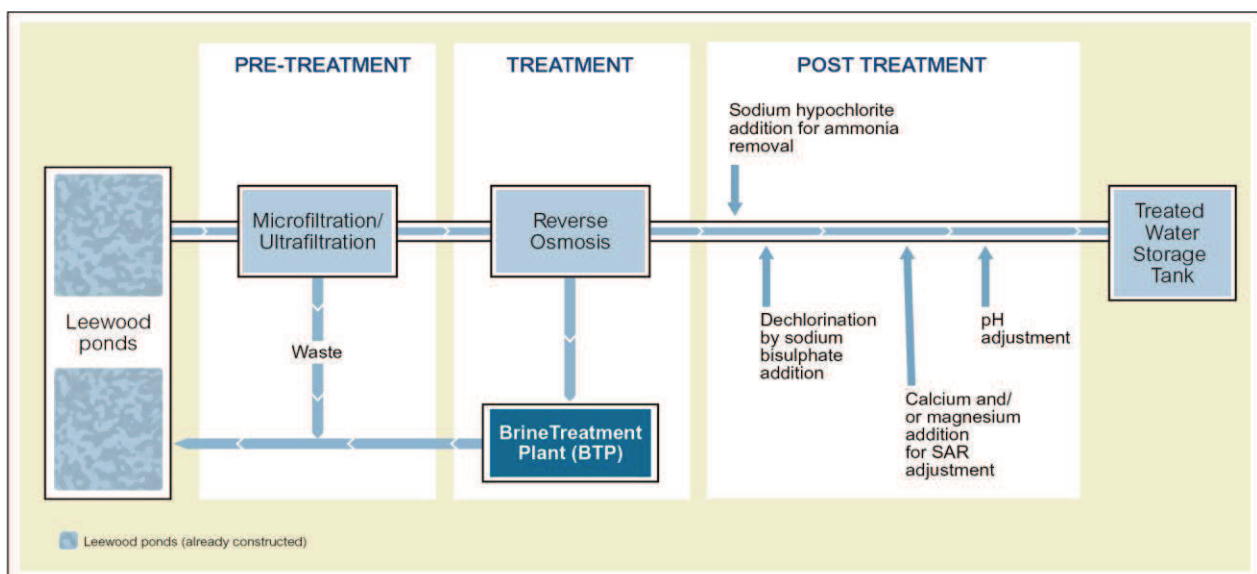


Figure 2-4 Water treatment plant process

Treated water from the RO is expected to have a total dissolved solids (TDS) content of less than 650 milligrams per litre, and a high sodium adsorption ratio (SAR) due to the low calcium and magnesium. The SAR of the treated water will be adjusted to appropriate levels for irrigation use during post treatment (discussed in further detail in Section 2.6.3.2).

The expected water quality of the treated water that will be used for irrigation is shown in Table 2-9. This water quality will be achieved for water fed from either the produced water or the brine stream. The chemical dosing will ensure that the water quality is optimal for soil /water interactions and ongoing soil structure maintenance during irrigation use.

Table 2-9 Expected irrigation water quality

Parameter	Expected treated water ¹
pH	6-8.5
TDS (mg/L)	<650
Salinity (mS/cm)	1.0
Turbidity (NTU)	<1
SAR	<5
Calcium (mg/L)	52
Magnesium (mg/L)	0.04
Sodium (mg/L)	131
Potassium (mg/L)	7
Ammonia-N (mg/L)	6
Boron (mg/L)	0.7
Alkalinity (mg/L CaCO ₃)	262
Chloride (mg/L)	120
Fluoride (mg/L)	0.3
Sulfate (mg/L)	0.0
Total N (mg/L)	Feed reduced by 50%
Total P (mg/L)	Feed reduced by 94%
Silica (mg/L SiO ₂)	0.9

2.6.1.2 Brine treatment plant

The brine treatment plant will concentrate brine from the water treatment plant to reduce the volume of brine required to be managed. The brine treatment plant will produce approximately 0.5 megalitres of brine per day.

The expected footprint for the brine concentrator is approximately 20 by 20 metres within a bunded area situated within a platform of 110 by 180 metres to accommodate a five megalitre treated water storage tank and access roads, refer to Appendix 1.

¹ Treated water following chemical dosing, prior to entering the irrigation system.

2.6.1.3 Water pumps and flowlines

Pumps will be located around the site to enable the transfer of water and brine between the storage and treatment and irrigation infrastructure components and will include:

- transfer pumps adjacent to the produced water, brine and treated water ponds
- within the water treatment plant as part of the treatment process
- transfer pumps within the WBTP to transfer flow from the water treatment plant and brine treatment plant to the various storage ponds and tanks.

The majority of the transfer pumps will be skid mounted (or in containers) equipment manufactured offsite and delivered to site for installation. Pumps will be in a duty/standby configuration and controlled via a local control panel which will be connected to the overall site system controls. These will be able to be operated remotely.

Water flowlines are proposed to be installed to allow transfer of water and brine for the treatment process. Flowlines will vary in size ranging from approximately 110 to 400 millimetres in diameter. In general, buried flowlines will be high density polyethylene, while above ground pipework will consist of high density polyethylene, polyvinylchloride, carbon steel and various grade of stainless steel depending on pressure and application.

Indicative pump and flowline locations are shown in the site layout drawing in Appendix 1.

2.6.1.4 Fuel gas conditioning skid and associated infrastructure

A new fuel gas conditioning skid (FGCS) will be provided at Leewood to treat field gas for use in power generation for the activity. The skid will remove all liquid droplets and solid contaminants from the gas, and adjust the gas temperature to the injection requirements of the gas generator. The FGCS will be supplied by field gas from a proposed connection to the existing buried gas flowline that runs in a north-south direction through the middle of the Leewood property. The new FGCS will be located on a reinforced concrete slab foundation.

Water drainage from the new FGCS will be directed to a concrete sump with instrumentation linked to the control system. Once the sump reaches a set level, water will be pumped from the sump to the water treatment plant waste collection system.

2.6.1.5 Treated water storage tank

A treated water storage tank will store water that has been treated in the water treatment plant prior to its reuse. It will comprise a galvanised steel panel tank with an internal polypropylene bladder. It will have roof bracing for structural integrity, but no roof panelling, to allow ventilation. The tank will be sized for a maximum operating volume of approximately five megalitres of treated water.

The tank will include level sensors and transmitters to:

- alert operators in the event of a high level in the tank level to initiate operator action if required
- close the tank discharge valve in the event of low tank level to avoid air entrainment and pump damage
- modulate discharge flow rate to maintain a tank level setpoint, under normal operation when the irrigation area can accept water.

2.6.1.6 Potable water treatment system

A small potable water treatment system will be installed to treat water extracted from the licenced bore at Leewood. This will consist of a sand or micro-filtration and chlorine dosing system.

2.6.1.7 Chemical storage

Chemicals will be stored adjacent to the water treatment plant in bunded containers with appropriate separation of chemical classes. The chemical storage and unloading areas will be designed in accordance with the relevant Australian Standards (including *AS 3780 The storage and handling of corrosive substances* and *AS1940 The storage and handling of flammable and combustible liquids*) requirements. Safety showers will be provided, in accordance with Australian Standards at each chemical storage area.

Chemical storage and mitigation measures are discussed in more details in Section 6.1.8 of this REF.

2.6.1.8 Power generation

Power generation infrastructure for the WBTP will consist of:

- one containerised gas generator of about 1,400 kWe
- one 800 kWe resistive load bank
- two backup diesel generators of approximately 800 and 200 kWe
- a HDPE pipeline running from the gas line riser and easement to the fuel gas conditioning skid.

The gas generator will be the primary source of power onsite. Gas will be supplied from the proposed fuel gas conditioning skid. If the gas generator is off-line or there is no gas supply to the site, then back up power supply will be generated via one of the diesel generators. The backup generators have been sized to supply only for critical equipment and lighting.

It is expected that the gas generator will be housed in a twelve metre container. The generator units are expected to be about 3.2 metres high. The additional exhaust and cooling system on top of the unit, incorporating a single stack, would add about another 6.8 metres in height (producing a resultant height of approximately 10 metres).

2.6.1.9 WBTP amenities and ancillary facilities

WBTP amenities including the control room will support the operation of the proposed activities at the site. The control room will oversee the WBTP operations including the transfer of produced water and brine between the infrastructure onsite via the pumps and flowlines. The onsite laboratory facility will allow for testing as required for the WBTP process control.

A site office area will be constructed in the area to the south of the ponds, which will comprise office space and amenities for employees, as well as associated car parking. It is anticipated the site office and car park will remain for the duration of operations. The proposed office and car park locations are shown in the site layout drawing in Appendix 1.

Sewage from the ablution facilities of the WBTP will be collected in an effluent tank and transported offsite for disposal at a licensed waste facility. Sewage will not be treated in the WBTP.

2.6.1.10 Irrigation infrastructure

The concept irrigation design, provided in Appendix 3, combines two technologies enabling irrigation of 97.8 hectares. It employs a centre-pivot irrigator fitted with Variable Rate Irrigation technology to cover 49.5 hectares and a subsurface drip irrigation system to cover 48.3 hectares. This configuration was designed to accommodate the area and soil types at the site. The dual system will be capable of delivering peak water demand of 12 millimetres per day across the 97.8 hectares. The maximum daily capacity would be 11.7 megalitres per day. The systems would be able to be operated simultaneously.

The centre-pivot irrigator and the subsurface drip irrigation systems will be supplied by separate mains and pumps, as detailed in Appendix 3. These will be separated as the subsurface drip irrigation system has extra requirements for filtration and disinfection. The whole irrigation system – pumps station, irrigation infrastructure and soil moisture sensors would be monitored and capable of being controlled remotely via telemetry.

2.6.1.11 Treated water pipeline

A pipeline is proposed to be constructed at Leewood, extending to the property boundary, which will enable the provision of treated water for third party beneficial use for agricultural irrigation offsite. Treated water consistent with the quality of water which is to be irrigated on the Leewood site will be able to be provided for third party use. The provision of treated water to third parties for off-site agricultural irrigation will be subject to separate assessment and approvals and does not form part of the activity for the purposes of this REF.

The exact location of the pipeline within the Leewood site is yet to be determined. However, the pipeline would not be located within the Brigalow and is expected to be contiguous with the existing gas pipeline alignment. It will be situated to avoid impacts to identified ecological and heritage values as outlined in Sections 6.2, 6.5 and 6.6.

2.6.1.12 Beneficial reuse of treated water for irrigation off-site

The operation of an offsite irrigation scheme by another user would be guided by an Irrigation Management Plan that seeks to ensure:

- the design takes into account baseline soil sampling and consideration of any sensitive environmental receptors
- soil structure, stability and productive capacity is maintained
- irrigation efficiency through use of control systems to adjust application rates or other factors to maintain performance
- erosion is minimised and effective stormwater runoff controls are implemented
- sufficient storage capacity within the system to address wet weather conditions, e.g. water storage dams
- a program of regular and appropriate monitoring is implemented to measure, record and identify any actions required to ensure the environmental performance of the system
- the productive use of the water resource for a beneficial use.

The supply of the treated water for irrigation will be the subject of an agreement between Santos and the user. Construction of a pipeline outside of the Leewood property and operation of an offsite irrigation scheme by another user are not considered part of the proposed activity, and are not assessed within this REF.

2.6.2 Construction

2.6.2.1 Construction activities

It is anticipated that construction activities will take place over a period of approximately 50 weeks, weather dependent. The works will be closely staged wherever possible to ensure timely delivery. Construction works will be managed by a Principal Contractor and be carried out in accordance with the *Work Health and Safety Act 2011* and associated regulations.

The typical construction process for the proposed activity is outlined in Table 2-10. The construction contractor appointed by Santos will determine the precise construction methodology.

Estimated cut and fill quantities for the civil works are provided in Table 2-11.

Table 2-10 Estimated WBTP construction activities

Stage	Activities
Mobilisation (6-8 weeks)	- Site establishment including services identification, survey, mobilisation, installation of temporary security fencing, amenities and exclusion fencing. - Vegetation removal and removal of existing infrastructure, as required. Where possible, timber shall be mulched and stockpiled for reuse during restoration. - Construction of erosion and sediment controls in accordance with <i>Managing Urban Stormwater: Soils and Construction – Volume 1</i> (Landcom, 2004) (the Blue Book). - Clear, strip and stockpile topsoil in designated area to be established by the relevant construction contractor for use in site restoration on completion of works.
Amenities and services (2 weeks)	- Subgrade and grade layers installation and compaction. - Set up/construction of demountable site offices, amenities buildings, storage compound and laydown area. - Laying concrete slab foundations. - Set up of temporary diesel generators for construction site power.
Earthworks (6-8 weeks)	- Excavation and construction of foundations to provide adequate structural support for buildings, unit processes for the WBTP, pumps, modular treatment units and chemical storage facilities. - Cut and fill balancing to minimise need for additional fill materials to the site (refer to Table 2-11 of the REF). - Pump out of groundwater and rainwater captured during excavation. - Open trenching for the installation of buried services, conductions, connections to incoming flowlines and site drainage piping. - Backfilling, compaction of backfilling materials and stockpiling. - Spoil movements.
Structures (2 weeks)	- Delivery of demountable buildings to the site. - Lifting and placing steel frames and demountables using cranes. - Erection of steel frame buildings.
Internal roadworks (4-6 weeks)	Construction of the internal permanent roadways including hardstand, turning and parking areas.
Mechanical and electrical (10-12 weeks)	- Unloading and installation of WBTP components and equipment. - Installation of piping. - Pipe welding and cutting. - Installation of cable trays, lighting, etc. - Testing of power and instrumentation wiring.
Flowlines (6-8 weeks)	- Trench excavation. - Installation of piping.
Irrigation area (8 weeks)	- Land clearing. - Amelioration of soils to enable the breakdown and stabilisation of the poorly drained soils on-site. This will be done via application of gypsum and lime, deep ripping, fertiliser and cultivation (refer to Appendix 3 for further details). - Installation of centre-pivot, subsurface drip, pump station and main lines. - Installation of a treated water pipeline extending to Leewood property boundary. - Crop establishment (refer to Appendix 3 for further details).
Demobilisation and restoration (6-8 weeks)	- Removal of materials and plant from site. - Restoration to occur in accordance with a final landscape plan to be developed, so that rehabilitation and reinstatement works can be undertaken as soon as practicable following completion of construction activities. - Topsoil will be treated and spread over the disturbed area to encourage vegetation growth. - Stockpiled mulch from vegetation clearing works will be distributed around the site to reduce the risk of erosion of topsoil.

Table 2-11 Estimated cut and fill volumes (may change subject to detailed design)

Construction element	Material	Volume (m ³)
Water treatment plant bunded platform and treated water storage tank platform	General excavation: Topsoil, maximum depth not exceeding 0.25m. (Disposal of excavated material, topsoil to location on Leewood site defined by Santos).	1,285
	Filling: General: General fill.	4,385
	Filling: General: Selected fill (gravel fill; access tracks, power generation compound, WTP area, site offices).	1,200
Site access track	(660m total length) General excavation: Topsoil, maximum depth not exceeding 0.25 m. (Disposal of excavated material, topsoil to location on Leewood site defined by Santos).	440
	(660m total length) Imported gravel: Depth not exceeding 100-150 mm.	740
Pipework – trench excavation	Surplus excavated material to location on Leewood defined by Santos.	500

2.6.2.2 Staff and recommended construction hours

The total number of staff required for the construction period will vary between each stage of works. The construction workforce is estimated at a maximum of 50 staff during peak activities.

Construction activities will generally be undertaken from 7:00am to 6:00pm Monday to Sunday. Refer to Section 2.7.6 for further details.

2.6.2.3 Construction vehicle movements

Table 2-12 shows the approximate number of external peak heavy vehicle movements during the construction period.

Table 2-12 Peak heavy vehicle external movements during construction

Construction Stage	Construction activity	Estimated duration	Peak trips per day	Vehicle type	Activity use
1	Mobilisation	6-8 weeks	20	- Standard flatbed trucks 19 m-25 m articulated heavy vehicles - Low loader (minimal)	Delivery of plant equipment, construction amenities to site and temporary services
	Irrigation area		10	Standard flatbed trucks	Land preparation
2	Earthworks	6-8 weeks	40	Tippers for spoil transportation	Excavation and trenching
	Irrigation area		10	- Standard flatbed trucks - Articulated vehicles - Semi-trailers - Large Rigid Vehicles	Land preparation and installation
3	Concrete	2 weeks	20	Concrete trucks	Concrete trucks deliveries for foundation pours
	Irrigation area		5	- Standard flatbed trucks - Semi-trailers - Large Rigid Vehicles	Installation
4	Mechanical and electrical	10-12 weeks	20	N/A	Delivery and installation of WBTP plant and equipment

Construction Stage	Construction activity	Estimated duration	Peak trips per day	Vehicle type	Activity use
	Irrigation area	13 weeks	5	- Standard flatbed trucks - Semi-trailers - Large Rigid Vehicles	Installation

2.6.2.4 Access and construction traffic management

Access to the site during construction of the proposed activity will be from Old Mill Road which runs directly off the Newell Highway, to the south of the Leewood site.

Further discussions on site access and traffic management are provided in Section 6.3.2, as well as the traffic impact assessment provided in Appendix 4.

2.6.2.5 Plant and equipment

Locally sourced equipment and materials that can be easily transported to and from the site will be used where practicable for all construction activities. Potential construction equipment to be used may include, but is not limited to:

- 4WD
- vacuum truck
- water cart
- dozer
- excavator
- tipper
- mulcher
- concrete truck
- kerb profiler
- dump truck
- generator
- grader
- rollers
- whacker
- crane
- elevated work platform (EWP)/cherry picker
- hand tools
- truck and dog
- backhoe
- welder.

2.6.2.6 Site water requirements

Construction activities will require approximately 100 megalitres of water which is proposed to be sourced from the licensed water supply bore already on the Leewood property or an alternative appropriately licenced water supply bore. In addition, approximately 0.01 megalitres per day of potable water will be required for facilities during construction. This will be sourced from Narrabri's town water supply or another lawful source and trucked to site.

Water licensing requirements are discussed in Section 5.2.4.

2.6.3 **Operation**

2.6.3.1 Operational activities

The WBTP operational activities will include:

- water treatment plant operations, monitoring and maintenance

- brine treatment plant operations, monitoring and maintenance
- ancillary activities to support the above, utilities, power generation and other site operations, monitoring and maintenance
- pond operations and monitoring.

Further activities include:

- onsite irrigation of the treated water and management of the irrigation operation, including appropriate crop, water and soil management
- use of treated water both on and off-site for dust suppression, construction and drilling activities and emergency firefighting
- monitoring of all chemical storage levels, re-ordering of chemicals and managing chemical deliveries
- bund inspections and leak detection.

2.6.3.2 Water treatment plant

Once at the water treatment plant, the produced water or feed water will undergo a series of treatments comprising pre-treatment, treatment and post-treatment, as shown in Figure 2-4 and described in further details below.

Feed water to the water treatment plant may include:

- produced water,
- brine,
- condensate water from the fuel gas conditioning skid; and,
- WBTP solids streams (e.g. membrane filtration backwash) which will need to go through a solids removal step before being returned to the feed. The solids will be disposed of to landfill.

Pre-treatment

Pre-treatment of feed water enables the removal of solids and/or scale-causing compounds from the water. To remove solids and/or scale causing compounds, produced water will first undergo microfiltration/ ultrafiltration to remove solids between 0.01 – 0.1 microns within the feed water. The final pre-treatment process involves using a biocide for bio-fouling control. This step controls the growth of microorganisms, both in the microfiltration/ultrafiltration and RO stages.

Treatment

Following pre-treatment, feed water is transferred to the RO plant for treatment. Here the produced water is pumped through a semi-permeable membrane, separating treated water into one stream and salts into another stream known as rejected concentrate or 'brine'. Feed water is pumped at high pressure through the membranes, typically separating over 99 per cent of the TDS from the water.

Post Treatment

Post treatment of the produced water involves a series of steps in order to chemically balance the treated water prior to its beneficial reuse, in particular its use for irrigation. This includes:

- dechlorination by sodium bisulphate addition (this is dosed prior to the RO to protect the RO membranes from oxidation by chlorine)

- addition of calcium and magnesium to lower the sodium adsorption ratio (SAR)
- adjustment of pH by acid or caustic addition, if required.

The SAR of the treated water is of particular importance as it will be used for irrigation. The SAR is an indicator of the relative proportion of sodium ions in water to those of calcium and magnesium. In general, the higher the SAR, the less suitable the water is for irrigation. Chemical dosing of the treated water to lower the SAR assists to maintain or improve soil structure stability.

Similarly, the elevated electrolyte concentration of the treated water following chemical dosing will encourage aggregation of soil particles and assist in soil permeability when applied as irrigation water. The added calcium may also assist with maintenance of soil structure.

Additional chemical treatments may be required for subsurface drip irrigation to avoid potential blockages and maintain the structural integrity of the soil profile over the life of the proposed activity.

Solids handling

Solids, mainly algae, removed in the microfiltration/ ultrafiltration process are backwashed from the system and further treated to remove the solids in the form of a wet cake and the water (filtrate) is returned to the head of the process.

Primary dewatering

To assist the removal of solids, a process known as coagulation and flocculation (whereby chemicals are dosed into the water in a tank and stirred to encourage the suspended solids particles to coalesce and produce a thickened sludge for further treatment) is utilised:

- coagulants (inorganic) and/or flocculants (polymer) are added to promote the agglomeration and flocculation of fine and colloidal material for fast settling, flotation or filtration
- acid may be added to adjust the pH to facilitate the effectiveness of the coagulant.

The clarified water is directed back to the head of the process for further treatment.

Secondary dewatering

The thickened sludge is then passed over a secondary dewatering device under slight pressure to remove more water and produce a wet cake of approximately 15 to 20% solids content. The wet cake is then discharged into skips for removal from site to an approved waste disposal facility. The clarified water is directed back to the head of the process for further treatment. A small amount of polymer is sometimes added to the thickened sludge to improve the solids content of the cake.

All equipment will be installed in a customised container.

2.6.3.3 Brine treatment plant

Brine from the reverse osmosis plant will be sent to the brine treatment plant to further recover treated water and concentrate brines beyond the limit of the water treatment plant. A membrane brine concentrator within the brine treatment plant will use a high pressure membrane process to concentrate dissolved solids in solution by using reverse osmosis and recovering additional treated water.

The main output from the membrane brine concentrator is concentrated brine which will be transferred to the brine storage ponds.

2.6.3.4 Managed irrigation system

There is approximately 100 hectares of irrigable land available on an adjacent paddock within the eastern portion of the Leewood property. A combination of centre-pivot and subsurface drip irrigation will be employed to irrigate approximately 97.8 hectares. At this stage, lucerne has been identified as a suitable crop for most of the site because of its perennial nature, high soil cover percentage, long growing season, and water use capacity. It is also a crop that has commercial value in the region. A blend of lucerne and pasture grasses has been identified for the subsurface drip irrigation areas. An alternative crop to lucerne and pasture grasses (i.e. another suitable fodder crop) may be used if determined to be suitable based on its planting, soil preparation and watering requirements.

Based on using lucerne as the crop species, it is anticipated that harvesting would occur five times per year. Ongoing operations would require annual fertilisation, weed control and possibly light cultivation to aid infiltration. Further details of the irrigation scheme, including a site water balance, are provided in the Concept Irrigation Design report in Appendix 3.

Small volumes of treated water will also be used for irrigation of landscaped areas, vegetated screenings and rehabilitated areas as required. In future, other crop types may be grown on the Leewood property. These crop types will be selected to meet the water balance requirements of the overall facility.

Following chemical dosing, the treated water would be classified as 'medium strength effluent' according to Table 3.1 of the *Environmental Guidelines: Use of Effluent by Irrigation* (DEC, 2004) as it was ranked as 'medium' in TDS concentration (600-1,000 mg/L). It would be considered 'low' in the other five categories listed (total nitrogen, total phosphorous, biochemical oxygen demand, grease and oil, and other pollutants (e.g. metals, pesticides)).

The salinity of the treated water following chemical dosing would be rated as 'low' (between 0.65 and 1.3 mS/cm) and suitable for moderately sensitive crops according to Table 3.4 of DEC (2004).

The guideline outlines a number of environmental performance objectives that apply to the use of effluent for irrigation. These performance objectives, and details of how the proposed activity meets them, are outlined in Table 2-13.

Table 2-13 Environmental performance objectives – Environmental Guidelines: Use of Effluent by Irrigation (DEC, 2004)

Environmental performance objective	Summary of how the proposed activity meets the objective
Protection of surface waters	The irrigation system is located, designed, constructed and operated to protect surface waters. The irrigation area is located approximately 450 m from the nearest natural water body (Bohena Creek). The Leewood irrigation system has been designed so that runoff will be predominantly driven by rainfall, and will not be highly altered from conditions under a dryland pasture regime. Refer to Appendix 3 for further details.
Protection of groundwater	The irrigation area is located, designed, constructed and operated so that groundwater quality and levels are not affected by the irrigation activities. The Leewood irrigation system has been designed so that runoff will be predominantly driven by rainfall, and will not be highly altered from conditions under a dryland pasture regime. Refer to Appendix 3 for further details.
Protection of lands	The irrigation system improves the capacity of the land to grow plants, and doesn't result in deterioration of land quality through soil structure degradation, salinisation, waterlogging, chemical contamination or soil erosion. The proposed irrigation scheme will include extensive amelioration by deep ripping, cultivation, fertiliser, lime and gypsum to improve production.
Protection of plant and	Design and management of the irrigation system does not compromise the health and

Environmental performance objective	Summary of how the proposed activity meets the objective
animal health	productivity of plants, domestic animals, wildlife and the aquatic ecosystem. The IMP will ensure the ongoing protection of plant and animal health. The treated water for irrigation will not be high in nutrients.
Prevention of public health risk	The irrigation scheme is sited, designed, constructed and operated so as not to impact public health. The closest residence is approximately 360 m to the east of the irrigation area. The Newell Highway is approximately 20 m to the east of the drip irrigation area and approximately 25 m to the east of the spray irrigation area, respectively. The treated water for irrigation sources will not be high in nutrients. It will also not contain heavy metals as these would be removed by membranes during treatment, nor would any organic compounds be expected to be found in the treated water. Therefore there will be minimal risk to public health, beyond those associated with standard fertiliser and chemical application.
Resource use	Water balance modelling indicates that the irrigation system at Leewood will be able to beneficially reuse at least 90 per cent of the available treated water from the WBTP, the remainder being used for construction, dust management, drilling and firefighting. Any use of the treated water by another user would also be a beneficial use of this water resource. Further, this approach minimises the use of other sources of water for these purposes, e.g. bore water and town water.
Community amenity	The irrigation system is located, designed, constructed and operated to avoid unreasonable interference with any commercial activity or the comfortable enjoyment of life and property offsite. The closest sensitive receiver to the irrigation area is approximately 360 m to the east. Potential impacts of the proposed irrigation activity relating to odour, dust, insects and noise are considered to be negligible and manageable, as outlined in Chapter 6.

The guideline also identifies sensitive receptors and requires an assessment of the potential impacts of an effluent irrigation scheme. These are identified in Table 2-14, along with the recommended and estimated buffer distances between the effluent irrigation area and water resources and public areas. The guideline states that the size of the buffer zone is to be based on the sensitivity of the receiving environment, the strength of the effluent, the level of effluent treatment, proposed impact mitigation strategies, the method of effluent application and irrigation management practices such as irrigation scheduling. Narrower buffers may be appropriate where high quality effluent, a low volume of effluent or vegetated filter strips are used. The treated water to be applied within the irrigation area is classified as “medium strength effluent” according to Table 3.1 of the guidelines because it was ranked medium in TDS concentration (600-1,000 mg/L). It would be ranked as low for the other categories listed in Table 3.1 of the guidelines including total nitrogen, total phosphorous, BOD, other pollutants like metals and pesticides, and grease and oil. Wider buffers may be necessary where there are limiting site characteristics such as soil or slope.

Table 2-14 Sensitive receptors of effluent irrigation schemes and associated buffer distances

Sensitive area	Recommended separation distance under the Effluent Irrigation Guidelines		Approximate separation distance for proposed activity
	Low strength effluent	Medium to high strength effluent	
Natural water bodies (e.g. rivers, lakes)	50 m	50 m	450 m (Bohena Creek).
Other waters: e.g. artificial waters with beneficial uses, drainage channels, small streams, intermittent streams, farm dams	Site-specific	Site-specific	370 m (farm dam).
Domestic well used for household water	Site-specific	250 m	1.7 km (registered bore).
Town water supply bore	Site-specific	1,000 m	> 3 km (vicinity of Narrabri township).
Where spray irrigation gives	50 m	50 m	360 m (residence).

Sensitive area	Recommended separation distance under the Effluent Irrigation Guidelines		Approximate separation distance for proposed activity
rise to aerosols near houses, schools, playing fields, roads, public open space and waterbodies			25 m (Newell Highway) The only component of issue within the treated water is TDS. Potential spray drift from the irrigation system will be minimised (refer to Section 6.2.1).
Other sensitive areas (e.g. waters in drinking water catchments, aquatic ecosystems with high conservation value, wetlands, native stands of vegetation)	Site-specific	250 m	10 m (Pilliga Box Woodland community). The only component of issue within the treated water is TDS. Treated water will not be directly sprayed onto the vegetation within the Brigalow Woodland community exclusion zone, located in the northern portion of the site. Potential spray drift from the irrigation system will be minimised (refer to Section 6.2.1).

2.6.3.5 Other beneficial re-uses of treated water

Aside from the managed irrigation system, treated water will also be beneficially used in other operational activities both on and off site. These activities may include:

- dust suppression (to minimise the generation of dust)
- construction and drilling activities
- firefighting
- watering of landscaped and rehabilitation areas
- use for off-site irrigation of agriculture by another user (not assessed in this REF).

Similar to the post treatment requirements for irrigation, treated water that is used for operational activities may require SAR adjustment prior to its use.

A procedure for beneficially re-using the treated water (other than in on site irrigation) is provided in Section 2.7.2.

2.6.3.6 Chemical usage

Typical chemical types and volumes to be used for the WBTP are outlined in Table 2-15 with further detail provided in Appendix 5. Additional chemicals may be used, depending on operational requirements and final plant design. If required, any additional chemicals that are classed as a Dangerous Good will be notified to OCSG and Santos will comply with any necessary further assessment requirements for additional chemicals used during the activity.

Table 2-15 Typical chemical storage summary

Material	Dangerous Goods Class	Approximate quantity stored on site (tonnes)
Hydrochloric acid	8 PG II	1.8
Sulphuric acid	8 PG II	1.8
Caustic soda	8 PG II	1.3
Sodium hypochlorite	8 PG III	2.2
Aqueous ammonia	8 PG III	1.4
Sodium bisulphite	8 PG III	0.5
Citric acid	Non-Dangerous Good	1.0
Antiscalant	Non-Dangerous Good	0.3
Calcium chloride	Non-Dangerous Good	1.0
Ethylenediaminetetraacetic acid	Non-Dangerous Good	0.5
Polyaluminium chloride	Non-Dangerous Good	1.12
Aluminium chlorohydrate	Non-Dangerous Good	1.2
1,2-benzisothiazolin-3-one*	9 PG III	3.0
Osmocide (DBNPA)*	8 PG III	1.0
Kuriverter IK-110*	8 PG III	2.0

*Note: Additional biocides added to table as optional disinfection chemicals – final will be decided during process commissioning. Not all biocide chemicals will be stored on site at the same time.

Diesel fuel required for power generation will be stored in accordance with legislative requirements in a storage area adjacent to the generators, also shown in Appendix 1. It is anticipated that storage capacity of approximately 20,000 litres will be required at Leewood during construction and operation. The diesel will be stored and labelled in accordance with the *Work Health and Safety Regulation* (2011).

2.6.3.7 Staff and hours of operation

The proposed activity will operate 24 hours per day, seven days per week with staff in attendance on a regular day shift. There is likely to be two full time operators working day shift with 24 hour remote monitoring to a central control facility. Remote access is available via laptop computer, and alarm messages are sent to operators when the plant is unattended.

2.6.3.8 Operational vehicle movements

Access to Leewood during operation will be via the existing access driveway adjacent to the southern boundary. Operational traffic will generally be associated with employees travelling to and from site, deliveries, maintenance activities and occasional visitors.

Based on the likely number of employees accessing the site during operation, it is anticipated that there will be up to five vehicles arriving and leaving during each of the weekday AM and PM peak hours, with operational deliveries and visitors assumed to be less than five vehicles per week. Operational vehicle movements associated with irrigation activities will be minor, with up to 10 trucks per day associated with irrigation, harvesting and crop management generated during operation.

2.6.4 Decommissioning and rehabilitation

Once construction of the proposed activity is completed, disturbed areas of the site will be stabilised in accordance with *Managing Urban Stormwater: Soils and Construction – Volume 1* (Landcom, 2004), referred to as 'the Blue Book'.

The proposed activity will operate for up to five years to support Santos' exploration and appraisal activities. Any operation beyond this would be subject to further environmental assessment and approval. Should this not occur, the proposed activity would be decommissioned and the site rehabilitated in accordance with the conditions of PAL 2.

Decommissioning and rehabilitation of the ponds was considered under the *Leewood – Produced Water and Brine Management Ponds REF* (RPS, 2012).

The final landform of the site would depend on the requirements of the proposed future use. The western side of the property would be converted back to grazing land. However, the irrigation area may be retained if requested by the future user.

At the end of operations, up to approximately 500 megalitres of concentrated brine may be stored in the ponds. This would either be transported to a suitable waste management facility for disposal, or a salt crystalliser would be installed to crystallise the brine and reduce the overall volume of brine and salt product that would be transported to a waste management facility and/or another site for a lawful beneficial reuse.

Decommissioning and rehabilitation works for the proposed activity would generally involve (where necessary):

- draining any remaining produced water and brine from the ponds and processing it in the water treatment plant and brine treatment plant
- disposing of the concentrated brine and/or solid salt product to a licensed waste management or other facility
- decommissioning and removing the WBTP, treated water storage tank and other surface infrastructure
- capping and covering buried flow lines
- dismantling and removing temporary buildings and structures
- removing the centre pivot and sub-surface irrigation infrastructure (unless to be retained for the future user)
- levelling, ripping and contouring the site
- soil amendment of the irrigation area
- reseeding with suitable pasture grasses (as required by future user)
- weed control
- disposing any remaining wastes at a licensed landfill.

A detailed rehabilitation strategy for the site will be developed towards the end of the life of the proposed activity. If a salt crystalliser is proposed to be installed at the end of the project's operation to assist in further treatment of the brine, further approval would be sought from OCSG.

In the event that no further approvals are granted, the rehabilitation criteria provided in Table 2-16 would apply to the site.

Table 2-16 Rehabilitation completion criteria for Leewood site

Phase		Activity	Timing	Completion criteria
Decommissioning of site infrastructure	Produced water and brine ponds.	Empty waste from ponds and dispose at suitably licensed landfill. Remove pond lining and dispose. Demolish embankments and backfill ponds.	Within 12 months of cessation of operations.	Ponds levelled and site clear.
	Water and brine treatment plant, water storage tank and other above ground infrastructure.	Dismantle and remove all plant, equipment, containers, waste materials, tanks and temporary buildings.	Within 12 months of cessation of operations.	Site cleared of all above ground infrastructure.
	Subsurface flowlines.	Flush and cap pipes at each end and remain <i>in situ</i> .	Within 12 months of cessation of operations.	Decommissioning in accordance with APEA Code of Practice, Upstream PE Gathering Networks – CSG Industry, Version 2.0.
	Centre pivot and subsurface irrigation infrastructure.	Unless agreed with the future land user, dismantle and remove centre pivot and excavate and dispose of subsurface irrigation infrastructure.	Within 12 months of cessation of operations.	Site cleared of irrigation infrastructure (unless agreement to leave in place has been reached with future land user).
Landform establishment		Grade and shape site to reinstate, as far as practicable, the original contour and drainage. Install erosion and sediment controls to minimise runoff channelling/erosion.	Within 12 months of cessation of operations.	No areas of instability or slumping. No areas of active erosion. Site landform established that is suitable for final agricultural land use and compatible with surrounding landscape.
Ground cover establishment		Reseed suitable pasture grasses across site (except across irrigation area if to be retained).	Within 12 months of cessation of operations.	75% groundcover established (except across irrigation area if to be retained).
Weed management		Control weed species by physical and/or chemical means taking into account the requirements of the <i>Noxious Weeds Act 1993</i> .	Until ground cover achieves target rehabilitation performance criteria, as per above.	Weeds do not dominate after disturbance or after rain.
Monitoring and reporting		Report to be submitted to OCSG following completion of all rehabilitation activities in accordance with condition 3 of PAL 2.	At completion of rehabilitation.	Report submitted.

2.7 Mitigation strategy

Santos seeks to conduct its activities in a way that avoids and minimises potential impacts on the environment. This is based on developing a thorough understanding of the environment, and developing techniques tailored to specific locations. Santos' approach to sustainability seeks to:

- ensure that all employees and contractors receive appropriate training to fulfil their individual and environmental responsibilities
- proactively pursue the identification of all hazards and eliminate or, if not possible, manage the risk to as low as reasonably practicable
- establish annual environmental objectives and targets and implement programs to achieve them
- as a minimum comply with relevant legal and other requirements
- incorporate environmental performance in the annual appraisal of employees and contractors and recognise accordingly
- implement strategies to minimise pollution, manage waste effectively, use water and energy efficiently and address relevant cultural heritage and biodiversity issues.

In addition, Santos uses compliance tracking and incident management systems throughout its operations. These internal systems will be applied to monitor performance against legislative requirements.

A suite of mitigation measures and a statement of commitments have been developed, as outlined in Sections 6.0 and 9.0 of this REF and are based on a hierarchy of impact avoidance and management of residual risks. The commitments will be applied when carrying out the proposed activity and are consistent with many of the principles used in the various guidelines in NSW in relation to biodiversity conservation, Aboriginal cultural and other heritage protection, noise, dust, stormwater, sediment and erosion control, and waste management measures.

The following sections outline the strategies to be employed by Santos and contractors during the proposed activity to ensure appropriate management of soils, water, waste, greenhouse gases (GHG) and noise.

2.7.1 Soil and water protection strategy

2.7.1.1 Erosion and sediment control

Erosion and sediment controls will be implemented consistent with the guidelines, principles and recommended minimum design standards contained in *Managing Urban Stormwater: Soils and Construction – Volume 1* (the Blue Book), as necessary, through all stages of the proposed activity.

Erosion and sediment control measures will be finalised during detailed design. Various technologies to manage sedimentation and erosion during the construction of the proposed activity may include:

- silt fences and silt traps
- settlement/sedimentation ponds
- swale drains and bunds to divert surface water away from the construction works
- silt fencing
- mulching on slopes to reduce scouring and erosion
- erosion control blankets on batters to prevent erosion
- use of a previously developed Santos weed management procedure.

All works will be undertaken to minimise the impact of erosion and sedimentation on the surrounding environment.

2.7.1.2 Soil monitoring

Ten soil moisture monitoring stations will be located across the irrigation area. Five of the monitoring stations will measure the most active rootzone in the top 100 centimetres and the other five will be equipped to measure soil moisture and salinity flux throughout and at the bottom of the rootzone. The derived data will be used to estimate the volume and rate of water moving through the unsaturated zone. Based upon monitoring bore log data describing the unsaturated zone beneath the rootzone any potential impacts to groundwater can be estimated by hydrogeological modelling.

A soil sampling protocol will also be established that uses approximately 10 benchmark testing zones representing various soil types and positions on the landscape. The zones will be up to 2000 square metres in size. These zones will be sampled by coring at set locations annually to a depth of three metres. The core holes will be plugged with bentonite chips to prevent water from running into the holes and skewing future results. The composited samples will be analysed for pH, ECe, SAR and the results will be used to monitor any flux in salt in the soil profile.

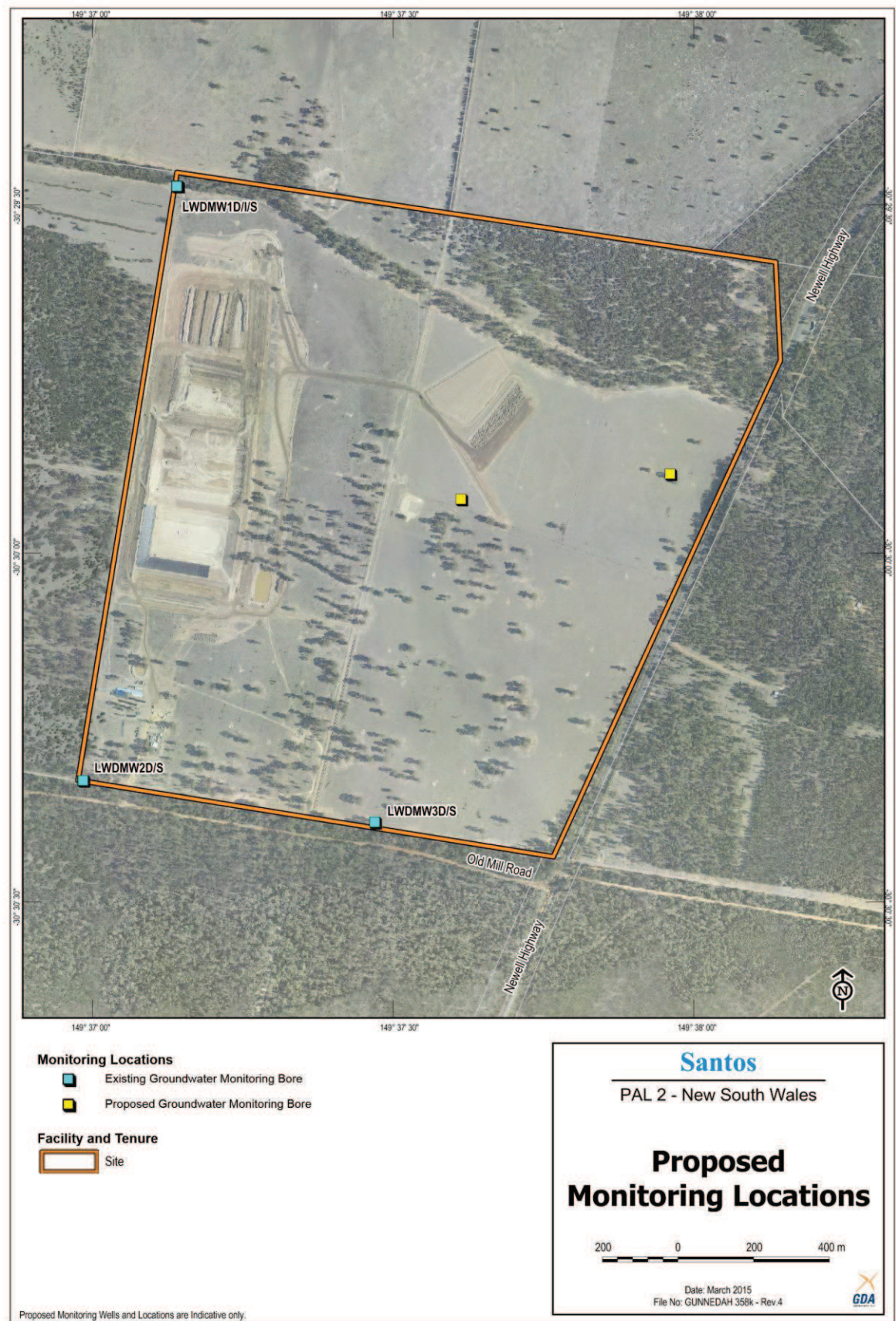


Figure 2-5 Existing and proposed water monitoring locations

2.7.1.3 Surface water protection

Potential surface water impacts and mitigation measures are identified in Section 6.1.3 of this REF.

Santos holds EPL 20350 and will ensure that all above ground tanks containing material that are likely to cause environmental harm are bunded or have an alternative spill containment system in place.

As outlined in Section 2.7.1.1, erosion and sediment controls consistent with the Blue Book will be implemented, as necessary, throughout all phases of the proposed activity. During site establishment, construction and rehabilitation activities, the site will regularly be inspected to ensure mitigation measures are effective and that risks to surface waters from pollution are mitigated.

2.7.1.4 Surface water monitoring

Surface water monitoring is important in predicting and measuring any potential impact of CSG activities within the Namoi catchment. To enable this, the baseline water quality characteristics of the catchment must be understood, against which any change can be measured, monitored and investigated.

Environmental consultant URS has designed and implemented a baseline surface water sampling plan for Santos within the Narrabri region. The sampling program commenced in February 2012, with approximately 30 locations considered to be regular monitoring sites throughout the monitoring program period to date. Due to the ephemeral² nature of tributaries within the Namoi catchment, including Bohena Creek, most locations can only be sampled periodically. The closest regular monitoring points downstream to the proposed activity are described in Table 2-17.

Table 2-17 Regular surface water monitoring locations

Monitoring ID	Site description	Easting	Northing
NAR_7506_SURF_W	Bohena Creek off Newell Hwy picnic area	755014	6625004
NAR_7510_SURF_W	Bohena Creek crossing, Newell Hwy	756470	6628742

These monitoring points will be inspected monthly and sampled when water is present. Sampling is undertaken in accordance with the requirements of AS/NZS 566.6:1998, *Guidance on sampling of rivers and streams*.

In situ measurements for physico-chemical parameters are obtained at each monitoring location using a water quality meter. The following *in situ* parameters are recorded:

- pH
- dissolved oxygen (DO)
- EC

² An ephemeral waterbody is one in which water flows for a short period following precipitation or snowmelt.

- TDS
- water temperature.

Surface water samples are obtained using the grab sampling technique, a sample methodology set out in AS/NZS 5667.1:1998 and 5667.6:1998, and with consideration of ANZECC (2000). Comprehensive analysis is undertaken by a National Association of Testing Authorities (NATA) accredited laboratory. The analytic suite includes:

- physiochemical analytes
- dissolved anions
- dissolved cations
- dissolved metals
- total metals.

Reporting is undertaken monthly following completion of the laboratory analysis. It is anticipated that surface water sampling will continue for the life of the CSG program.

Water monitoring results are available on the Santos Water Portal:

<http://www.santoswaterportal.com.au/water-monitoring-map.aspx?extent=16561000.-3600000.16787000.-3491000>.

2.7.1.5 Groundwater monitoring

Groundwater monitoring will be undertaken at Leewood to monitor groundwater levels and quality as part of Santos' broader groundwater monitoring program.

Existing and proposed groundwater monitoring bores at the site are identified on Figure 2-5.

In 2012, three sets of 'nested' groundwater monitoring bores were drilled to approximately 36 metres below ground level on the Leewood property. These bores provide baseline data regarding the unsaturated, static water levels and groundwater quality. As shown in Figure 2-5 the bore GW970427 is upgradient of the irrigation system but in the area influenced by seasonal inundation. GW970421, downgradient of the Leewood ponds and the irrigation area and GW970427 are also likely to be influenced by seasonal inundation.

Two additional monitoring wells are proposed to be installed to monitor groundwater in the vicinity of the irrigation area. One will be located near the edge of the centre-pivot, down-gradient from the existing groundwater monitoring bore (GW970427). The other monitoring well will be located at the edge of the irrigated area near the northeast corner of the property. These two new wells will be screened in the first groundwater encountered.

Once the wells are drilled and allowed to settle they will be sampled for static water level and chemical analysis and will be sampled six monthly.

The installation of pressure transducers with data recording capabilities within these two additional monitoring wells will assist in monitoring groundwater and soil moisture at the site during operations.

Results will be monitored and any significant variation from baseline conditions will be investigated. In addition to groundwater monitoring results being available on the Santos Water Portal, an annual Groundwater Monitoring Report will be submitted to the EPA. The report will provide an analysis and interpretation of monitoring results for groundwater monitoring locations across Santos' operating areas.

2.7.2 Beneficial re-use of treated water as dust suppression and rehabilitation

Only treated water will be used for dust suppression and in rehabilitation activities both on and off site as the water will meet ANZECC 2000 guidelines.

The operation of dust suppression and rehabilitation activities will take into consideration:

- management of spraying to avoid ponding and runoff of water
- avoiding of spraying during rainfall events
- adjustment of application rates based on road conditions and anticipated frequency of application
- routine visual inspection to check for any ponding or runoff.

2.7.3 Waste management strategy

The proposed activity will generate a number of waste streams. The main waste types that require offsite disposal and their estimated volumes generated during site establishment, construction and rehabilitation and operation activities are identified in Table 2-18.

Table 2-18 Estimated waste volumes for offsite disposal

Waste generating activity	Waste	Estimated volume
Construction	Construction material waste including plastics, asphalt, concrete, pipe off cuts, cabling and wiring, cured resins, paints and glues, etc.	Approximately 70 m ³
	Recyclables including glass, PET bottles, aluminium, scrap metal, rope spacers, paper and cardboard packaging waste.	20 m ³
	Chemical waste containers such as paint/solvent containers.	20 m ³
	Drained oil filters, empty oil containers and oil adsorbent materials that do not contain free liquids.	6 m ³
	General food and household waste.	10 m ³
Decommissioning	Concentrated brine	Up to approximately 500 ML

In addition to the above constant waste streams, there will be a number of intermittent waste producers during operation which include:

- microfiltration/ ultrafiltration system – intermittent cleaning waste
- RO system – intermittent cleaning waste
- waste associated with crop management and harvesting activities.

During operation the WBTP will generate a small amount of waste water from the pre-treatment, brine concentrator and pilot scale mixed salt brine crystalliser processes. General site wastes and food wastes will also be generated during this phase of the proposed activity.

Waste will be segregated according to its classification under the *Waste Classification Guidelines Part 1: Classifying Waste* (DECCW, 2009) and stored appropriately on site. These wastes will be removed from the site at the completion of construction and throughout operation for disposal or recycling at appropriately licensed waste management or recycling facilities.

Sewage waste, during both construction and operation, will be stored onsite and will be collected periodically and disposed of at a licensed facility.

2.7.4 Incident management strategy

Santos' Pollution Incident Response Management Plan provides information on site responsibilities, actions, reporting requirements, community consultation and resources available to ensure an effective and timely response is undertaken for pollution incidents or emergencies. It achieves this by:

- identifying the Santos incident management structure
- displaying notification and escalation criteria
- defining roles and responsibilities of the Incident Management Team members
- describing scenario based response procedures
- identifying key resource contact details
- describing community consultation requirements following an incident
- providing tools and templates for use in an incident response and recovery.

The Plan will be reviewed and updated to include the proposed activity, if approved, prior to commencement of construction.

Prior to Santos' acquisition of Eastern Star Gas in November 2011, a number of incidents had occurred at the Bibblewindi Water Treatment Plant. Santos carried out a review of operations and in December 2011, Santos temporarily shut down all operations in PEL 238 and PAL 2 near Narrabri, including the Bibblewindi Water Treatment Plant.

In early 2012 Santos released a report on the operational issues, including evidence of an unreported release of saline water from the Bibblewindi facility and brought them to the attention of the regulator. Santos has since decommissioned and removed the Bibblewindi Water Treatment Plant and is well advanced in rehabilitating the impacted area.

The design and operation of the Leewood WBTP will ensure that the risk of any uncontrolled release from the plant is minimised. Control and alarms systems which monitor and account for the volume of water pumped and processed from the produced water storage pond all the way through the water and brine treatment plant process to the treated water storage tank and brine storage ponds will assist in leak prevention. In addition to this the entire process plant area is contained within a bund so that any spill that potentially may occur in the plant area will be captured and contained.

Potential incidents at the site from the proposed activity and incident management measures are outlined in Table 2-19.

Table 2-19 Potential incidents and management measures at Leewood

Hazard	Description	Likelihood of causing environmental harm	Management measures
Failure of the WBTP to properly treat produced water	Treated water does not meet conductivity (TDS) limit or other parameters (e.g. calcium, magnesium, sodium).	Low	Electrical conductivity is measured online on a continuous basis. All treated water from the plant is contained in an interim treated water tank prior to post treatment. If the EC set point is not met and maintained, an alarm will trigger. The water will be reprocessed. EC meters are calibrated on a routine basis to ensure readings are within the specified requirements. It is noted that samples are undertaken on a periodic basis for other elements, with TDS being the online leading indicator of change.
Loss of containment from WBTP units, pipes or manifolds	Untreated produced water is released in an uncontrolled manner from the process plant.	Low	As stated in Condition O5.3 of EPL 20350, "all above ground tanks containing material that is likely to cause environmental harm must be bunded or have an alternative spill containment system in place". The entire process plant area is contained within a bund so that any spill that potentially may occur in the plant area will be captured and contained. Leaks are prevented by comprehensive control and alarms systems. The systems monitor and account for the volume of water pumped and processed from the produced water storage ponds all the way through the process to the treated water storage tank and brine storage ponds. If any discrepancy is detected the plant will automatically shut down and an alarm is sent to the plant operator. If the plant operator is not present on site, a remote access system can be used to shut the plant down.
Failure of the monitoring system to measure discharge	A measuring device required to detect a loss of containment fails leading to an uncontrolled release to the environment.	Low	HAZID, HAZOP and risk studies are undertaken during the design process to ensure that a rigorous structure process is used to identify, plan for and manage the risks associated with any process design. Where a risk of loss of containment due to failure of an instrument or measurement device is identified, this instrument is selected or backed up by additional equipment or safeguards.
Overtopping of treated water storage tank	The capacity of the tank is exceeded due to a rain event or blockage.	Low	Regular monitoring. Unblock spillway and drawdown tank. Divert treated water back to produced water storage pond.
Bush fire	Natural occurring bushfire burning surrounding vegetation and materials.	Medium	Severe weather warnings to be communicated to site staff. Emergency response will be under the direction of Santos who will have a representative in the Rural Fire Service response centre. Fire breaks and fire extinguishers will be located throughout the site. Chemical storage and unloading areas will be designed and managed in accordance with the relevant Australian Standards requirements.

Hazard	Description	Likelihood of causing environmental harm	Management measures
Man-made fire	Fire caused directly or indirectly by site activities.	Medium	Training for staff to prevent accidental ignition, provision of fire breaks and fire extinguishers located throughout the site. Chemical storage and unloading areas will be designed and managed in accordance with the relevant Australian Standards requirements.
Chemical spills	Loss of containment of a chemical from a chemical storage container, vessel or area of plant.	Medium	Chemical storage and unloading areas will be designed and managed in accordance with the relevant Australian Standards requirements. HAZID, HAZOP and risk studies are undertaken during the design process to ensure that a rigorous structure process is used to identify, plan for and manage the risks associated with any process design. This assessment process reviews chemical storage and handling within the plant and places strict controls. In addition, bunding will be in place to reduce the risk of loss of containment.

2.7.5 Greenhouse gas emission management strategy

Climate change is a long-term issue, requiring urgent but informed action to stabilise atmospheric GHG concentrations. As a global stakeholder in the energy business, Santos recognises its social and environmental responsibility to pursue strategies that address the issue of climate change.

Santos is committed to working with government, industry and the community to address climate change with specific focus on addressing energy efficiency, adaptation strategies, the transition to lower emission technologies and reporting transparency.

Santos' Climate Change Policy outlines the organisation's approach to climate change and realisation of the vision to 'lower the carbon intensity of its products'. The policy identifies the following commitments:

- continue to reduce the carbon intensity of Santos' products by focusing on energy efficiency, technology development and by embedding a carbon price in all activities
- use energy more efficiently by identifying opportunities to implement energy efficiency projects and report their progress
- examine the commercial development of low emission technologies, including storage solutions, which will contribute towards long-term emission reduction targets
- pursue no flaring or venting of associated gas, unless there are no feasible alternatives
- continue to publicly disclose Santos' GHG emissions profile and carefully examine forecast emissions
- understand, manage and monitor climate change risk and develop appropriate adaptation strategies for our business
- assist governments and engage with other stakeholders on the design of effective and equitable climate change regulations and policy
- inform employees about its commitment to climate change and ensure climate change initiatives continue to be implemented
- report progress against these commitments to the Board.

Santos has publicly reported its GHG emissions since 2004 with independent assurance provided annually. As a result, Santos has established comprehensive governance processes which will ensure that the emissions associated with the proposed activity will be accurately reported under the *National Greenhouse and Energy Reporting Act 2007* (Cth) (NGER Act). Santos' governance system includes:

- annual independent assurance of GHG emissions
- regular audits in relation to implementation of the Environmental, Health and Safety Management System (EHSMS)
- risk-based internal audits are administered to ascertain conformance with, and effectiveness of the EHSMS Standards
- monitoring and review of energy efficiency opportunities
- other audits of compliance with internal policies and procedures related to GHG reduction through the internal audit program.

2.7.6 Noise management strategy

Noise generated by the proposed activity will be regulated under EPL 20350 for CSG exploration, assessment and production at the Narrabri Gas Field.

Condition L4 of EPL 20350 provides construction activity limits as follows:

*L4 Hours of operation
Construction activities limits*

L4.1 Standard construction hours

Unless otherwise specified by any other condition of this licence, all construction hours activities are:

- a) restricted to between 7:00am and 6:00pm Monday to Friday;*
- b) restricted to between the hours of 8:00am and 1:00pm Saturday; and*
- c) not to be undertaken on Sundays or Public Holidays.*

L4.3 Exceptions to standard construction hours

The following activities may be carried out outside of the hours permitted by Condition L4.1:

- a) Construction work that causes $L_{Aeq(15\text{ minute})}$ noise levels that are not more than 5dB above rating background level at any residence not subject to a private negotiated agreement, in accordance with the Interim Construction Noise Guideline (DECC, 2009);*
- b) The delivery of plant, equipment and materials which is required to be delivered outside of the standard construction hours by Police and/or other authorised authorities; and*
- c) Emergency works to avoid loss of life, damage to property and/or environmental harm.*

The licensee must on becoming aware of the need to undertake emergency work – notify the NSW Environment Protection Authority Environment Line on 131 555.

Construction for the proposed activity will generally be carried out from 7:00am to 6:00pm Monday to Sunday. The rating background level of the site is 30 dB(A) at all times (refer to Section 4.6). Therefore, construction work that causes noise levels no more than 35 dB(A) at any residence not subject to a private negotiated agreement, may be undertaken outside of standard construction hours in accordance with

condition (a) above. Construction activities will be managed to ensure that noise levels of 35 dB(A) are not exceeded at any residence outside of standard construction hours unless that residence is subject to a private negotiated agreement. Specific measures to ensure that this level is not exceeded are provided in Section 6.1.6.3.

Condition L3 of EPL 20350 provides noise limits for operational activities as follows:

L3 *Noise limits*
 Operational activities limits

L3.1 *Noise generated at the premises must not exceed the noise limits specified in the table below:*

Location	Day Noise Limit LAeq(15 minute)	Evening Noise Limit LAeq(15 minute)	Night Noise Limit LAeq(15 minute)
any residential sensitive receptor not subject to a private negotiated agreement.	35dB(A)	35dB(A)	35dB(A)

Compliance with these limits is generally expected. This is discussed further in Section 6.1.6.

2.8 Access arrangements

Leewood is a Santos owned property. Therefore no access agreement is required for works on this land.

2.9 Other approval requirements

Assessment and determination of the proposed activity under Part 5 of the EP&A Act, and approval under the *Petroleum (Onshore) Act 1991* (Petroleum Act), is required before the activity can commence.

An environment protection licence (EPL) is required under the NSW *Protection of the Environment Operations Act 1997* (POEO Act); refer to Section 5.2.3 for further details. Santos holds an EPL (EPL 20350) for coal seam gas exploration, assessment and production at the Narrabri Gas Field. Once the proposed activity is approved under Part 5 of the EP&A Act, Santos will apply to the EPA for a variation of the EPL seeking that the proposed activity be added to the existing EPL.

A water use approval under section 89 of the *Water Management Act 2000* will be required for the proposed use of treated water including the irrigation of agricultural land and other proposed beneficial reuses.

Section 5 sets out further details of regulatory requirements.

3.0 THE SITE

The site is located within the Santos-owned property known as Leewood, formally described as Lot 1 DP 771141.

Figure 2-1 illustrates the extent of the site, while a detailed survey of Leewood is provided in Appendix 6.

Leewood is predominantly cleared of vegetation and has been used in the past for grazing activities. Plates 3-1 to 3-9 illustrate Leewood. The site is currently accessed via Old Mill Road, a State forest road that runs along the southern boundary of the property. Leewood covers an area of approximately 246 hectares.



Plate 3-1 Leewood – view east along northern boundary



Plate 3-2 Leewood – vegetation in north-eastern portion of lot



Plate 3-3 Leewood – view east along southern boundary



Plate 3-4 Leewood – view south-east from centre of lot



Plate 3-5 Leewood – dam located in south-eastern corner of lot



Plate 3-6 Leewood – dam located in central portion of lot



Plate 3-7 Leewood – produced water and brine ponds



Plate 3-8 Leewood – site entrance looking towards from the site



Plate 3-9 Leewood – Old Mill Road looking toward intersection with the Newell Highway

4.0 EXISTING ENVIRONMENT

4.1 Topography

Leewood is relatively flat, with reduced levels ranging from 248.78 metres Australian Height Datum (AHD) along the eastern boundary (central section), to 244.79 metres AHD along the eastern boundary (northern section). Typical grades across the property are approximately one in 400. Refer Survey Plan (Appendix 6).

Leewood slopes generally towards an overland flow channel (drainage feature) from the south-east to north-west. There is also a slight depression in the land surface at the north-east of the site along the eastern boundary.

4.2 Climate

The Bureau of Meteorology weather station considered the most representative of the site is Narrabri West Post Office (station 053030, opened 1891); while Narrabri Airport AWS (station 054038, opened 2001) is the closest station to the site with recent temperature statistics (Narrabri West Post Office statistics end at 2002). The local climate is temperate with higher rainfall during the summer months. The average daily maximum temperature is 26.6°C, while the average daily minimum temperature is around 12.0°C (BoM, 2015). Annual rainfall is 661.6 millimetres and is known to range between 297.4 millimetres (lowest record) and 1012.1 millimetres (highest record).

As shown in Table 4-1, based on mean temperature records the warmest month is January and the coolest month is July. January receives the greatest rainfall and April the least.

Table 4-1 Mean climate data from February 1891 to December 2014

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean max temp (°C) ¹	34.5	33.2	30.6	26.9	22.4	18.3	17.9	20.0	24.2	28.2	31.1	32.4
Mean min temp (°C) ¹	20.0	19.6	16.3	12.3	7.1	5.7	4.0	4.8	8.2	12.0	16.4	18.1
Mean rainfall (mm) ²	83.3	63.1	58.6	38.2	47.5	48.5	46.5	40.4	42.1	51.9	61.2	76.8

Note:

1. BoM station 054038 – from July 2001 to December 2014

2. BoM station 053030 – from February 1891 to December 2014

4.3 Soils

Thirty-four soil profiles within the site were described and sampled by BeneTerra Australia, as part of the investigation works for the irrigation concept design (refer to Appendix 3). Eighteen of these sites were soil pits dug to 140 centimetres with an excavator, while the remaining 16 were sampled to a depth of 150 cm using a hydraulic push tube corer.

4.3.1 Soil classification

Based on similarities in morphology, chemistry and management requirements, five soil units were defined for the proposed irrigation area within the site (shown in Figure 4-1):

- Red Chromosol (1ha) – a friable brown loam over a friable red clay loam. Well drained, and chemically and physically amenable to root growth.
- Brown Chromosol (4ha) – A friable brown loam over a hard brown clay. Moderately drained, and moderately chemically and physically amenable to root growth.
- Brown Sodosol-transitional (6ha) – very similar to the Brown Sodosol unit for most of its properties (see

description below). The soils of this unit were shallower than the other Sodosol units, with a sandstone parent material encountered at around 120 centimetres.

- Brown Sodosol (58ha) – A hardsetting brown sandy clay loam (or clay loam, sandy) over a very hard columnar brown clay. Well drained in the 15 centimetres or so of loam at the surface, changing sharply to much lower porosity clay upon which water perches for extended periods following heavy rainfall (remaining saturated for several days to a week). Root growth often extends to the full depth excavated, but is restricted by the coarse soil structure and moderate salinity of the subsoil, particularly below one metre.
- Grey/Brown Sodosol (31ha) – Similar to Brown Sodosol unit, but with the following distinctions. Often a thicker surface soil, possibly built up from erosion off the up-slope soils, usually with a distinctly bleached subsurface horizon above the coarsely structured subsoil. The subsoil is grey or grey brown, indicating poorer drainage than the other soil units. However, it appears this is due to landscape induced inundation i.e. due to drainage line flooding, rather than to lower internal permeability of the soil.

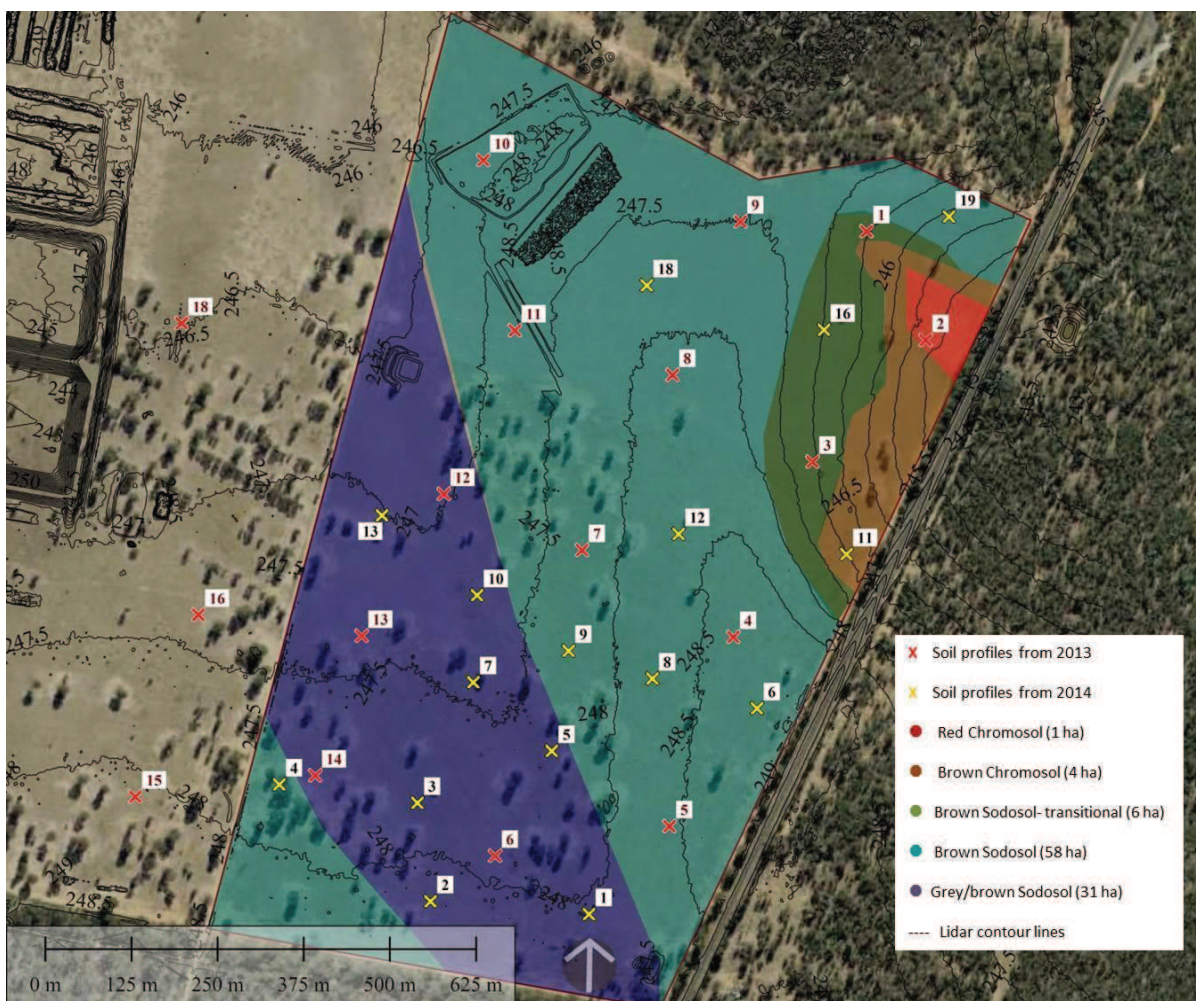


Figure 4-1 Soil sampling points and soil type distribution across irrigation area

The majority of the soils were identified as *Magnesian Mesonatric Grey or Brown Sodosols; medium, non-gravelly, clay loamy/clayey, deep* according to the Australian Soil Classification.

The soils in the northwest corner of the property tended to be shallower with most presenting a sandstone parent material within 1.2 metres. About half of these soils (five hectares) were identified as *Mottled*,

Mesotrophic Brown or Red Chromosol; medium or thick, non-gravelly, loamy/clay loamy, deep according to the Australian Soil Classification.

For the purposes of the irrigation concept design (Appendix 3) the soils on the irrigation areas of the site were further grouped into two irrigation management classes – A and B. These were differentiated primarily due to their landscape position:

- Class A soils: Chromosols and Brown Sodosols – more upland soils
- Class B soils: Grey/Brown Vertosols – lower lying soils.

4.3.2 Soil limitations

4.3.2.1 Chemical

All of the soil units exhibited exchangeable sodium percentages greater than 10 in the surface 40 centimetres which ranks as a 'severe limitation'. These soils are therefore considered to be sodic, and will exhibit dispersive qualities. Surface application of gypsum can decrease this limitation to slight or moderate. The ESP of the deeper soil, 40 to 100 centimetres, averaged 28 on the soils analysed but is not as critical a limitation as the surface ESP. This restriction can be mitigated through deep incorporation (e.g. via ripping) of gypsum into the soil.

Salinity posed a slight to moderate limitation for these soils in the 70 to 100 centimetre depth zone. However, some healthy roots were observed beyond 100 centimetres in many of the profiles. There were no indications that the water table or bedrock would be a limitation.

The saturated hydraulic conductivity of the subsoil presents the main limitation as it would likely be in the range of one millimetre per hour. This contrasts sharply with approximately 20 millimetres per hour in the surface soil. This can be mitigated through careful irrigation scheduling that fills the surface horizon and allows enough time for that soil water to drain into the subsoil. Soil amelioration techniques such as ripping and injection of gypsum (and possibly organic matter) will improve saturated hydraulic conductivity in the upper subsoil, possibly to as high as six millimetres per hour, reducing this limitation to a 'moderate' level.

These soils have ample water holding capacity. The surface pH is acidic (and commonly strongly acidic), but is easily amended with lime. Cation exchange capacity is not a concern as the soils have high clay content and, unlike most effluent waters, the irrigation source will not be nutrient rich. The site will require the addition of phosphorus (P), potassium (K) and sulphur (S) based fertilisers in order to optimise productivity of irrigated crops.

4.3.2.2 Physical limitations

The key physical limitations of the site relate to the impeded drainage of the majority of the soils. All the Sodosol units (95 per cent of the area) have coarsely structured, columnar subsoils which will perch water and drain slowly and unevenly. The poor subsoil drainage is greatly exacerbated for the 31 hectares of grey brown Sodosols that are subject to higher levels of overland flow associated with the drainage line.

The massive (structureless) clay loam and sandy clay loam surfaces of all the soils of the site have particle size distributions that make them highly susceptible to compaction when they are wet. Their lack of shrink/swell capacity also means they have little self-repair potential once compaction has occurred. As the subsoils will perch water, saturation of the surface soil following heavy rainfall is likely to extend for several days to a week after rain/overland flow stops. These drainage/waterlogging related issues will restrict water scheduling options, as well as the trafficability of the site. Mitigation measures to manage these limitations are detailed in Section 6.1.1.2.

4.3.3 Presence of metals in soil

Twenty-six soil samples taken from within the irrigation area of the site were analysed for heavy metals, including uranium and mercury. The soil profiles selected were chosen as a representation of the soil types described across the site, with the range of depths sampled including from the ground surface to 150 centimetres below ground level. The results of these analyses are provided in Appendix 3. None of the metals were measured at levels above the *National Environment Protection (Assessment of Site Contamination) Measure 1999* (amended 2013) thresholds.

4.3.4 Contaminated land

A search of the list of NSW contaminated sites notified to the EPA (available at <http://www.epa.nsw.gov.au/clm/publiclist.htm>) indicated records of seven contaminated sites within the Narrabri LGA. None of these sites are located near the proposed activity. There are no known sites of contamination at the Leewood property.

4.4 Land use

The site is located on a property privately-owned by Santos. The site has been previously cleared for cattle grazing and currently comprises grassy paddocks with minimal scattered tree cover, as well construction works associated with the produced water and brine ponds (refer to Figure 2-1). The site is zoned for Primary Production (RU1) and is primarily surrounded by other primary production land, with the exception of land zoned for Forestry (RU3) to the south.

An Agricultural Impact Statement (AIS) has been prepared for the proposed activity (Appendix 7). The site is located within land zoned RU1 Primary Production under the Narrabri Local Environment Plan (LEP). It is bounded by the Pilliga East State Forest to the south, while the properties located to the north and west of the site contain cleared paddocks used for mainly grazing and cropping.

The dominant land use in the Namoi catchment is sheep and cattle grazing which accounts for 51 per cent of land use by area. Wheat, cotton and other broad acre crops are grown along the alluvial floodplains. Of the 801 square kilometres irrigated in the year 2011, around 718 square kilometres was used for cotton production in the Lower Namoi catchment (DECC, 2011).

The *Strategic Regional Land Use Plan – New England North West Region* (the SRLUP) includes Strategic Agricultural Land (SAL) mapping (refer Figure 4-2). SAL is highly productive land that has both unique natural resource characteristics as well as socio-economic value. Biophysical Strategic Agricultural Land (BSAL) is a particular category of SAL which is defined as land with the best quality landforms, soil and water resources which are naturally capable of sustaining high levels of productivity with minimal management practices. Leewood and the broader surrounding areas are not classified as BSAL. In addition, no Critical Industry Clusters (CICs) have been identified in the New England North West Region. CICs are defined as a localised concentration of interrelated productive industries based on an agricultural product.

Leewood has been mapped as having soils with inherent Class 3 and 5 land and soil capability (LSC). Lands in LSC Class 3 are described as having moderate limitations and are capable of sustaining high impact land uses using more intensive, readily available and accepted management practices. Lands in LSC Class 5 are described as having severe limitations and are not capable of sustaining high impact land uses except where resources allow for highly specialised land management practices to overcome limitations (e.g. high value crops).

There are six potential sensitive receivers within two kilometres of the Leewood property boundary, the locations of which are shown in Figure 4-3. The nearest receiver (R4) to the proposed activity is located

approximately 360 metres to the east. The next nearest receiver (R5) is approximately 750 meters to the west; however consultation with the landowner has confirmed that this residence is not permanently occupied. There are two additional receivers (R3 and R6) located to approximately 1.3 kilometres east of Leewood, and two receivers (R1 and R2) located 1.4 kilometres to the north and 1.6 kilometres to the north west, respectively.

The site is not located within an Environmentally Sensitive Area of State Significance, as defined under the *State Environmental Planning Policy (Mining, Petroleum Production and Extractive Industries) 2007* (Mining SEPP) (refer Table 4-2).

Table 4-2 Environmentally sensitive areas

Is the proposed activity located on or within any of the following:	Yes/No
Coastal waters of the State	No
Lands protected under SEPP 14 – Coastal Wetlands?	No
Lands protected under SEPP 26 – Littoral Rainforests?	No
Aquatic reserves dedicated under the <i>Fisheries Management Act 1994</i> or a marine park under the <i>Marine Parks Act 1997</i> ?	No
Wetland areas dedicated under the Ramsar Wetlands Convention?	No
A World Heritage Area declared under the World Heritage Convention?	No
Land identified in an environmental planning instrument as being of high Aboriginal cultural significance?	No
An area reserved or dedicated under the <i>National Parks and Wildlife Act 1974</i> ?	No
Land, places, buildings or structures listed on the State Heritage Register?	No
Is the proposed activity located within land reserved or dedicated within the meaning of the <i>Crown Lands Act 1989</i> for preservation of flora, fauna, geological formations or for other environmental protection purposes?	No
Land identified as being critical habitat under the <i>Threatened Species Conservation Act 1995</i> or Part 7A of the <i>Fisheries Management Act 1994</i> ?	No

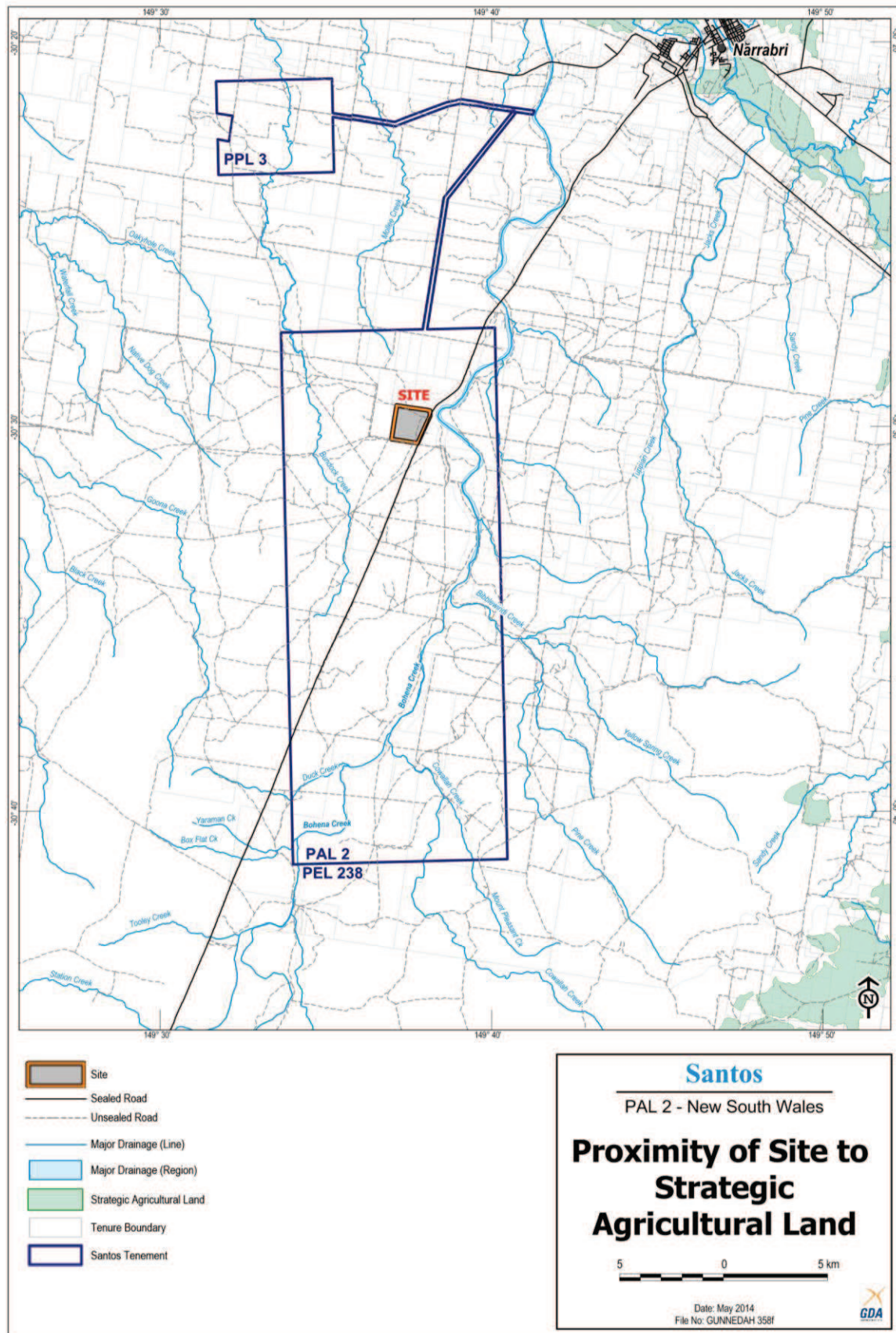


Figure 4-2 Proximity of site to Strategic Agricultural Land

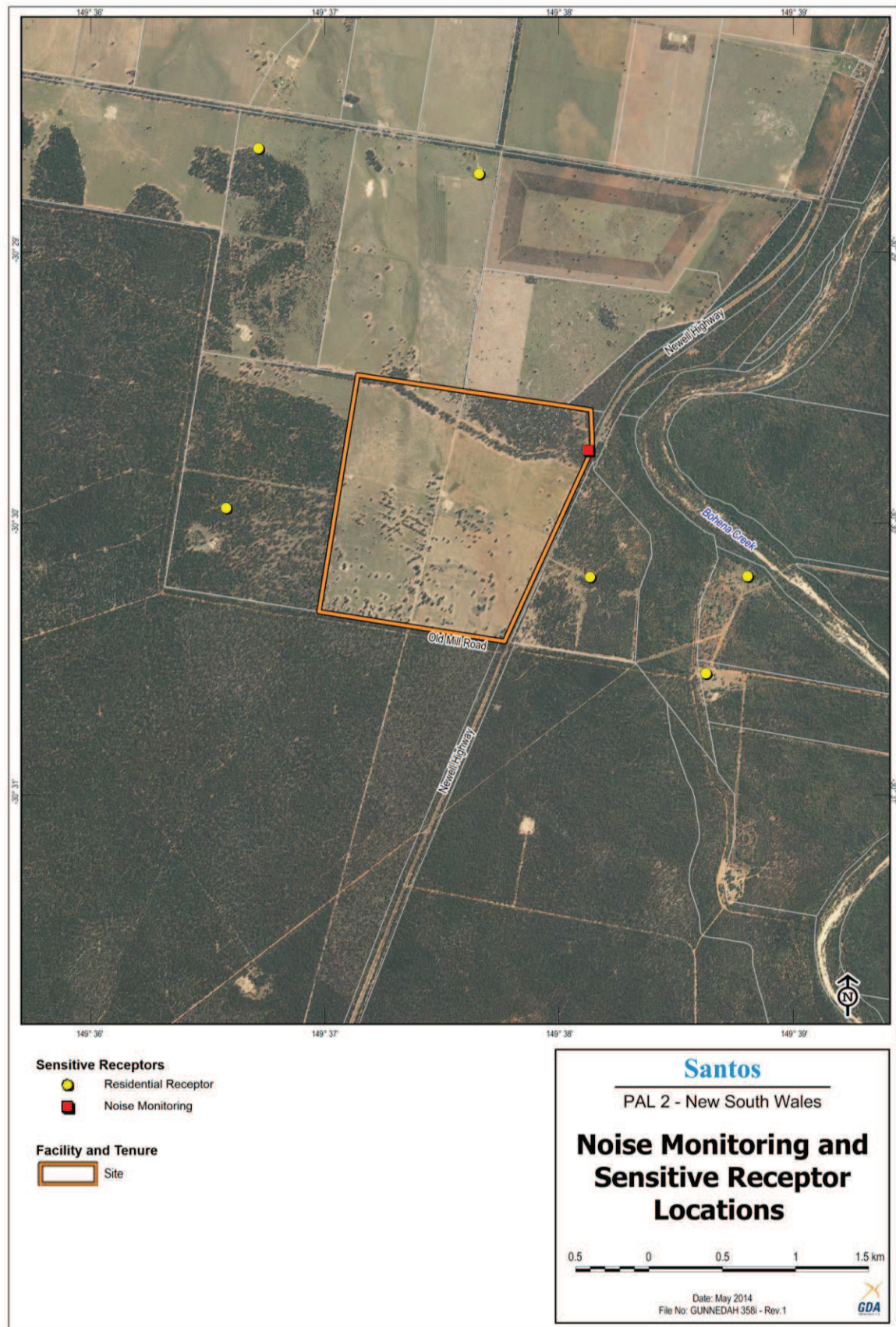


Figure 4-3 Noise monitoring and sensitive receptor locations

4.5 Air

The air quality in the vicinity of the site is influenced by the common land use practices in the area, including agricultural production and forestry operations. Regional air quality is likely influenced by additional land uses practices including mining activities, vehicle and heavy machinery movements, bushfires, burn-offs and use of combustion heaters.

There are no OEH air quality monitoring stations within the local vicinity of the site; however, the primary air pollutants of concern within the Narrabri region are likely to be dust (particulate matter PM₁₀) caused by mining operations, transport of coal and farming activities such as ploughing, and fine particulates (PM_{2.5}) from vehicle emissions. Fugitive dust and exhaust emissions from vehicles and machinery, particularly on dirt roads, and smoke from bushfires influence the local air quality of the site.

4.6 Noise

Unattended and attended noise monitoring at the project site was previously conducted by GHD in December 2013. Noise monitoring was conducted at the Leewood site in the north eastern corner near to the Newell Highway. The monitoring location is shown in Figure 4-3.

Table 4-3 presents a summary of the long term unattended noise monitoring results.

Table 4-3 Summary of unattended noise monitoring results (GHD, 2013)

Location	Rating background levels (L _{A90})			Ambient noise levels (L _{Aeq} , 15min)		
	Day ¹	Evening ²	Night ³	Day ¹	Evening ²	Night ³
Leewood	32	30	30 ⁴	65	64	61

Note:

1. Day is defined as 7:00 am to 6:00 pm, Monday to Saturday and 8:00 am to 6:00 pm Sundays & Public Holidays.

2. Evening is defined as 6:00 pm to 10:00 pm, Monday to Sunday and Public Holidays.

3. Night is defined as 10:00 pm to 7:00 am, Monday to Saturday and 10:00 pm to 8:00 am Sundays and Public Holidays.

4. Measured noise level was less than 30 dB(A). RBL set to 30 dB(A) in accordance with the *Industrial Noise Policy* (INP) (EPA, 2000).

Short term attended noise measurements were also carried out by GHD to characterise the existing noise environment. The attended measurements were carried out at the long term monitoring location. Table 4-4 presents a summary of the attended measurements. The measurements show that there is no significant industrial noise in the vicinity of the project site and that road traffic noise is a major contributor at the monitoring location.

Table 4-4 Attended noise measurement results (GHD, 2013)

Location	Date/time	Measured noise level (dB(A))		Notes
		L _{Aeq}	L _{A90}	
Leewood	10/12/2013 04.00 am	61	24	Road traffic noise from Newell Highway, mainly heavy vehicles and the occasional light vehicle, low insect noise, no wind.
	10/12/2013 04.16 am	60	23	Road traffic noise from Newell Highway, mainly heavy vehicles and the occasional light vehicle, low insect noise, no wind.
	11/12/2013 7.00 am	66	35	Road traffic noise from Newell Highway, mix of heavy vehicles and light vehicles, truck idling at truck stop, birds, light breeze, Leewood construction site not audible.
	11/12/2013 7.15 am	65	34	Road traffic noise from Newell Highway, mix of heavy vehicles and light vehicles, truck idling at truck stop, birds, light breeze, Leewood construction site not audible.

The water and brine storage ponds at Leewood were under construction during the noise monitoring period, however it is indicated by attended measurement that the construction works did not influence the long term noise monitoring.

The measured RBL for daytime is 32 dB(A) at the noise monitoring location, which is in close proximity to the Newell Highway. Figure 4-3 shows that the receiver locations are at a much greater offset distance to the highway than this monitoring location.

It is expected that at distances further from the Newell Highway, background noise levels would be lower as there are no other significant noise sources in the vicinity of the site and receivers. The lowest RBL that can be used for assessment under the *Industrial Noise Policy* (INP) (EPA, 2000) is 30 dB(A). In light of this, the daytime RBL has been set to 30 dB(A) for the proposed activity.

4.7 Geology

The surficial geological layer of the majority of the site is described as being Quaternary colluvium and/or residual deposits, and comprises talus, scree and sheet wash. These can take the form of boulder, gravel or sand, and may include minor alluvial or sand plain deposits. The southwest corner of the site is mapped as a Cainozoic sand plain, and may include some residual alluvium. It is sand dominant, also containing gravel and clay. Siliceous sands are dominant components of the parent material forming the soils, and consequently all the soils described at the site presented coarse sand fragments that were easily distinguishable in most horizons.

4.8 Availability of services

A buried gas pipeline associated with Santos' Wilga Park Power Station is located within an existing fenced right of way through the Leewood property. The existing Leewood water flowline from the Bibblewindi Facility (approved by DRE on 19 March 2013) runs parallel to the buried gas pipeline, terminating at the pond inlets.

Other various services are located both below and above ground within or adjacent to the site. The location, type and depth, or height, of all existing services will be confirmed and marked out in the interests of safety and protection of existing services prior to construction. Impacts to these services are not anticipated as a result of the proposed activity. Services include:

- electrical
- water
- gas.

4.9 Surface water

The site is located within the Namoi River catchment, which covers an area of approximately 42,000 square kilometres stretching from Woolbrook in the east to Walgett in the west. The catchment is bounded by the Great Dividing Range in the east, the Liverpool Ranges and Warrumbungle Ranges in the south and the Nandewar Ranges and Mount Kaputar to the north. Major tributaries of the Namoi River include Coxs Creek and the Mooki, Peel, Cockburn, Manilla and Macdonald rivers, all of which join the Namoi River upstream of Boggabri (Namoi Catchment Management Authority (NCMA), 2014).

Figure 4-4 shows the drainage in the vicinity of the site.

The site is located within the Bohena sub-catchment of the Namoi River catchment. The Bohena sub-catchment covers an area of approximately 830 square kilometres south of Narrabri and is the northern extension of the Borah sub-catchment. The sub-catchment is drained by Bohena, Cowallah and Bibblewindi

creeks (NCMA, 2014). Surface water quality within the catchment is influenced by agricultural runoff, spray drift, and vapour transport (NCMA, 2014).

There are no permanent, natural flows within the site, with Bohena Creek comprising the major drainage feature within the vicinity of the site. It is ephemeral in nature and flows only when significant rainfall occurs in the catchment. It is located approximately 450 metres to the east of the north-east corner of the Leewood property.

Mollee Creek is located to the north west of Leewood. A headwater tributary of Mollee Creek traverses Leewood and flows from the southeast to north through the property. Approximately one kilometre upstream (south east) of Leewood, it crosses the Newell Highway via two 1200 by 650 millimetre box culverts. The tributary is ephemeral and not well defined at the location of the proposed works. Mollee Creek enters the Namoi River more than 30 kilometres downstream of Leewood.

A flood study assessment for Leewood was undertaken by Golder Associates (Appendix 12 of RPS 2012). It identified those areas of the property affected by both the 50 year annual recurrence interval (ARI) and 100 year ARI (100 year ARI is shown in Figure 4-5). Flow velocities were also modelled and were low at rates between 0.33 and 0.80 metres per second.

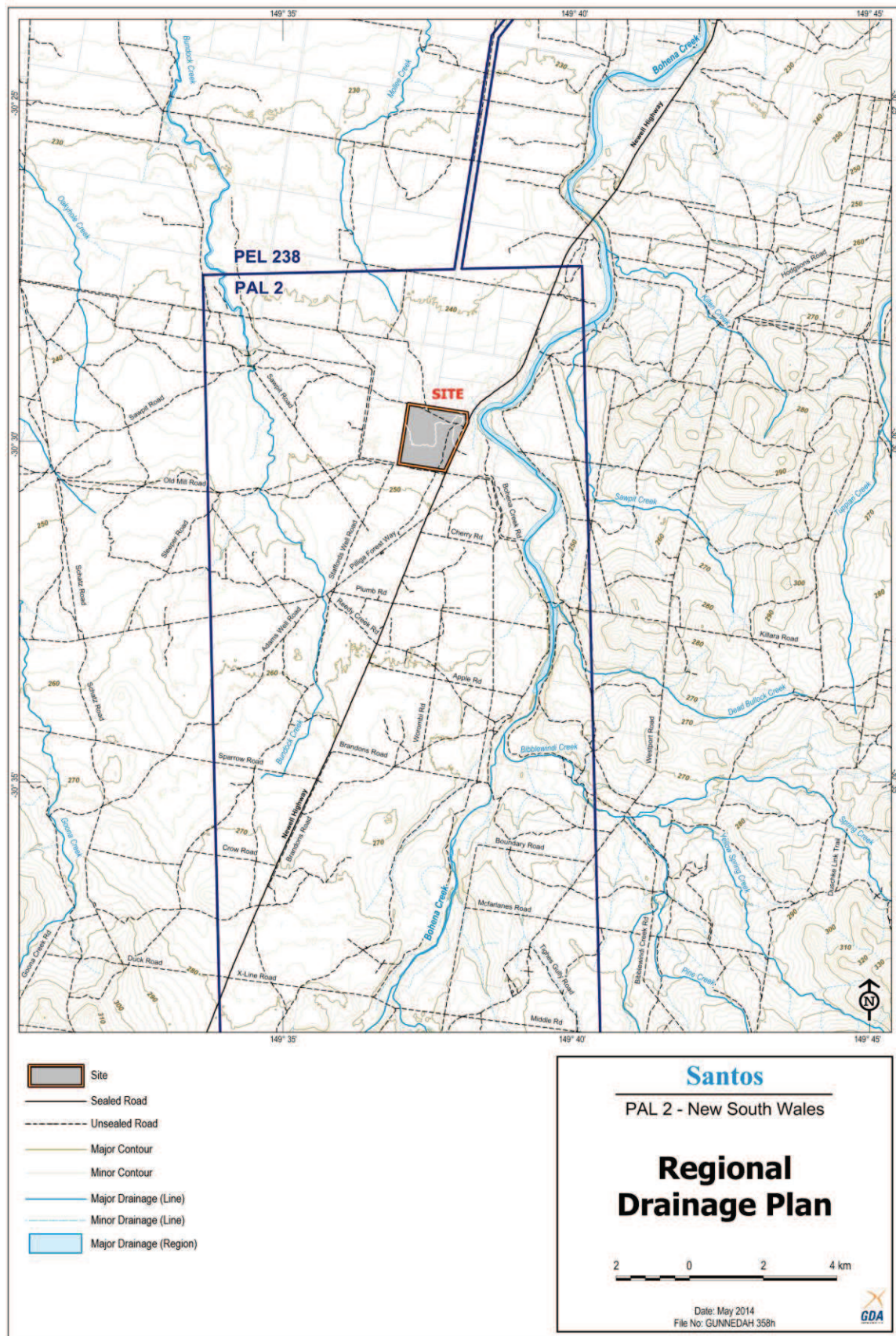


Figure 4-4 Regional drainage plan

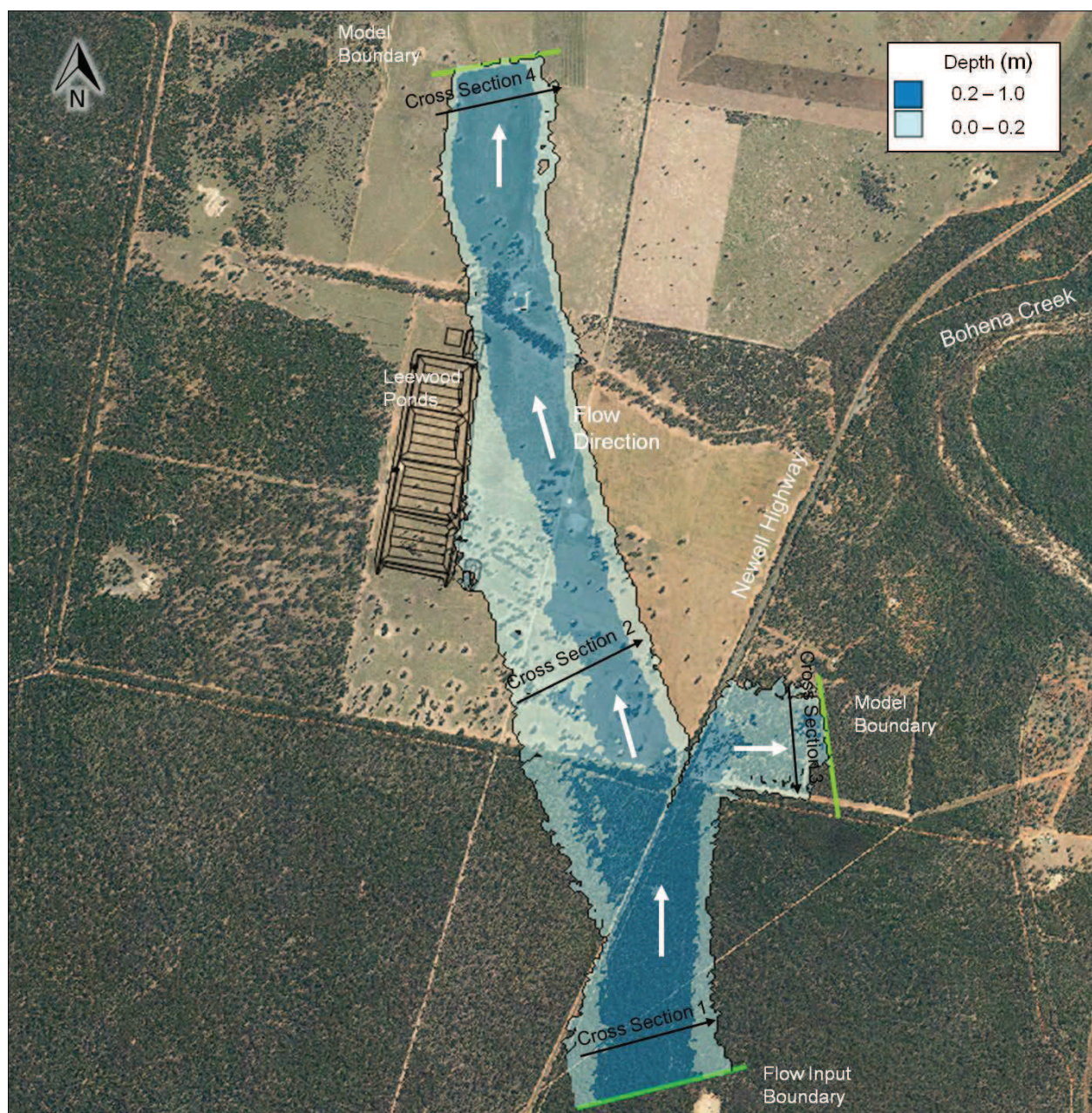


Figure 4-5 100 year ARI flood extent at Leewood (source: Flood Study Assessment, Golder 2012)

4.10 Groundwater

Groundwater in the Namoi River catchment supports the irrigation industry and also provides the water supply for many towns and intensive industries. There are a total of 700 license holders in the Namoi River catchment. Groundwater sources include all water contained in the unconsolidated alluvial sediment aquifers associated with the Namoi River and its tributaries (NCMA, 2014).

The closest high priority groundwater dependent ecosystems (Hardy's Spring, Mayfield Spring and Eather Spring) are located more than 20 kilometres east of Leewood.

Five licensed groundwater bores are located within the Leewood property (NSW Government, 2014), as detailed in Table 4-5.

Table 4-5 Licensed groundwater bores within the Leewood property (source: NSW Government, 2014)

Well	Maximum depth (m)	Authorised purpose	Located within Southern Recharge groundwater source of the Great Artesian Basin
GW970421	36.1	Monitoring bore	Yes
GW970424	36.0	Monitoring bore	Yes
GW970426	17.7	Monitoring bore	Yes
GW970427	34.0	Monitoring bore	Yes
GW970656	204.0	Industrial (low security) mining	No

An additional nine licensed groundwater bores are located within three kilometres of the Leewood property (NSW Government, 2014), as detailed in Table 4-6.

Table 4-6 Licensed groundwater bores within 3km of the Leewood property (source: NSW Government, 2014)

Well	Maximum depth (m)	Authorised purpose	Located within Southern Recharge groundwater source of the Great Artesian Basin	Water bearing zone(s)
GW000017	124.8	Stock	No	39.6 m and 121.9 m (consolidated rock)
GW006577	67.7	Stock	Yes	23.1, 41.1 and 67.0 m (unconsolidated rock)
GW006594	68.5	Domestic/stock	Yes	53.3 and 68.5 m (unconsolidated rock)
GW033822	76.2	Domestic/stock	Yes	43.6 – 50.9 m (unconsolidated rock)
GW034495	57.9	Domestic/stock	Yes	49.6 – 51.4 m (unconsolidated rock)
GW070729	58.5	Domestic/stock	No	31.1 – 31.4 m and 50.9 – 51.2 m (unconsolidated rock)
GW965057	91.5	Irrigation/stock	Yes	41.2 – 41.3 m
GW966135	91.0	Domestic/stock	Yes	No water bearing zone details provided.
GW970567	2.2	Monitoring bore	No	1.0 – 2.2 m

As shown in Table 4-5, three groundwater monitoring bores were drilled to about 36 metres below ground level on the Leewood property. Static water levels ranged from 20.7 to 29.5 metres below ground level. This translates to water levels of 216.72 mAHD to 227.47 mAHD. Excavations for geotechnical test pits (up to five metres deep) and the produced water and brine ponds (up to 1.5 metres deep) near the proposed treated water storage tank did not encounter groundwater.

The alluvial aquifers within the vicinity of the site are associated with Bohena and Bibblewindi Creeks, with minor thin veneers of alluvium in some tributary creeks. The alluvial sandy soil veneer does not form an aquifer except where Bohena Creek meets the major alluvial aquifer system associated with the deep paleo-channels of the Namoi River.

The alluvium of Bohena Creek and major tributaries consist of clean, medium to coarse quartz sands which are up to about six metres thick. The water table in the alluvium of Bohena Creek varies from surface level following periods of creek flow, to an estimated two metres below surface level during dryer periods.

Groundwater flow is to the north along the creek channel, with discharge eventually to the Namoi River and/or the major alluvial aquifers associated with the river.

4.11 Threatened species, populations and ecological communities

Ecological field surveys were undertaken at Leewood between 30 April and 11 May 2012 and again on 19 September 2012 as part of the *Leewood – Produced Water and Brine Management Ponds REF* (RPS, 2012). The results of these surveys, in relation to the proposed activity, are discussed in the Ecological Assessment in Appendix 8.

4.11.1 Flora

In total 59 flora species were recorded on the site during the field survey, including six weed species.

Targeted searches did not confirm the presence of any threatened flora species listed under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) or *Threatened Species Conservation Act 1995* (TSC Act) within Leewood.

4.11.2 Fauna

There are 24 species listed under the TSC Act and/or the EPBC Act that have potential or are known to occur on the site and that are considered to have potential to be impacted by the proposed activity. These species are listed in Table 4-7.

Table 4-7 Species and communities considered potential, likely or known to occur on the site with potential to be impacted

Scientific name	Common name	TSC Act ¹	EPBC Act ¹
<i>Anthochaera phrygia</i>	Regent Honeyeater	CE	E, M
<i>Ardea alba</i>	Great Egret, White Egret	–	M, Mar
<i>Ardea ibis</i>	Cattle Egret	–	M, Mar
<i>Chalinolobus dwyeri</i>	Large-eared Pied Bat	V	V
<i>Chalinolobus picatus</i>	Little Pied Bat	V	–
<i>Chthonicola sagittata</i>	Speckled Warbler	V	–
<i>Circus assimilis</i>	Spotted Harrier	V	–
<i>Glossopsitta pusilla</i>	Little Lorikeet	V	–
<i>Hamirostra melanosternon</i>	Black-breasted Buzzard	V	–
<i>Hieraaetus morphnoides</i>	Little Eagle	V	–
<i>Lathamus discolor</i>	Swift Parrot	E1	E, Mar
<i>Macropus dorsalis</i>	Black-striped Wallaby	E1	–
<i>Melanodryas cucullata cucullata</i>	Hooded Robin (south-eastern form)	V	–
<i>Merops ornatus</i>	Rainbow Bee-eater	–	M, Mar
<i>Miniopterus schreibersii oceanensis</i>	Eastern Bentwing-bat	V	–
<i>Ninox connivens</i>	Barking Owl	V	–
<i>Nyctophilus corbeni</i> (syn. <i>Nyctophilus timoriensis</i> (South-eastern form))	South-eastern Long eared Bat/Corben's Long-eared Bat	V	V
<i>Phascolarctos cinereus</i>	Koala	V	V
<i>Pomatostomus temporalis temporalis</i>	Grey-crowned Babbler (eastern subspecies)	V	–
<i>Pteropus poliocephalus</i>	Grey-headed Flying-fox	V	V

Scientific name	Common name	TSC Act ¹	EPBC Act ¹
<i>Saccolaimus flaviventris</i>	Yellow-bellied Sheath-tail-bat	V	–
<i>Stagonopleura guttata</i>	Diamond Firetail	V	–
<i>Tyto novaehollandiae</i>	Masked Owl	V	–
<i>Vespadelus troughtoni</i>	Eastern Cave Bat	V	–

Note:

1. CE = critically endangered, E = endangered, V = vulnerable, M = migratory, Mar = marine.

A total of 53 fauna species were recorded on the site including 40 bird, two amphibian, two microchiropteran bat and nine mammal species. No threatened fauna or migratory species listed under the EPBC Act were recorded.

One species, the Grey-crowned Babbler, listed as Vulnerable under the TSC Act was recorded multiple times across the site. Nesting sites were also recorded for this species in the vegetation in the north east corner of the property.

No migratory species were identified during the targeted searches.

4.11.3 Vegetation

The north eastern portion of Leewood is vegetated. The remainder has been cleared and exists as grassland with scattered paddock trees. Leewood is surrounded by State forest to the west, south and east (beyond the Newell Highway).

Two vegetation communities were identified at the site (refer Figure 4.6):

- (1) Pilliga Box – White Cypress Pine Grassy Open Woodland on Alluvial loams, Darling Riverine Plains and Brigalow Belt South

The condition of this community varied throughout the site. The remnant patches of intact Pilliga Box woodland were considered to be in moderate condition and had some impact from stock but retained high species diversity and covered an area of 17.4 hectares. These remnant patches are located in the north of the site and along the access road to the site and dominated by Pilliga Box (*Eucalyptus pilligaensis*) with other canopy species such as White Cypress Pine (*Callitris glaucophylla*) and Narrow-leaved Ironbark (*Eucalyptus crebra*). Bullock (*Allocasuarina leuhmannii*) and Deane's Wattle (*Acacia deanei*) dominated the sub-canopy layer and the ground cover consisted mostly of native grasses including Tall Chloris (*Chloris ventricosa*), Bristly Lovegrass (*Eragrostis setifolia*), Purple Lovegrass (*Eragrostis lacunaria*), Hairy Panic (*Panicum effusum*) and Slender Bamboo (*Austrostipa verticillata*).

The 'poor condition' areas of this community were identified as the paddock areas where a few scattered paddock trees remain. These areas have been strongly influenced by stock grazing and consequently the shrub layer was almost non-existent and the ground layer was largely comprised of a few grass species. This area of the community covered 210 hectares and was identified as Derived Grassland.

This community is not commensurate with any Threatened Ecological Communities (TEC) listed under the *Threatened Species Conservation Act 1995* (TSC Act) or *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

- (2) Brigalow Woodland

This community covers an area of 19.1 hectares in the far north east of the site and will not be impacted by the proposed activity. It comprises low woodland with a dense canopy dominated by Brigalow (*Acacia harpophylla*). Occasionally Pilliga Box (*Eucalyptus pilligaensis*) and Belah (*Casuarina cristata*) occur on the

edges of this community. The shrub and ground layers were sparse but consisted of species such as *Eremophila* species, *Sclerolaena* species, Small-leaf Bluebush (*Maireana microphylla*), Nardoo (*Marsilea hirsuta*) and Caustic Weed (*Chamaesyce drummondii*).

This community is considered to be in poor-moderate condition. The soil is compacted due to grazing, restricting the growth of understorey and ground layer species. As a result, the fauna guild which it attracts is limited. The dense array of Brigalow is healthy however its growth appears stunted likely due to poor soil quality.

This community is commensurate with the TEC '*Brigalow within the Brigalow Belt South, Nandewar and Darling Riverine Plains Bioregions*' under the TSC Act and '*Brigalow (Acacia harpophylla dominant and co-dominant)*' under the EPBC Act. This is discussed further in Section 6.2.1.

A total of six weed species were also recorded on Leewood. One of these species, *Opuntia* spp. Prickly Pear/Tiger Pear is considered to be a class 4 noxious weed in NSW under the *Noxious Weeds Act 1993* (NW Act).

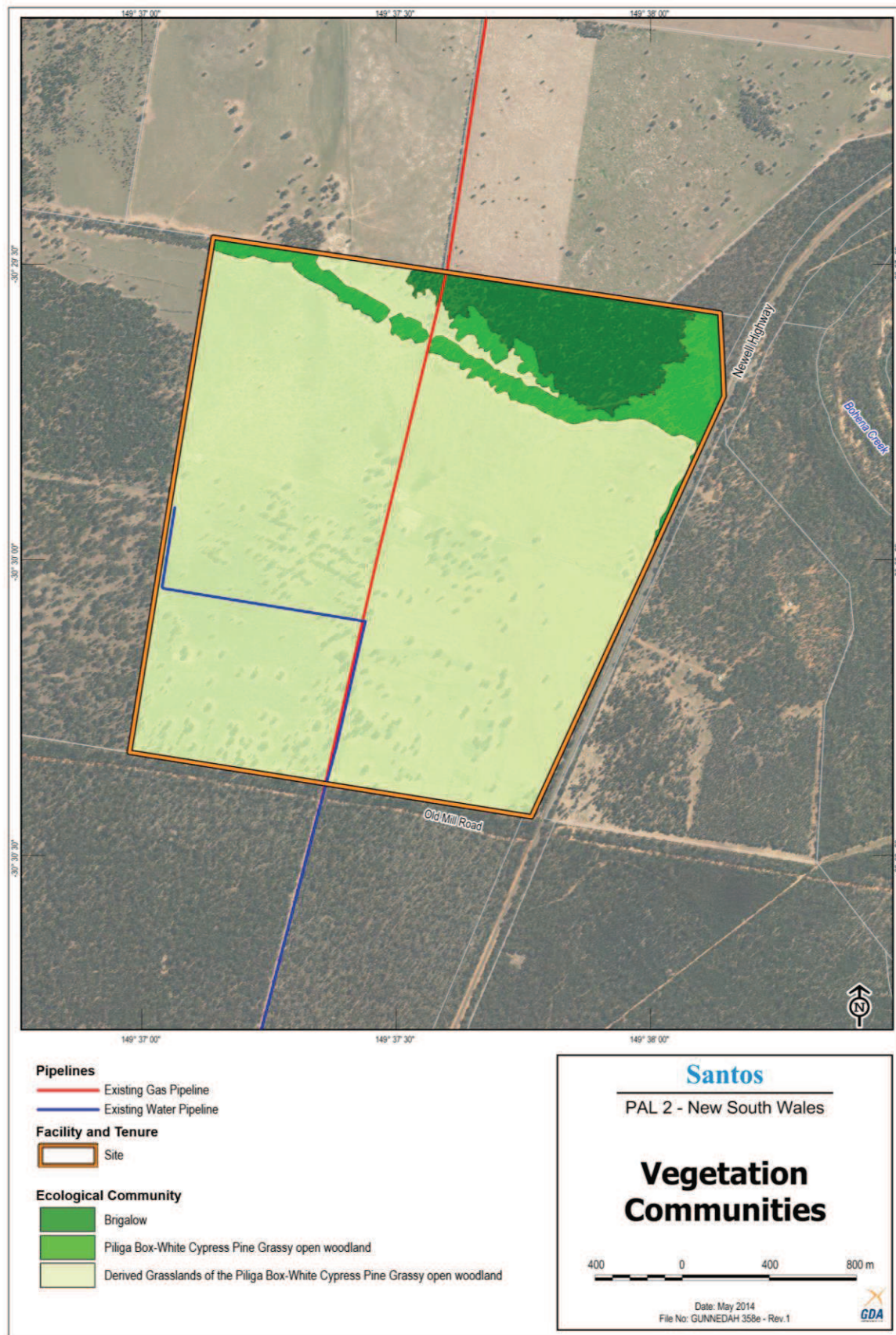


Figure 4-6 Vegetation communities

4.12 Traffic conditions

The site has frontages to the Newell Highway along the eastern boundary and Old Mill Road (also known as Dog Proof Fence Road) along the southern boundary. The latter is used as the main access route to the site.

4.12.1 Newell Highway

The Newell Highway is a classified State Road and is a major north-south inland transport corridor linking NSW with Victoria and Queensland. Adjacent to the site, it is a two-way sealed rural highway configured with a two-lane, seven metre wide carriageway, with approximately 0.5 metre sealed shoulder. The current pavement condition is good in the vicinity of Old Mill Road, with no major defects. The posted speed limit is 110 kilometres per hour.

Traffic volume data collected on the Newell Highway throughout April 2012 indicates that the average daily traffic along the Newell Highway was approximately 1,860 vehicles, with peak hourly flows of 169 vehicles. The proportion of heavy vehicles on the Newell Highway is approximately 40 per cent of the average daily traffic.

The Level of Service (LOS) is a performance standard which describes the efficiency of traffic travelling along a stretch of road or at an intersection. It considers various factors for rural roads, including terrain, speed and proportion of heavy vehicles. In order to achieve a LOS B, traffic volumes are required to be less than 530 vehicles per hour with a 15 per cent heavy vehicle proportion. Assuming a 40 per cent heavy vehicle proportion along this section of the Newell Highway, this equates to 350-400 vehicles per hour. Given that the traffic volumes are approximately 169 vehicles in any peak hour, the LOS along the Newell Highway is, at worst LOS B.

4.12.2 Old Mill Road

Old Mill Road is an unsealed forestry road travelling in an east-west direction for approximately 35 kilometres along the northern boundary of Pilliga East State Forest. It is understood to be managed and maintained by Forestry Corporation of NSW (FCNSW). There is an existing FCNSW speed limit of 60KPH.

Old Mill Road connects with the Newell Highway at a priority controlled T-intersection. Santos completed an upgrade of the intersection with the Newell Highway and Old Mill Rd as part of works associated with Leewood Phase 1. This upgrade ensures appropriate access for all vehicles including up to 25m long B-double trucks. The upgrade works included the following:

- drainage works
- installation of a clean gravel surface
- spray seal surface of Old Mill Road at the Newell Highway intersection over a distance of approximately 30 metres.

4.13 Aboriginal cultural heritage

The types of Aboriginal cultural heritage sites expected to occur within the site and surrounding region are influenced by a range of factors including the geology, vegetation, landform and the availability of natural resources and shelter. The main types of sites previously recorded in the Narrabri region and which might be expected to occur within the vicinity of the site are artefact scatters, scarred trees and open campsites.

A due diligence Aboriginal cultural heritage investigation was carried out for the site in accordance with the *Due Diligence Code of Practice for the Protection of Aboriginal Objects in New South Wales 2010* (Appendix

9). As part of this investigation, Central Queensland Cultural Heritage Management (CQCHM) undertook a desktop review of the environmental and archaeological contexts, including an analysis of the surrounding landscape, a review of prior archaeological investigations, a search of the Aboriginal Heritage Information Management Systems (AHIMS) database maintained by OEH and a visual inspection of Leewood.

A search was undertaken of the National Native Title Tribunal (NNTT) registers in October 2013. This search identified one native title claimant, being the Gomeroi People. Their claim extends over an area of 111,340 square kilometres. This claim was filed with the NNTT on 20 December 2011 and has subsequently been registered by the NNTT. Santos is actively engaged with the Gomeroi native title claim group's elected representatives including inviting their participation in the due diligence cultural heritage investigation.

The AHIMS search results indicated that there were no previously recorded Aboriginal heritage sites within one kilometre of Leewood.

In accordance with the Santos Aboriginal Engagement Policy and consistent with leading industry practice, Santos sought the participation of local Aboriginal knowledge holders (Narrabri Local Aboriginal Land Council and Gomeroi native title representatives) in the archaeological field survey of Leewood. The survey was conducted by CQCHM over two days from 10 April 2014 to 11 April 2014. Four items of Aboriginal heritage were identified during the investigation, two scarred trees and two isolated quartz artefacts. The locations of these items are shown in Figure 2-1. These items have been fenced off and will remain fenced.

No other landscape features, such as sand dune systems, ridge lines, cliff faces, caves or rock shelters, which indicate the likely existence of Aboriginal objects, are located in the area of the proposed activity at Leewood.

4.14 Historic cultural and natural heritage

Searches of the Australian Heritage Database (National and Commonwealth heritage), the State Heritage Register (State heritage), the State Heritage Inventory (local and s170 heritage) and the Narrabri LEP 2012 were undertaken on 26 February 2014. The searches revealed no items of National, Commonwealth, State or local heritage items, nor items listed under s170 of the *Heritage Act 1977* (Heritage Act), on or near the site.

Components of the Sydney University Giant Air-shower Recorder (SUGAR) array were identified at Leewood during field investigations undertaken by RPS between 30 July 2012 and 5 August 2012. A SUGAR station, comprising two pits are located along the western boundary of Leewood (as shown in Figure 2-1). The SUGAR station is not registered on the SHR or Narrabri LEP 2012. These sites were fenced off prior to the construction of the Leewood ponds and will remain fenced. The pits will not be impacted by the proposed activity as they are located on the western boundary of the Leewood property.

Also present in the vicinity of the site is a Travelling Stock Route (TSR), located to the north east of the site (as shown in Figure 2-1). The TSRs were authorised public tracks used for the movement of stock from one location to another and have been in use since the early nineteenth century.

5.0 REGULATORY CONTEXT

5.1 Commonwealth legislation

5.1.1 Environmental Protection and Biodiversity Conservation Act

The EPBC Act provides for the protection of certain Matters of National Environmental Significance (MNES) listed under the Act, which are:

- World Heritage Areas
- National Heritage Places
- Ramsar wetlands of international importance
- Commonwealth listed threatened species and ecological communities
- listed migratory species
- Commonwealth marine areas
- Great Barrier Reef Marine Park
- water resources, in relation to coal seam gas and large coal mining development
- nuclear actions.

Under the EPBC Act, Commonwealth approval is required from the Minister for the Environment (Minister) for any action that will have or is likely to have a significant impact on a MNES, or on the environment of Commonwealth land or on the environment if the action is proposed to be taken by a Commonwealth agency (known as a 'controlled action').

A person proposing to take a controlled action must refer the proposed activity to the Minister for determination. A person proposing to take an action that the person thinks is not a controlled action may refer the proposed activity to the Minister for the Minister's decision whether or not the action is a controlled action.

An EPBC Act Protected Matters Search Report was generated for a 10 kilometre radius surrounding the site to determine whether any MNES will likely be affected by the proposed activity. In addition, an Ecological Assessment was prepared to determine whether the proposed activity will be likely to impact on any nationally listed threatened species or ecological communities, or migratory species.

An assessment of the proposed activity against MNES is provided in Section 6.7. The proposed activity will be unlikely to have a significant impact on any MNES or the environment on Commonwealth land and is not proposed to be taken by a Commonwealth agency. Therefore, the proposed activity is unlikely to constitute a controlled action and Santos does not propose to lodge a referral to the Minister.

5.1.2 Native Title Act

The objectives of the *Native Title Act 1993* are to:

- recognise native title rights and sets down basic principles in relation to native title in Australia
- provide for the validation of past acts which may be invalid because of the existence of native title
- provide for a future regime in which native title rights are protected and conditions imposed on acts

affecting native title land and waters

- provide a process by which native title rights can be established and compensation determined, and by which determinations can be made as to whether future grants can be made or acts done over native title land and waters
- provide for a range of other matters, including the establishment of a National Aboriginal and Torres Strait Islander Land Fund.

As detailed in Section 4.13, a search was undertaken of the NNTT registers which identified one native title claimant, being the Gomeroi People.

Santos has been in discussions with Native Title Services Corporation, which is the native title representative body for NSW. They have also engaged with the Gomeroi Native Title Applicants in preliminary negotiations towards a native title agreement. It is noted however that the Leewood property is a freehold estate granted prior to 23 December 1996 and is therefore not subject to native title claims.

5.2 NSW Legislation

5.2.1 Petroleum (Onshore) Act

The Petroleum Act regulates the onshore exploration for and production of petroleum. Under the Petroleum Act, petroleum means:

(a) any naturally occurring hydrocarbon, whether in a gaseous, liquid or solid state, or

(b) any naturally occurring mixture of hydrocarbons, whether in a gaseous, liquid or solid state, or

(c) any naturally occurring mixture of one or more hydrocarbons, whether in a gaseous, liquid or solid state, and one or more of the following, that is to say, hydrogen sulphide, nitrogen, helium, carbon dioxide and water,

and includes any substance referred to in paragraph (a), (b) or (c) that has been returned to a natural reservoir, but does not include coal or oil shale or any substance prescribed to be a mineral for the purposes of the Mining Act 1992.

The holder of an assessment lease has the exclusive right to prospect for petroleum and to assess any petroleum deposit on the land comprised in the lease. An assessment lease is designed to allow retention of rights over an area in which a significant petroleum deposit has been identified, if mining the deposit is not commercially viable in the short term but there is a reasonable prospect that it will be in the longer term. The holder is allowed to continue prospecting operations and to recover petroleum in the course of assessing the viability of commercial mining.

The proposed activity will be undertaken in accordance with PAL 2, granted under the Petroleum Act. The conditions of PAL 2 require activities to be undertaken in accordance with an approved Petroleum Operations Plan. The Petroleum Operations Plan for PAL 2 has recently been updated to reflect the proposed activity and other future operations within PAL 2 and has been approved by OCSG.

5.2.2 Environmental Planning & Assessment Act

5.2.2.1 Overview

The EP&A Act regulates development carried out in NSW. The carrying out of development is regulated under either Part 4 or Part 5 of the EP&A Act.

Development is required to be assessed under Part 5 of the EP&A Act if the relevant environmental planning instruments provide that the development does not require consent or is not exempt development, and the development is either carried out by a determining authority or requires the approval of a determining authority.

The *State Environmental Planning Policy (Mining, Petroleum Production and Extractive Industries) 2007* (Mining SEPP) aims 'to provide for the proper management and development of mineral, petroleum and extractive material resources for the social and economic welfare of [NSW]'. Clause 6 of the Mining SEPP provides that development for the purposes of "petroleum exploration" may be carried out without development consent. "Petroleum exploration" includes prospecting and assessment of petroleum under a PEL or a PAL. The proposed activity is being carried out for the purposes of petroleum exploration under PAL 2 and requires approval of the Director-General under the conditions of PAL 2. This has the effect that development consent is not required and the proposed activity is required to be assessed under Part 5 of the EP&A Act.

A determining authority, for the purposes of this activity, is defined in Part 5 to include a public authority whose approval is required before an activity may be carried out. The OCSG is the determining authority for the purposes of Part 5 of the EP&A Act for the proposed activity.

5.2.2.2 Determining authorities and the REF

Under Part 5 of the EP&A Act, a determining authority is required to examine and take into account to the fullest extent possible all matters affecting or likely to affect the environment by reason of the proposed activity.

Additionally, clause 228 of the *Environmental Planning and Assessment Regulation 2000* sets out the factors that must be taken into account concerning the impact of an activity on the environment.

The determining authority is required to consider whether the proposed activity is likely to significantly affect the environment or threatened species, populations or ecological communities, or their habitats to determine whether an Environmental Impact Statement (EIS) or Species Impact Statement (SIS) is required. In deciding whether there is likely to be a significant effect on threatened species, populations or ecological communities or their habitats, section 5A of the EP&A Act requires the following factors to be taken into account (the 'seven part' test of significance):

(a) in the case of a threatened species, whether the action proposed is likely to have an adverse effect on the life cycle of the species such that a viable local population of the species is likely to be placed at risk of extinction,

(b) in the case of an endangered population, whether the action proposed is likely to have an adverse effect on the life cycle of the species that constitutes the endangered population such that a viable local population of the species is likely to be placed at risk of extinction,

(c) in the case of an endangered ecological community or critically endangered ecological community, whether the action proposed:

(i) is likely to have an adverse effect on the extent of the ecological community such that its local occurrence is likely to be placed at risk of extinction, or

(ii) is likely to substantially and adversely modify the composition of the ecological community such that its local occurrence is likely to be placed at risk of extinction,

(d) in relation to the habitat of a threatened species, population or ecological community:

(i) the extent to which habitat is likely to be removed or modified as a result of the action proposed, and

(ii) whether an area of habitat is likely to become fragmented or isolated from other areas of habitat as a result of the proposed action, and

(iii) the importance of the habitat to be removed, modified, fragmented or isolated to the long-term survival of the species, population or ecological community in the locality,

(e) whether the action proposed is likely to have an adverse effect on critical habitat (either directly or indirectly),

(f) whether the action proposed is consistent with the objectives or actions of a recovery plan or threat abatement plan,

(g) whether the action proposed constitutes or is part of a key threatening process or is likely to result in the operation of, or increase the impact of, a key threatening process.

This REF has been prepared to assist the determining authority in meeting its obligations under section 111 of the EP&A Act. In particular, the “seven part” test has been applied to the proposed activity in Appendix 8 of the REF. The REF concludes that the proposed activity is not likely to significantly affect the environment or threatened species, populations or ecological communities or their habitats.

5.2.2.3 Narrabri Local Environmental Plan 2012

While the proposed activity does not require consent under Part 4 of the EP&A Act, consideration has been given to the relevant zone objectives under the Narrabri LEP. The site is located within land zoned RU1 Primary Production, the objectives of which are to:

- encourage sustainable primary industry production by maintaining and enhancing the natural resource base
- encourage diversity in primary industry enterprises and systems appropriate for the area
- minimise the fragmentation and alienation of resource lands
- minimise conflict between land uses within this zone and land uses within adjoining zones
- allow for non-agricultural land uses that will not restrict the use of other land for agricultural purposes.

The proposed irrigation activities fit with the zone and surrounding land uses, while other activities within the site will not restrict the use of other land for agricultural purposes. The natural resource base relied upon by the industries within the area will not be significantly affected by the proposed activity. The proposed activity will not significantly affect the development of agriculture, agricultural-related enterprises in the area nor will it result in fragmentation or alienation of resource lands. The proposed activity will not result in conflict between land uses within the RU1 Primary Production zone or land uses within adjoining zones. Therefore, the proposed activity is considered to be a suitable activity within the RU1 Primary Production.

5.2.3 **Protection of the Environment Operations Act**

One of the primary objectives of the *Protection of the Environment Operations Act 1997* (NSW) (POEO Act) is to ‘protect, restore and enhance the quality of the environment in NSW, having regard to the need to

maintain ecologically sustainable development'. The POEO Act requires EPLs be obtained for the carrying out of 'scheduled activities' or to pollute waters.

All petroleum exploration, assessment and production titles and activities are required to hold an EPL. Santos holds a licence (EPL 20350) for the Narrabri gas field which includes the produced water and brine storage ponds at Leewood. If the proposed activity is approved, Santos will apply to have EPL 20350 modified to include the proposed activity, including the discharge of treated water on-site through managed irrigation.

The load-based licensing (LBL) scheme under the POEO Act sets out limits on pollutant loads that can be emitted by holders of an EPL, including load-based fees. Schedule 1 of the *Protection of the Environment Operations (General) Regulation 2009* lists all licensed activities that attract load-based fees, including petroleum exploration, assessment and production. Assessable pollutants applying to petroleum exploration, assessment and production include:

- air pollutants
 - benzene
 - benzo(a)pyrene (equivalent)
 - fine particulates
 - hydrogen sulfide
 - nitrogen oxides and nitrogen oxides (summer)
 - sulfur oxides
 - volatile organic compounds (VOCs) and VOCs (summer).
- water pollutants
 - biological oxygen demand (BOD)
 - oil and grease
 - salt
 - suspended solids
 - total polycyclic aromatic hydrocarbons (PAHs)
 - total phenolics.

Load limits of these pollutants will need to be monitored and reported under the EPL. The main assessable pollutant in the irrigation water is salt and this is likely to be subject to load based licence fees calculated based on the amount of salt released during the irrigation activities.

5.2.4 Water Management Act 2000

5.2.4.1 Aquifer Interference Approval

The maximum depth of excavation for the proposed activity is approximately five metres, and would be unlikely to result in aquifer interference. Groundwater was not detected during the geotechnical investigation at Leewood or during construction of the produced water and brine ponds. Static water levels at the on-site groundwater monitoring bores ranged from 20.7 to 29.5 metres below ground level.

5.2.4.2 Water use approval

A water use approval under section 89 of the WM Act will be required for the proposed use of treated water including the irrigation of agricultural land and other proposed beneficial reuses. An exemption to this requirement applies where an aquifer interference approval under section 91 of the WM Act has been granted for an activity. This type of approval has not yet commenced; therefore a water use approval will be sought for these activities. If at any stage leading up to a water use approval being sought the aquifer interference approval commences, Santos may instead apply for an aquifer interference approval for the extraction activities.

5.2.4.3 Water access licences

Under Part 2 of Chapter 3 of the WM Act, it is an offence to take water from a source regulated by the WM Act unless in accordance with a water access licence. Water used for the construction of the proposed activity will be sourced from the licensed water supply bore already on the Leewood property or an alternative appropriately licenced water supply bore. Water treated onsite at the WBTP will be used to meet onsite operational water demands.

A WAL is also required for the taking of groundwater regulated by the WM Act, whether for consumption or incidentally, unless an exemption applies. The proposed activity is not expected to take any groundwater due to the shallow depth of the proposed earthworks (less than five metres) and known depths of those aquifers regulated by the WM Act (greater than 10 metres).

5.2.4.4 Flood work approval

Under section 90 of the WM Act, a flood work approval is required to construct and use flood work at a specified location. Flood work is defined within the WM Act and includes a work in the vicinity of a river or within a floodplain (as declared under the WM Regulation) that is of such a size or configuration that it is likely to have an effect on the flow of water to or from a river or the distribution or flow of floodwater in times of flood. Clause 13 of Schedule 9 of the WM Act provides that any land that was designated as a floodplain under Part 8 of the *Water Act 1912* is taken to be a floodplain for the purposes of the WM Act.

There are a number of floodplains declared under the *Water Act 1912* located nearby but not on the site. The closest is the Namoi River: Narrabri to Wee Waa floodplain located approximately 22 kilometres north of the site. Therefore, a flood work approval is not required for the proposed activity.

5.2.5 **Threatened Species Conservation Act**

The TSC Act sets the framework for the listing of threatened species, populations and ecological communities, and key threatening processes in NSW, and the preparation and implementation of recovery plans and threat abatement plans.

The TSC Act also provides the mechanism for applying for and obtaining licences to take actions which could result in harm to a threatened species, population or ecological community, or their habitat, or damage to critical habitat.

Section 5A of the EP&A Act lists seven factors that must be taken into account in determining the significance of a potential impact on 'threatened species, populations or ecological communities (or their habitats)' listed under the TSC Act (included in Section 6.2.1). The assessment of significance (7-part test) is used to determine whether activities are 'likely' to cause 'a significant impact' on threatened biota and thus whether an SIS is required.

The ecological assessment prepared for the proposed activity identified 21 threatened fauna species listed under the TSC Act that are potential, likely or known to occur on the site with potential to be impacted upon by the proposed activity. In addition, the proposed activity requires the removal of 99.6 hectares of disturbed Derived Grassland. However, the ecological assessment concluded that the proposed activity is unlikely to have a significant impact on threatened species, populations or ecological communities (or their habitats). Potential impacts to biodiversity are discussed in Section 6.2.1.

5.2.6 National Parks and Wildlife Act

5.2.6.1 Threatened Species

Part 8A of the *National Parks and Wildlife Act 1974* (NPW Act) regulates the undertaking of activities which may impact on threatened species, populations and ecological communities listed under the TSC Act and their habitats. The NPW Act provides that a person must not harm any animal that is a threatened species, population or ecological community, pick any plant which is part of a threatened species, population or ecological community, damage any critical habitat or damage any habitat of a threatened species, population or ecological community without a licence being obtained under the NPW Act or TSC Act or unless another exception applies.

The NPW Act provides that these requirements do not apply if the action was essential for the carrying out of an activity in accordance with an approval of a determining authority under Part 5 of the EP&A Act where the determining authority has complied with Part 5.

5.2.6.2 Aboriginal Cultural Heritage

The NPW Act conserves places, objects and features of significance to Aboriginal people.

It is an offence under the NPW Act to:

- harm or desecrate an object that the person knows is an Aboriginal object except in accordance with an Aboriginal Heritage Impact Permit (AHIP)
- harm or desecrate Aboriginal objects and Aboriginal places except in accordance with an AHIP or where the person can show they exercised due diligence to reasonably determine that no Aboriginal object will be harmed.

A cultural heritage assessment of the site was prepared in accordance with the *Due Diligence Code of Practice for the Protection of Aboriginal Objects in New South Wales 2010* (DECCW, 2010). The assessment determined that the proposed activity will not impact on any known Aboriginal objects or places, despite the presence of four Aboriginal objects within the site (two scarred trees and two isolated stone artefacts). Provided that the mitigation measures identified in Section 6.5.2 were carried out, impacts to any known or unknown Aboriginal objects or places should be avoided. Therefore, an AHIP is not required for the proposed activity.

5.2.7 Noxious Weeds Act

The NW Act is a NSW government instrument outlining the definition, declaration, and control of noxious weeds throughout the State. Local government bodies have the responsibility to ensure that the NW Act is complied with within their boundaries.

Landowners or occupiers have obligations under the NW Act to control any declared weed on their property. Council is required to conduct inspections of private properties to check compliance with the NW Act and Noxious Weed Officers have the authority to issue control notices for any breach.

Under the actions of this Act, a level of control can be applied to reducing the abundance and distribution of exotic weeds within Australia.

One noxious weed, *Opuntia* spp. Prickly Pear/Tiger Pear, was identified in the site. Under the provisions of the NW Act, this species is classified as a Class 4 weed. This means that the growth and spread of the plant must be controlled according to the measure specified in a management plan published by the local control authority and the plant may not be sold, propagated or knowingly distributed. Management of these species will be undertaken in accordance with the Narrabri Shire Council Management Plan for Prickly Pear (Plan No. PP01/2006, as revised 1 March 2011).

5.2.8 Heritage Act

The main objective of the *Heritage Act 1977* is to encourage the conservation of the heritage of NSW. The Leewood site is not listed on the State Heritage Register under the Heritage Act.

The Heritage Act also prevents impacts on 'relics', which are defined as:

any deposit, artefact, object or material evidence that:

(a) relates to the settlement of the area that comprises New South Wales, not being Aboriginal settlement, and

(b) is of State or local heritage significance.

Under the Heritage Act, it is an offence to disturb or excavate any land knowing or having reasonable cause to suspect that the disturbance or excavation will or is likely to result in a relic being discovered, exposed, moved, damaged or destroyed unless the disturbance or excavation is carried out in accordance with an excavation permit.

Two items of potential heritage significance were identified at Leewood during the archaeological field surveys. The proposed activity will not impact these items provided that the mitigation measures identified in Section 6.6.2 are carried out.

6.0 ENVIRONMENTAL IMPACTS AND MITIGATION

This section of the REF addresses the potential environmental impacts associated with the proposed activity and identifies mitigation measures to ensure any impacts are appropriately managed. Potential impacts following the implementation of mitigation measures have been categorised in accordance with the ESG2 Guidelines. Impact categories include:

- negligible
- low adverse
- medium adverse
- high adverse
- positive.

The potential impacts associated with the proposed activity, including the impact categorisation following the implementation of mitigation measures are summarised in Section 7.

Table 6-1 addresses the specific impact assessment questions posed in Chapter 4 of the ESG2 Guidelines for each type of potential impact. Each of these questions has been discussed in detail in the following sections of the REF. The table responds to each question, identifies where in the REF it is discussed in further detail or why it has not been addressed.

Table 6-1 Compliance with Chapter 4 of the ESG2 Guidelines

Issue	Response/reference
4.1 Physical and chemical impacts	
Is the proposed activity likely to impact on soil quality or land stability?	No. The design and operation of the Leewood WBTP will ensure that the risk of any uncontrolled release from the plant is minimised. Comprehensive control and alarms systems which monitor and account for the volume of water pumped and processed throughout the entire system will assist in leak monitoring and prevention. The application of amended treated irrigation water and undertaking of land preparation activities, including soil amelioration, are likely to maintain or improve the soil quality and structure within the irrigation area on-site. Potential minor impacts during construction and operation associated with soil erosion and sediment loss, soil compaction and waterlogging, increased soil salinity and soil contamination can be adequately addressed with mitigation, including erosion and sediment control, appropriate irrigation practices, and management of topsoil and chemicals. Refer Sections 2.7.1, 2.7.4 and 6.1.1.
Is the activity likely to affect a waterbody, watercourse or wetland or natural drainage system?	No. The proposed activity will not result in the redirection of flow of any watercourse. It is considered highly unlikely that the proposed activity will result in the pollution of waters. Under certain irrigation scenarios there would be more surface runoff and deep drainage than the current land use, however the changes in water loss mechanisms are considered to be minimal. Surface water and groundwater monitoring will be undertaken throughout operation of the proposed activity. Refer Sections 2.7.1, 6.1.2 and 6.1.3.
Is the activity likely to change flood or tidal regimes, or be affected by flooding?	No. Leewood is affected by the 1:100 year flood level. Approximately one-third of the irrigation area is proposed within the 100 year ARI affected land, as

Issue	Response/reference
	well as a small section of hardstand area surrounding the treated water storage tank. Subsurface irrigation infrastructure will be installed in this part of the irrigation area rather than a pivot system, and irrigation scheduling would be managed to take into consideration prolonged rainfall. It is considered unlikely that the proposed activity would cause changes to the downstream flood regime and that the proposed activity would be unduly impacted by flooding. Refer Sections 4.9 and 6.1.3.
Is the activity likely to affect coastal processes and coastal hazards, including those under projected climate change conditions?	No. The site is not located within the coastal zone and will not be affected by coastal processes or hazards. Accordingly, this has not been addressed further in the REF.
Does the activity involve the generation or disposal of gaseous, liquid or solid wastes or emissions?	Yes. Small quantities of emissions and GHGs will be released due to the use of diesel and gas generators at Leewood during both construction and operation. These minor levels of emissions are not expected to affect air quality. Additional waste will be produced in small quantities during construction and operation, and will be recycled or disposed of at an appropriately licensed facility. Produced water will be treated for beneficial reuse, reducing the quantity of liquid wastes. The proposed activity will involve the generation of brine. The brine will be concentrated as much as possible via the treatment process and stored on site in the Leewood ponds. In the longer term, the ponds would be decommissioned and site rehabilitated, with the remaining pond contents being sent to the relevant licensed waste facility, as required. An EPL is required for the proposed activity. Refer Sections 6.1.4, 6.1.5 and 6.1.7.
Will the activity involve the emission of dust, odours, noise, vibration, or radiation in the proximity of residential/urban areas or other sensitive locations?	Yes. Construction activities will generate noise at some of the nearest residential receivers during both standard hours and outside of standard hours for certain construction scenarios. Impacts can be appropriately mitigated, in consultation with the landowners. Dust and vibration generated during construction activities will not significantly impact upon sensitive receivers as they do not exceed relevant criteria. Similarly during operation, dust, noise and vibration will have negligible impacts as they generally do not exceed relevant criteria. Refer to Sections 6.1.4 and 6.1.6.
Does the proposed activity involve the use, storage or transport of hazardous substances or the use or generation of chemicals which may build up residues in the environment?	Yes. Small quantities of chemicals and diesel fuel will be stored within the site and used during the proposed activity. Their use, storage and transport will be appropriately managed to minimise the risk of spills occurring. Refer Section 6.1.8.
4.2 Biological impacts	
Is any vegetation to be cleared or modified (including vegetation of conservation significance)?	Yes, however no vegetation of significance will be cleared. The construction of the proposed WBTP and associated infrastructure will be likely to result in the clearing of approximately 1.8 ha of Derived Grassland. The proposed irrigation area for the treated water will likely result in the disturbance of a further 97.8 ha of Derived Grassland. Refer Section 6.2 and Appendix 8.
Is the activity likely to have a significant effect on threatened flora or fauna species, populations, or their habitats, or critical habitat; or an endangered	No. No threatened ecological communities or threatened flora will be impacted by the proposed activity. While a number of threatened fauna species were identified as having the potential to occur within the site, the

Issue	Response/reference
ecological community or its habitat? (i.e. the threatened species <u>assessment of significance</u>)	proposed activity will not result in the removal of high quality habitat. Further, it is considered more likely that such fauna species would occur offsite due to better habitat characteristics. Refer Sections 6.2 and 6.7 and Appendix 8.
Does the activity constitute or is part of a key threatening process?	No. Refer Section 6.2 and Appendix 8.
Does the activity have the potential to endanger, displace or disturb fauna (including fauna of conservation significance) or create a barrier to their movement?	Yes, fauna may be disturbed or displaced. Removal of some vegetation may impact fauna. However, the quality of habitat to be removed is poor and impacts would be minor. Refer Section 6.2 and Appendix 8.
Is the activity likely to impact on an ecological community of conservation significance?	No. The proposed activity will not require the removal of any ecological community of conservation significance. Refer Sections 6.2 and 6.7, and Appendix 8.
Is the activity likely to cause a threat to the biological diversity or ecological integrity of an ecological community?	No. The proposed activity will predominantly impact previously disturbed land, including Derived Grassland. Refer Sections 6.2 and 6.7 and Appendix 8.
Is the activity likely to introduce noxious weeds, vermin, feral species or genetically modified organisms into an area?	No. <i>Opuntia</i> spp. Prickly Pear/Tiger Pear has been identified in the site. Mitigation has been proposed to ensure this species is appropriately managed. Refer Section 6.2 and Appendix 8.
4.3 Community impacts	
Is the activity likely to have an impact on the safety of the community?	No. All works are located within the Santos-owned Leewood property and is not accessible by the public. Refer Section 6.3.1.
Is the activity likely to cause a bushfire risk?	No. Parts of the site are expected to exhibit moderate to high bushfire hazard mainly due to the extent of vegetation cover. Standard site safety protocols and emergency procedures will be implemented to ensure that onsite bushfire risks are appropriately managed during both construction and operations. Refer Section 6.3.1.
Is the activity likely to affect existing community services or infrastructure?	No. All works are located within the Santos-owned Leewood property. The proposal will result in minor increases of traffic on the local road network, including the Newell Highway. There may be some impact to accommodation availability in Narrabri during construction; however this is not anticipated to be significant. Refer Sections 6.3.2 and 6.3.4.
Is the activity likely to cause impacts on the visual or scenic landscape?	Yes. Visual impacts associated with the proposed activity will mainly be in relation to the WBTP and associated infrastructure, as during operation the cropping activities within the irrigation area are consistent with surrounding land uses. Plant and equipment at the WBTP and associated infrastructure will be visible during construction and operation, but given its distance from the Newell Highway and neighbouring residences, will have a negligible impact on scenic amenity. Refer Section 6.3.3.

Issue	Response/reference
Does the activity affect sites of importance to the local or broader community for their recreational or other values or access to these sites?	No. All works are located within the Leewood property and is not accessible by the public. Refer Sections 6.3.3 and 6.3.4.
Is the activity likely to affect economic factors?	Yes. The proposed activity will have a negligible impact on the local economy, given the scale of the project. Refer Section 6.3.5.
4.4 Natural resource impacts	
Is the activity likely to result in the degradation of an area reserved for conservation purposes?	No. There are no areas reserved for conservation that would be affected by the proposed activity. This has not been addressed further in the REF.
Is the activity likely to affect the use of, or the community's ability to use, natural resources?	No. The proposed activity will not require significant quantities of natural resources. Refer Section 6.4.
Is the activity likely to involve the use, wastage, destruction or depletion of natural resources including water, fuels, timber, or extractive materials?	Yes. Once natural gas from the existing WPPS pipeline is connected to the site, approximately 63,000 GJ/yr gas will be used onsite during operation of the proposed activity. This is considered to be a beneficial use of CSG from exploration and appraisal activities. The proposed activity will not require significant quantities of other natural resources. Refer Section 6.4.
4.5 Aboriginal cultural heritage impacts	
Will the activity disturb the ground surface or any culturally modified trees (e.g. a scar tree)?	Yes, the proposal will disturb the ground surface. The proposed activity involves disturbance of approximately 99.6 ha for the construction of the WBTP and associated infrastructure, and preparation of the irrigation area. A cultural heritage assessment of the site was prepared in accordance with the <i>Due Diligence Code of Practice for the Protection of Aboriginal Objects in New South Wales 2010</i> (DECCW, 2010). The assessment determined that while two scar trees have been identified on the site, the proposed activity will not impact on these trees as mitigation measures based on the Avoidance Principle will be implemented. Refer section 6.5 and Appendix 9.
Does the activity affect known Aboriginal objects or Aboriginal places?	No. A cultural heritage assessment of the site was prepared in accordance with the <i>Due Diligence Code of Practice for the Protection of Aboriginal Objects in New South Wales 2010</i> (DECCW, 2010). The assessment determined that while two isolated stone artefact flakes have been identified on the site, the proposed activity will not impact on these objects and each flake is surrounded by fencing. Refer section 6.5 and Appendix 9.
Is the activity located in areas where landscape features indicate the presence of Aboriginal objects?	No. Refer section 6.5 and Appendix 9.
Can harm to objects or disturbance of landscape features be avoided?	Yes. No harm to objects or landscape features is proposed. Refer section 6.5 and Appendix 9.
Does the proposed activity affect areas subject to native title claims, indigenous land use agreements or joint	Yes. The Gomeroi People have filed a claim over an area of 111,340 km ² which includes the Narrabri LGA and the site. Santos has engaged with

Issue	Response/reference
management?	Native Title Services, which is the native title representative body for NSW, in respect to this matter. Santos has also had preliminary discussions with the Gomeroi Native Title Applicants in the lead up to a native title agreement. Refer Sections 5.1.2 and 6.5.
4.6 Historic cultural or natural heritage impacts	
What is the impact on places, buildings, landscapes or moveable historic heritage items?	Nil. Two identified items of potential European heritage significance (i.e. SUGAR pits) have been identified on Leewood. The proposed activity will avoid impacts to the items. Refer Section 6.6.
Is any vegetation of cultural landscape value likely to be affected (e.g. gardens and settings, introduced exotic species, or evidence of broader remnant land uses)?	No. There is no vegetation of cultural landscape value within the site. This has not been addressed further in this REF.
4.7 Matters of National Environmental Significance	
Is the proposed activity likely to impact on MNES under the EPBC Act?	No. The proposed activity will not impact of any MNES. Refer Section 6.7.
4.8 Cumulative Impacts	
Is the proposed activity likely to have any significant cumulative impacts?	No. Refer Section 6.8.

6.1 Physical and chemical impacts

6.1.1 Soil quality and land stability

6.1.1.1 Impacts

Construction of the proposed activity will require vegetation clearing and land disturbance (see Section 6.2.1). These works, while temporary, have the potential to cause soil degradation and loss of topsoil, soil compaction and soil erosion, including sedimentation of waterways.

Should topsoil to be stockpiled at Leewood be stored for an extended period (i.e. greater than 12 months), impacts to the structure, biological activity, chemical properties and organic content may be affected.

During construction and operation, the proposed activity could result in soil contamination as a result of spilled or leaked chemicals, fuel or oil. Spills or leaks could occur during handling, use, storage or transit of chemicals, fuels and oils. Spills or leaks may also occur during refuelling or maintenance of plant or equipment. Any incidence of spills or leaks on-site would likely be minor. Measures to reduce the risk of contamination as a result of the proposed activity are identified in Section 6.1.1.2.

Loss of containment of untreated produced water from WBTP units, pipes or manifolds could result in an uncontrolled release to the environment and subsequent soil contamination. The design and operation of the Leewood WBTP will ensure that the risk of any uncontrolled release from the plant is minimised. Comprehensive control and alarms systems which monitor and account for the volume of water pumped and processed throughout the entire system will assist in leak monitoring and prevention. Incident management measures to prevent leakages are outlined in Section 2.7.4.

During operation, the main potential impacts to soil will occur across the irrigation area. As stated in Section 4.3.1, the soils within the irrigation areas of the site were grouped into two management classes – A and B.

The irrigation system design and operations would treat these as different management zones, as outlined in the irrigation concept design report (Appendix 3). Therefore irrigation infrastructure, cropping and irrigation scheduling would vary according to the irrigation management class of the soil to minimise potential impacts.

As outlined in Section 4.3.2, the soil on-site has a number of inherent limitations due to its sodic nature. Without chemical dosing, the addition of irrigation water to the sodic soil could present the following issues:

- limiting of leaching, which could cause salt to accumulate over time and the development of saline subsoils, as sodicity reduces flow of water through soil
- crusting and sealing of the soil, which could impede water infiltration leading to potential increased runoff, as sodicity causes dispersion in the soil surface
- acceleration of erosion, which could cause the appearance of gullies and tunnels, as sodicity increases dispersion in the subsoil
- a dense, cloddy and structureless soil as it destroys aggregation.

However, as discussed in Section 2.6.3.2, prior to being used for irrigation purposes, water from the WBTP will be treated to a level that conforms with the *Environmental Guidelines: Use of Effluent by Irrigation* (DEC, 2004). The addition of chemicals to the treated water will make the water suitable for the intended soils and will serve to maintain or improve soil structure stability. This will be closely monitored as outlined in 2.7.1.2.

As outlined in Table 2-10 of Section 2.6.2.1, the following soil preparation activities will be undertaken during construction:

- application of gypsum – displaces the sodium within the soil, reducing its sodicity and dispersivity
- application of lime – neutralises soil acidity, and additional calcium would also ameliorate sodium
- deep ripping – breaks up the hard, coarse subsoil to assist in water infiltration
- application of fertiliser (during soil preparation, and continuing on throughout operation) – increases the nitrogen levels in soils, a limiting nutrient onsite.

The salinity of the treated water to be applied to the irrigation area would be rated as 'low' according to the DEC Guidelines (2004), as described in Section 2.6.3.4. Most irrigation waters carry a salt load that presents a risk of accumulation in the rootzone, particularly in arid regions or where high water tables exist. The annual rainfall of approximately 650 millimetres onsite will assist in offsetting salt deposition by irrigation water.

The expected EC of the treated water is 1.0 mS/cm. The estimated salt load of the treated water (using the calculation method described in DECC's *Load Calculation Protocol* (June 2009)) is 0.7004 mg/L. The total annual salt load to the soils over the irrigation area, based on an irrigation application rate of 372 millimetres per hectare or 3.7 ML/ha, is expected to be 1,859 kg/ha. Around 876 kg/ha of this is predicted to comprise sodium chloride salts. The remainder is attributed from calcium sulphate salts which have a positive effect on soil quality.

At an annual irrigation application rate of 372 millimetres or 3.7 megalitres per hectare, the annual salt input from irrigation is shown in Table 6-2.

Table 6-2 Annual salt loading from application of treated irrigation water

Salt added	Annual salt load (kg/ha)
Sodium	434
Calcium	242
Chloride	442
Sulphate	741
Total salts	1,859

The calcium sulphate salts typically have a positive effect on soil quality. Sodium chloride can impact soil stability (i.e. increased dispersibility), so the proposed irrigation system would provide control sensitivity such as deep drainage. Regular soil sampling and monitoring of salt accumulation in and beneath the rootzone would also be implemented.

The proposed irrigation area within the site is also prone to becoming waterlogged in the surface soil and would be untrafficable following extended rainfall periods, i.e. periods where continuous rainfall events exceed 50 millimetres. Land preparation and operational activities would be restricted during these periods. The irrigation schedule (application of the treated water) would be managed to minimise waterlogging and runoff. Traffic would also be kept to a minimum in the irrigation area to reduce soil compaction.

To gain a better understanding of the potential effects of irrigation of this site, three irrigation management schemes were modelled for comparison to the current rain-fed pasture setting. Details of this modelling are provided in the concept irrigation design report, provided in Appendix 3.

The four irrigation scenarios that were modelled using the HowLeaky modelling program were:

- Scenario 1 (baseline) – current dryland pasture under natural rainfall. This was simulated to compare the natural erosion, deep drainage and runoff from the site
- Scenario 2 – even irrigation of all 97.8 hectares, simulation based on an average year with one megalitre per day treated irrigation water
- Scenario 3 – even irrigation of all 97.8 hectares, simulation based on an average year with unlimited treated irrigation water
- Scenario 4 (likely management approach for the proposed activity) – irrigation split between Class A (68 ha) and B soils (30 ha), with priority given to watering Class B soils from October to May, and no irrigation of Class B soils from June to September. One megalitre per day treated irrigation water supply.

Irrigation events were set at 12 millimetres per application. An irrigation event was triggered once the soil water deficit reached 50 millimetres or 36 per cent of the 140 millimetre plant available water capacity (PAWC).

Three parameters having potential environmental impacts were modelled – runoff, deep drainage, and erosion and site sediment loss. The results of the modelling for these parameters are provided in Table 6-3.

Table 6-3 Water losses from system with potential environmental impacts = HowLeaky model output

Water loss mechanism	Scenario 1	Scenario 2	Scenario 3	Scenario 4 – Class A soils	Scenario 4 – Class B soils
Deep drainage (mm/yr)	4.0	3.9	16.9	4.3	5.7
Runoff (mm/yr)	14.2	13.5	39.6	14.6	17.6
Erosion and site sediment loss (t/ha-yr)	0.22	0.22	0.70	0.24	0.30

Discussions on the potential impacts of the proposed activity in relation to deep drainage and runoff are provided in Sections 6.1.2 and 6.1.3, respectively.

Under all four scenarios the paddocks were in permanent vegetative cover and the erosion and site sediments losses were predicted to be quite low at less than one tonne per hectare annually. The International Erosion Control Association best practices manual (IECA, 2008) states that erosion losses less than one tonne per annum are a desirable target and should result in less than 50 mg/L suspended solids which is necessary for maintaining pristine waterways.

6.1.1.2 Mitigation measures

The following measures will be implemented to avoid and/or minimise impacts on soil quality and land stability:

- Erosion and sediment controls will be implemented where necessary, in accordance with the guidelines, principles and recommended minimum design standards contained in *Managing Urban Stormwater, Soils and Construction – Volume 1* (the Blue Book). These controls will be maintained until disturbed areas of the site are stabilised
- A specific erosion and sediment control plan (ESCP) will be developed during detailed design and implemented for the proposed activity
- Any spills or leaks will be contained and cleaned up immediately. Contaminated material (such as contaminated soil or absorbent materials) will be removed from the site for disposal at a licensed waste facility
- Plant and equipment installed at the premises or used in connection with the licensed activity will be maintained and operated in accordance with condition O2.1 of EPL 20350
- A soil sampling and monitoring program, inclusive of the irrigation area will be implemented, as outlined in Section 2.7.1.2
- Soil amelioration, crop management and irrigation scheduling will occur generally as described in the concept irrigation design report (Appendix 3), to prepare and maintain the irrigation area throughout operation
- The site will be rehabilitated in accordance with Section 2.6.4 of the REF.

6.1.1.3 Potential impact category

The proposed activity will result in a negligible impact on soil quality and land stability. Construction related impacts will be temporary and managed using measures such as those outlined in *Managing Urban Stormwater: Soils and Construction* (Landcom 2004) ('the Blue Book'). While the total area of disturbance is 99.6 hectares, the majority of this will be for cropping and irrigation purposes. Soil amelioration will improve the productivity and structure of the soil over this area. The proposed soil monitoring program will ensure that there is no longer term degradation of the soil, including those caused by increased soil salinity and soil erosion and sediment loss.

6.1.2 **Groundwater**

6.1.2.1 Impacts

Minor impacts to groundwater may be associated with the construction and operation of the proposed WBTP and associated infrastructure, as well as the irrigation area.

Groundwater impacts during construction are considered to be highly unlikely, as the maximum depth of excavation for the proposed activity is approximately five metres and the known depths of those aquifers regulated by the WM Act is greater than 10 metres.

Under the irrigation scenarios that were modelled for the conceptual design irrigation report, deep drainage would increase slightly for the likely management approach for the proposed activity (Scenario 4 within Table 6-3) when compared to the current land use. The change in deep drainage is considered minimal as the greatest change modelled was an increase by 1.7 mm/yr. Therefore, no significant increase in groundwater level beneath the proposed irrigation site is likely to occur as a result of the proposed irrigation scheme.

Since deep drainage is minimally influenced by the proposed managed irrigation system, there is little likelihood of impacts on groundwater quality, including movement of salts and heavy metals.

The predicted salt concentrations of the treated irrigation water (TDS of less than 650 mg/L) indicates that it would not impact significantly upon groundwater quality as it would be similar to the highest quality groundwater (TDS of 631 mg/L) found on the site (refer to Appendix 3). Leaching of salts to maintain salinity levels within the soils of the irrigation area, as outlined in Section 6.1.1, may result in some additional release of ions to the soil solution with the input of irrigation water. This may lead to a negligible increase in salts entering groundwater.

Naturally occurring metals within the soils on-site were identified as low level and below *National Environment Protection (Assessment of Site Contamination) Measure 1999* (amended 2013) thresholds (Appendix 3), while the treated water is unlikely to contain heavy metals. The pH of applied treated water is also expected to be neutral and therefore not anticipated to result in any additional dissolution of heavy metal ions into the unsaturated zone and ultimately to groundwater.

6.1.2.2 Mitigation measures

The measures identified in Section 6.1.1.2 will also minimise potential impacts to groundwater. In addition, groundwater monitoring as per Section 2.7.1.5 will be implemented.

6.1.2.3 Potential impact category

The proposed activity will result in a negligible to low adverse impact on groundwater. With similar drainage rates as those associated with more vigorous vegetation under intensively managed irrigation activities, and good quality water being applied to the land, the risk of heavy metal and salinity movement to groundwater or changes in groundwater levels is considered unlikely. Ongoing groundwater monitoring on-site will ensure any adverse changes are able to be identified and are quickly addressed so that there is no significant impacts to the groundwater.

6.1.3 **Water body, watercourse, wetland and natural drainage systems**

6.1.3.1 Impacts

The potential impacts on surface water bodies associated with construction and operation of the proposed activity include erosion and sedimentation, surface water contamination due to chemical/fuel release, increase in runoff from the irrigation area, and impacts to flooding downstream of Leewood.

The likelihood of impacts due to erosion and sedimentation are discussed in Section 6.1.1.1. There is the risk that surface water contamination could occur during both construction and operation due to spills of oil, fuels or chemicals if not cleaned up appropriately.

Under the irrigation scenarios that were modelled for the conceptual design irrigation report (see Appendix 3), runoff would increase slightly for the likely management approach for the proposed activity (Scenario 4 within Table 6-3) when compared to the current land use. Scenario 4 shows runoff of 14.6 and 17.6 millimetres per year for Class A and B soils respectively, compared to 14.5 millimetres per year of runoff for Scenario 1 (pasture baseline).

Although the slopes are moderate and perennial cover will be maintained, the modelling indicates that some water will run off the irrigated area. The runoff will most likely be driven by rainfall events and is predicted to carry small amounts of sediment and possibly nutrients. As the irrigation schedule will be driven by crop water demand and availability of treated water, less (or no) water will be applied during periods of extended rainfall.

A key environmental performance objective of beneficial use of treated water for irrigation is to ensure that ground and surface waters do not become affected by any flow from irrigation areas. As the treated irrigation water is classified as medium strength effluent (refer to Section 2.6.3.4), it will be appropriately managed without a material change to the overland flow path.

Approximately one-third of the proposed irrigation area is located within flood-prone land (100 year ARI affected land, as shown in Figure 4-5), as well as a small section of hardstand area around the treated water storage tank. The irrigated land located within the flood-prone extent (Class B soil type) will occasionally be naturally inundated during prolonged rain events. However, the implementation of subsurface drip irrigation technology and targeted irrigation scheduling on this soil type will minimise the likelihood of inundation caused by the proposed irrigation activity. This has been demonstrated through the modelling, which indicates minimal changes in surface water runoff for the Class B soils (Table 6-3). It is considered unlikely that the proposed activity will cause significant changes to the downstream flood regime, or that the proposed activity will be significantly impacted by flooding.

Only treated water will be used for dust suppression and in rehabilitation activities. Management of these activities, as outlined in Section 2.7.2, will minimise the likelihood of ponding and runoff.

No surface water will be extracted for either the construction or operational phases of the proposed activity.

6.1.3.2 Mitigation measures

Implementation of the mitigation measures identified in Section 6.1.1.2 will ensure impacts in relation to erosion and sedimentation are minimised. Additional mitigation measures to minimise impacts to surface water include the following:

- Scheduling of irrigation activities will be managed generally in accordance with the concept irrigation design (Appendix 3), to minimise inundation and runoff
- During construction in the event that prolonged, severe wet weather or flooding is predicted, appropriate measures will be put in place to mitigate impacts of the wet weather
- The treated water storage tank will have high level alarms, or other appropriate controls, implemented to prevent overflows
- A surface water monitoring program will be implemented, as outlined in Section 2.7.1.4.
- Management measures for dust suppression and in rehabilitation activities will be implemented, as outlined in Section 2.7.2
- All above ground tanks containing material that is likely to cause environmental harm will be bunded or have an alternative spill containment system in place.

6.1.3.3 Potential impact category

The proposed activity will result in a negligible to low adverse impact on surface waterbodies, watercourses, wetlands and natural drainage systems. Construction related impacts will be temporary and managed using measures such as those outlined in the Blue Book. Potential issues associated with inundation and runoff from the irrigation area during operation will be mitigated through appropriate irrigation scheduling and management based on the soil types found on-site.

6.1.4 Air quality

An assessment of the potential air quality impacts, including odour, was prepared to consider the construction and operational noise associated with the proposed activity. This section provides a summary of the Air Quality and Odour Assessment, provided in Appendix 10.

6.1.4.1 Air quality assessment criteria

Air quality criteria are targets set to protect the general health and amenity of the community in relation to air quality. The criteria that are relevant to the proposed activity are taken from the *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW* (DEC, 2005).

The air quality targets for the relevant criteria pollutants relate to the total pollutant burden in the air and not just the pollutants from the proposed activity. Therefore consideration of background pollutant levels is required when using these targets to assess potential impacts. Table 6-4 shows the impact criteria relevant to the proposed activity.

Table 6-4 EPA air quality impact assessment criteria

Pollutant	Averaging Period	Criterion
Particulate matter > 10 µm (PM ₁₀)	Annual mean	30 µg/m ³
	24-hour maximum	50 µg/m ³
Particulate matter < 2.5 µm (PM _{2.5}) ¹	Annual mean	8 µg/m ³
	24-hour average	25 µg/m ³
Nitrogen dioxide (NO ₂)	1-hour	246 µg/m ³
	Annual	62 µg/m ³
Sulfur dioxide (SO ₂)	10-minute	712 µg/m ³
	1-hr	570 µg/m ³
	24-hr	228 µg/m ³
	Annual	60 µg/m ³
Carbon monoxide (CO)	15-minute	100 mg/m ³
	1-hour	30 mg/m ³
	8-hour	10 mg/m ³
Volatile organic compound (VOC) (as Benzene)	1-hour	29 µg/m ³
Odour	1-hour	6 OU

Note:

1. From Ambient Air NEPM PM2.5 advisory reporting standards (NEPC, 2003)

The *Protection of the Environment Operations (Clean Air) Regulation 2010* specifies in-stack concentration criteria relevant to scheduled premises for general activities and plant. The generator stacks must operate within these limits. Table 6-5 summarises the in-stack concentration limits for particulate matter and other relevant air quality parameters.

Table 6-5 In-stack concentration criteria under the POEO (Clean Air) Regulation 2010

Air quality parameter	Source	Group 6 (mg/m ³) ¹
Solid Particles (TSP) ²	Clean Air Regulation – Schedule 4 “Any activity or plant”	50
NO ₂ or nitric oxide (NO) or both as NO ₂ equivalent	Clean Air Regulation – Schedule 4 “Stationary reciprocating internal combustion engines”	450
VOCs, as n-propane	Clean Air Regulation – Schedule 4 “Any stationary reciprocating internal combustion engine using a gaseous fuel”	40 (125 ³)
	Clean Air Regulation – Schedule 4 “Any stationary reciprocating internal combustion engine using a liquid fuel”	1,140 (5,880 ³)

Note:

1. mg/m³ – milligrams per cubic metre2. Assumed to be also applicable to PM₁₀ and PM_{2.5}

3. as carbon monoxide (CO)

6.1.4.2 Ambient air quality

There is no onsite air quality monitoring data available for the Leewood property. Therefore the nearest locations with available data (Tamworth and Muswellbrook EPA monitoring sites, approximately 128 and 265 kilometres from the proposed activity) were used to provide an approximation of PM₁₀, PM_{2.5}, NO₂, and SO₂. Monitoring data for CO has been taken from Wyong.

The criterion and adopted background levels of these air quality parameters for the proposed activity are provided in Table 6-6. The adopted background levels for the assessment are likely to overestimate the expected levels of air pollutants at Leewood due to the presence of increased human activity surrounding the monitoring locations at Tamworth, Muswellbrook and Wyong including residential areas, major highways and industry.

Table 6-6 Ambient air quality

Parameter	Averaging Period	EPA Criterion	Ambient background level
PM ₁₀	Annual	30 µg/m ³	16.6 µg/m ³
	24 hr	50 µg/m ³	47.5 µg/m ³
PM _{2.5}	Annual	8 µg/m ³	7.3 µg/m ³
	24 hr	25 µg/m ³	20.5 µg/m ³
NO ₂	Annual	62 µg/m ³	19.1 µg/m ³
	1 hr	246 µg/m ³	86.1 µg/m ³
SO ₂	Annual	60 µg/m ³	6.0 µg/m ³
	24 hr	228 µg/m ³	62.9 µg/m ³
	1 hr	570 µg/m ³	423.3 µg/m ³
	10 min	712 µg/m ³	616.7 µg/m ³
CO	8 hr	10 mg/m ³	1.0 mg/m ³
	1 hr	30 mg/m ³	3.0 mg/m ³
	15 min	100 mg/m ³	4.4 mg/m ³
VOCs	1-hour	29 µg/m ³	N/A
Odour	1 hr	6 OU	N/A

6.1.4.3 Impacts

Construction air quality impacts

Potential impacts to regional air quality associated with the construction of the proposed activity will include the generation of particulate emissions, including visible dust plumes and elevated particulate matter less

than ten micrometres (PM₁₀). Particulate emissions will mainly be generated during construction activities including site preparation, and construction of the WBTP and irrigation infrastructure. There will also be potential impacts associated with exhaust emissions generated from diesel powered construction plant and machinery, as well as vehicle movements to and from the site.

A qualitative approach was used by Pacific Environment (Appendix 10) to assess the potential air quality impacts due to construction, as effects on airborne particle concentrations are generally temporary and relatively short-lived. The approach used for this assessment was based on that described by IAQM (2014), with the aim to identify risks and recommend appropriate mitigation measures.

All six of the nearest sensitive receivers (human receptors) are located at least 350 metres away from the boundary of the WBTP. While the listed Brigalow Woodland community in the north of the Leewood property is located adjacent to the proposed irrigation area, it is over 50 metres from the WBTP and associated infrastructure areas, as well as irrigation infrastructure, where most of the construction activities will occur.

In view of the outcomes of the construction screening analysis potential construction impacts are considered to be minimal.

Operational air quality impacts

During operation of the WBTP, air emissions will directly relate to the onsite generators. Smaller volume fugitive emissions will be associated with vehicles and process operations within the plant.

In-stack concentrations have been calculated based on the provided exhaust flow and emission rate information and worse case pollution mass rates, and are provided in Appendix 10.

All in-stack concentrations comply with the *Protection of the Environment Operations (Clean Air) Regulation 2010* limits. The supplier of the gas and diesel engines has provided a performance guarantee (Appendix A of the Air Quality and Odour Assessment, provided in Appendix 10) that both engines will comply with the in-stack concentration limits.

The operational air quality assessment on sensitive receivers is based on the use of the computer-based dispersion model, AERMOD, to predict offsite air quality and odour levels. The assessment is based on a conventional approach following the procedures outlined in DEC (2005).

To assess the effect that potential emissions could have on existing air quality, the dispersion model predictions for the two scenarios (diesel generator and gas generator) have been compared to relevant regulatory air quality criteria. Tables 6-7 to 6-9 present the predicted incremental air quality impacts at the six nearest sensitive receivers due to the operation of the proposed activity. At all sensitive receptors these are well below the criteria.

Table 6-7 Predicted incremental operational air quality (Scenario 1 – gas generator)

Pollutant	Avg. period	Units	EPA Criteria	Residence					
				1	2	3	4	5	6
PM ₁₀	Annual	µg/m ³	30	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	24 hr	µg/m ³	50	0.01	0.01	0.01	0.01	0.02	0.01
PM _{2.5}	Annual	µg/m ³	8	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	24 hr	µg/m ³	25	0.01	0.01	0.01	0.01	0.02	0.01
NO ₂	Annual	µg/m ³	62	<0.1	0.1	<0.1	0.1	0.2	<0.1
	1 hr	µg/m ³	246	4.2	4.3	4.4	6.5	5.1	4.7
SO ₂ ¹	Annual	µg/m ³	60	N/A	N/A	N/A	N/A	N/A	N/A
	24 hr	µg/m ³	228	N/A	N/A	N/A	N/A	N/A	N/A
	1 hr	µg/m ³	570	N/A	N/A	N/A	N/A	N/A	N/A
	10 min	µg/m ³	712	N/A	N/A	N/A	N/A	N/A	N/A
CO	8 hr	mg/m ³	10	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	1 hr	mg/m ³	30	0.0002	0.0003	0.0003	0.0004	0.0003	0.0003
	15 min	mg/m ³	100	0.0003	0.0003	0.0004	0.0005	0.0004	0.0004
VOC (as Benzene)	1 hr	µg/m ³	29	0.3	0.3	0.3	0.5	0.4	0.4

Note:

1. Given the fuel source, there is not anticipated to be any SO₂ emissions associated with the combustion emissions from the gas generator and therefore this parameter has not been assessed within Scenario 1.

Table 6-8 Predicted incremental operational air quality (Scenario 2 – diesel generator)

Pollutant	Avg. period	Units	EPA Criteria	Residence					
				1	2	3	4	5	6
PM ₁₀	Annual	µg/m ³	30	<0.01	0.01	<0.01	<0.01	0.01	<0.01
	24 hr	µg/m ³	50	0.06	0.08	0.05	0.10	0.15	0.09
PM _{2.5}	Annual	µg/m ³	8	<0.01	0.01	<0.01	<0.01	0.01	<0.01
	24 hr	µg/m ³	25	0.06	0.08	0.05	0.10	0.15	0.09
NO ₂	Annual	µg/m ³	62	0.2	0.5	0.1	0.3	0.8	0.1
	1 hr	µg/m ³	246	51.8	59.0	33.8	48.4	58.9	49.8
SO ₂	Annual	µg/m ³	60	<0.01	0.01	<0.01	<0.01	0.01	<0.01
	24 hr	µg/m ³	228	0.06	0.08	0.05	0.10	0.15	0.09
	1 hr	µg/m ³	570	0.86	0.98	0.56	0.80	0.97	0.82
	10 min	µg/m ³	712	1.25	1.42	0.82	1.17	1.42	1.20
CO	8 hr	mg/m ³	10	0.002	0.003	0.001	0.003	0.005	0.003
	1 hr	mg/m ³	30	0.012	0.013	0.008	0.011	0.013	0.011
	15 min	mg/m ³	100	0.015	0.018	0.010	0.014	0.018	0.015
VOC (as benzene)	1 hr	µg/m ³	29	1.1	1.2	0.7	1.0	1.2	1.0

Table 6-9 Predicted 99th percentile odour concentrations at sensitive receivers

Pollutant	Units	Odour 99 th percentile	Residence					
			1	2	3	4	5	6
Odour	OU	6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

With the addition of the measured and calculated ambient air quality estimates provided in Table 6-4, the total predicted impacts still do not exceed the EPA criteria, even at the nearest sensitive receiver (R3), located within one kilometre of the proposed activity. Therefore impacts are expected to be negligible.

6.1.4.4 Mitigation measures

Relevant mitigation measures to control dust are provided in Section 6.1.1.2. Additional mitigation measures that will be implemented to minimise impacts on air quality include:

- Air emissions from construction-related activities will not exceed the air quality criteria at any occupied residence on privately owned land, as set out in the table below (referenced from the Development Consent for the Bibblewindi Gas Exploration Pilot Expansion, dated July 2014).

Pollutant	Averaging period	Criterion ¹
TSP matter (long term criteria)	Annual	90 µg/m ³⁽²⁾
PM ₁₀ (long term criteria)	Annual	30 µg/m ³⁽²⁾
PM ₁₀ (short term criteria)	24 hour	50 µg/m ³⁽²⁾
Deposited dust PM ₁₀ (long term criteria) ³	Annual	2 g/m ² /month (maximum increase) ⁴
		4 g/m ² /month (maximum total) ²

Note:

- Excludes extraordinary events such as bushfires, prescribed burning, dust storms, sea fog, fire incidents, illegal activities or any other activity agreed to by the Secretary in consultation with EPA.
- Total impact (i.e. incremental increase in concentrations due to the development plus background concentrations due to other sources).
- Deposited dust is to be assessed as insoluble solids as defined by Standards Australia, AS/NZS 3580.10.1:2003: Methods for Sampling and Analysis of Ambient Air – Determination of Particulate Matter – Deposited Matter – Gravimetric Method.
- Incremental impact (i.e. incremental increase in concentrations due to the development on its own).

- air emissions from operations-related activities will not exceed the air quality criteria at any occupied residence on privately owned land, as outlined in Table 6-4 (referenced from the *Approved Methods for the Modelling and Assessment of Air Pollutants in NSW* (DEC, 2005))
- the proposed activity will be carried out by such practicable means as to prevent or minimize the emission of dust
- plant and equipment will be operated and maintained in a proper and efficient condition
- generator selection and exhaust configuration will be designed to ensure emission rates comply with the *Protection of the Environment Operations (Clean Air) Regulation 2010* in-stack concentration limits
- no offensive odours will be emitted from the proposed activity.

6.1.4.5 Potential impact category

The proposed activity will result in a negligible to low adverse impact on air quality. Particulate emissions are greatest during construction of the proposed activity; however the effects on airborne particle concentrations during this phase are generally temporary and relatively short-lived. Air emissions from generators during operation would have negligible impacts on sensitive receivers. The proposed mitigation measures would be effective in maintaining the existing amenity of nearby receivers during both construction and operation.

6.1.5 Greenhouse gases

6.1.5.1 Impacts

Direct GHG emissions (Scope 1 emissions) from the proposed activity include:

- removal of vegetation sinks for site preparation
- fuel use (diesel and gas) for site-based electricity generation
- fuel use on site for plant and equipment (including civil works)
- fuel use for transport of personnel and materials where this transport is under Santos operational control.

For this REF it has been assumed all delivery details provided by Santos fall within their operational control. In practice a portion of these emissions may more appropriately be assigned to other organisations.

Scope 2 emissions cover those resulting from the purchase of energy (electricity or steam) originating from outside the project boundary. No Scope 2 emissions are relevant to the proposed activity as no electricity from the grid will be purchased.

Scope 3 emissions (indirect emissions) have not been considered in this assessment as they form Scope 1 emissions for other organisations and need to be considered separately to avoid 'double counting' of the emissions profile. This is consistent with Australia's National Greenhouse and Energy Reporting Scheme (NGERS) where only Scope 1 and 2 emissions are included in the mandatory reporting.

Table 6-10 provides a summary of the estimated GHG emissions for the construction and operation of the proposed activity.

Table 6-10 Scope 1 GHG emissions profile

Project element	Site establishment and construction (T CO ₂ ^e)	Operation phase (T CO ₂ ^e /year)	Decommissioning (T CO ₂ ^e /year)
On-site power generation	2,100	4,385	315
Light vehicles (staff movements)	20	60	10
Heavy vehicles/deliveries	485	10	15
Construction equipment	215	2	185
Vegetation clearing	515	None	None
Estimated total	3,335	4,457	525
Estimated total 5 year program	–	22,285	–

Emissions will be monitored and reported in accordance with legislative requirements.

The primary risk associated with GHG emissions are their potential contribution to NSW and Australian GHG profiles. Australia's GHG Inventory for 2012 (the most current data available at the time of writing) is provided in Table 6-11. The potential GHG contribution of the proposed activity to Australia's existing GHG profile is extremely minor, being in the region of 0.0008 per cent and 0.0029 per cent of the national and State emissions profiles respectively.

Table 6-11 Australian and NSW GHG emissions profile

	Annual GHG emissions (T CO ₂ ^e)
Australian emissions	554,568,840
NSW emissions	154,721,100
Average annual estimated project emissions (operations phase)	4,457

6.1.5.2 Mitigation measures

Relevant mitigation measures to minimise impacts on air quality, including emissions, are provided in Sections 2.7.5 and 6.1.4.4. Additional mitigation measures that will be implemented to minimise impacts on GHG emissions include:

- legislative reporting requirements for GHG emissions (such as to inform NGERs calculations) will be undertaken during both construction and operation
- natural gas fuel will be used in preference to diesel where practicable during operation
- plant and equipment will be operated and maintained in a proper and efficient condition.

6.1.5.3 Potential impact category

The proposed activity will result in a negligible to low adverse impact on GHG emissions. The contribution of the proposed activity to Australia's existing GHG profile is extremely minor. The proposed mitigation measures would be effective in minimising risk of impact from generation of GHG emissions. Ongoing monitoring in accordance with the *National Greenhouse and Energy Reporting Act 2007* will be undertaken to ensure that any issues are identified and mitigated.

6.1.6 Noise and vibration

An assessment of the potential noise and vibration impacts was prepared to consider the construction and operational noise associated with the proposed activity. This section provides a summary of the Noise and Vibration Assessment, provided in Appendix 11.

6.1.6.1 Assessment criteria

Construction noise criteria

The *Interim Construction Noise Guideline* (ICNG) (DECC, 2009) is considered to be appropriate for consideration of noise impacts. The noise management level for works during the recommended standard hours is the RBL plus 10 dB(A) and for works outside of recommended standard hours is background plus 5 dB(A). Above this noise level the proponent needs to implement all feasible and reasonable work practices, as defined in the ICNG, to minimise noise impacts.

Operation noise criteria

In accordance with EPA requirements, the proposed activity has been assessed with consideration to the INP. The INP requires the comparison of the derived intrusive and amenity criteria, and the most stringent criteria are selected to be assessed against. Table 6-12 shows that for the proposed activity, the intrusive criteria represent the project specific operational noise criteria for residential receivers.

Table 6-12 Operational Noise Criteria dB(A)

Receiver	Period ¹	Amenity			Intrusive		Project Specific Criteria
		ANL ²	Existing Industrial Noise ³ L _{eq,Industrial}	Adjusted ANL L _{eq,period}	RBL	Intrusiveness Criteria RBL +5 L _{Aeq15min}	
R1-R6	Day	50	–	50	30	35	35
	Evening	45	–	45	30	35	35
	Night	40	–	40	30	35	35

Note:

1. Day (7.00am-6.00pm Monday to Saturday and 8.00am-6.00pm Sundays and Public Holidays), Evening (6.00pm-10.00pm), Night (10.00pm-7.00am, unless preceding a Sunday or Public Holiday).

2. ANL – 'acceptable noise levels' published in the INP.

3. No existing industrial noise was observed in the area.

The project specific operational noise criteria is set at 35 dB(A) for activities undertaken throughout the day, evening or night. It is consistent with Condition L3.1 of EPL 20350.

Sleep disturbance criteria

The EPA does not currently have an explicit policy regarding sleep disturbance caused by noise from construction or industrial operation activities. However there is some guidance mentioned in the INP application notes, which states *"The potential for high noise level events at night and effects on sleep should be addressed in noise assessments for both the construction and operational phases of a development."*

The INP application notes recommend that the LA₁(1 minute) noise level outside a bedroom window should not exceed the LA₉₀ background noise level by more than 15 dB(A) during the night-time period.

Road traffic criteria

The *NSW Road Noise Policy* (RNP) (DECCW, 2011) provides guidance, criteria and procedures for assessing noise impacts from existing, new and redeveloped roads and traffic generating developments. Additional specific relative increase criteria apply to traffic generating developments. The Road Noise Policy Application Notes (EPA, 2013) states the following:

"any increase in the total traffic noise level as a result of the development should be limited to 2 dB above that of the noise level without the development. This limit applies wherever the noise level without the development is within 2 dB of, or exceeds the relevant day or night noise assessment criterion."

Vibration criteria

Impacts from vibration can be considered both in terms of effects on building occupants (human comfort) and the effects on the building structure (building damage). Of these considerations, the human comfort limits are the most stringent and the peak particle velocity (PPV) is set at 0.14 mm/s.

For unoccupied building structures, the British Standard (BS 7385) sets guide values for building vibration based on the lowest vibration levels above which damage has been credibly demonstrated. The recommended limits (guide values) for transient vibration to ensure minimal risk of cosmetic damage to residential and industrial buildings is set at 15 mm/s at 4 hertz increasing to 20 mm/s at 15 hertz.