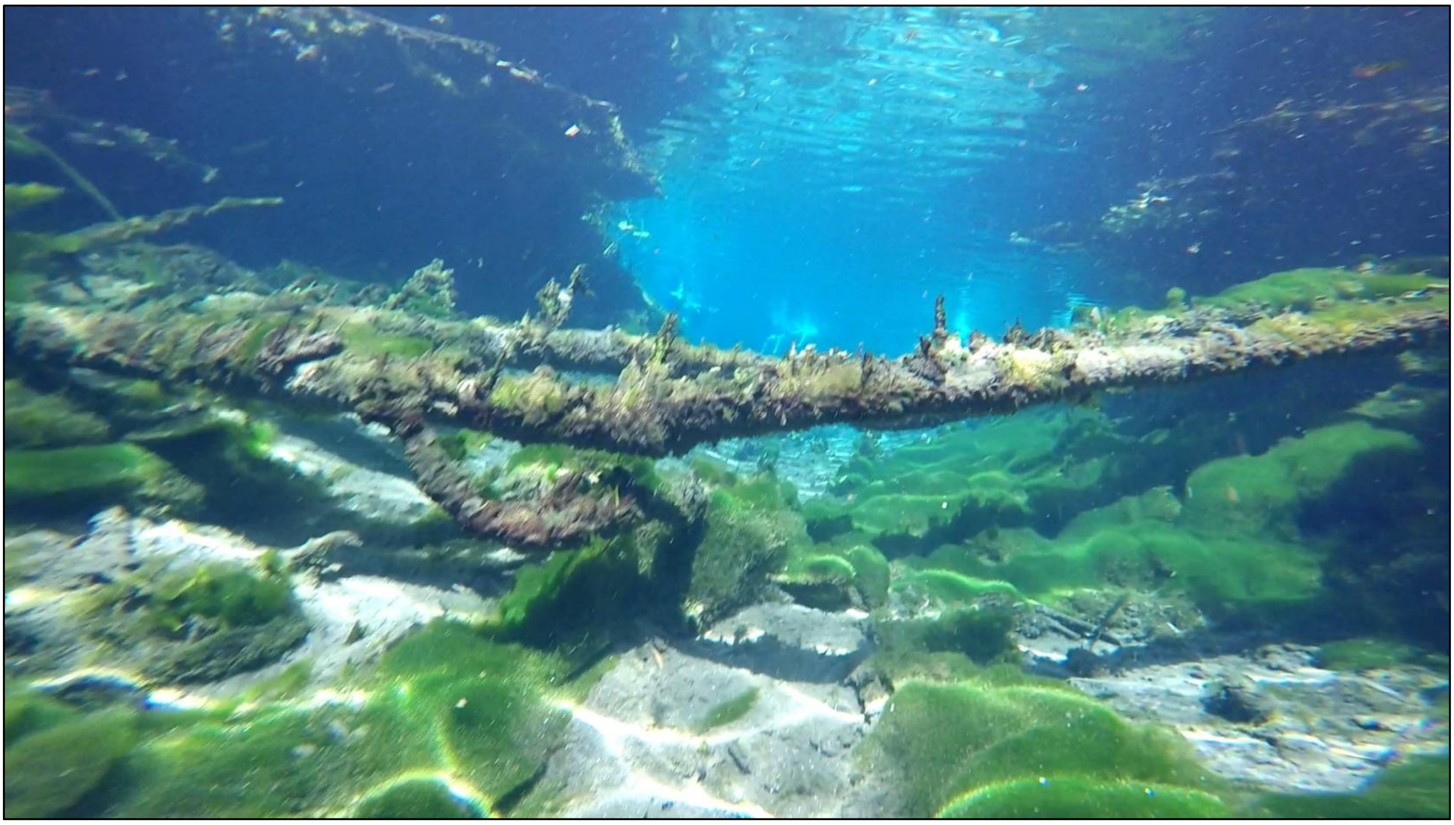

Department of Land Resource Management, Northern Territory Government

Groundwater Overlying the Beetaloo Sub-basin

Explanatory Report

April 2016

Executive summary

The Proterozoic Beetaloo Sub-basin is a subsurface basin with no surface expression in the study area and a thickness of greater than 3000 m. Cambrian sediments and volcanics overlying the Beetaloo Sub-basin occur to depths varying from 61 m to 686 m, based on the DME (2016) datasets. The base of the Velkerri Formation within the Beetaloo Sub-basin varies from 394 m to 3637 m below ground level, based on the same DME (2016) datasets. The depth of the prospective shale within the middle Velkerri Formation varies from 1000 to 1500 m in the northwest, to more than 3000 m in the deepest parts of the sub-basin (Scrimgeour, pers. comm., 2016). The Beetaloo Sub-basin consists of alternating sequences of sandstones and shales and is considered to have significant potential for both conventional and unconventional hydrocarbon accumulations, including shale gas (Ahmad and Munson, 2013). It is in this context that this study has been commissioned to describe groundwater system overlying the Beetaloo Sub-basin. The potential for groundwater sourced within the Beetaloo Sub-basin for industrial use is also introduced.

Key groundwater users include stock water, domestic water supply, agriculture, springs, baseflow for perennial rivers and the petroleum industry. Much of this groundwater use is associated with the sedimentary Cambrian to Ordovician aquifers and due to their high yields and quality, prior to petroleum exploration, there was little motivation to drill beyond deeper into the Proterozoic Beetaloo Sub-basin. The Cambrian Antrim Plateau Volcanics also currently provide an important aquifer, although usually outside the extent of the sedimentary basins. It is understood that a potential use of the deeper groundwaters from within the Beetaloo Sub-basin is for industrial use within the petroleum industry.

This report is intended to act as the explanatory notes for a groundwater map (Appendix 1) created to describe the groundwater systems overlying the Beetaloo Sub-basin in the Northern Territory. The focus of the report is not to describe the groundwater within the Beetaloo Sub-basin itself, rather the groundwater system and in particular the aquifers overlying and adjacent to the Beetaloo Sub-basin.

This report is subject to, and must be read in conjunction with, the limitations set out in section 1.2 and the assumptions and qualifications contained throughout the report.

The geology and hydrogeology in the study are discussed in terms of basin settings and geological age. The deeper and older Proterozoic Beetaloo Sub-basin strata underlie an expansive sheet of flat lying Cambrian volcanic rocks. Overlying much of the Cambrian volcanics, Cambrian to Ordovician sedimentary basin strata of the Daly, Wiso and Georgina basins form the major aquifer in the area. On top of this, for the majority of the study area, are the youngest (Mesozoic) strata considered in this study; the strata of the Carpentaria Basin.

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Appendices

Appendix A – Beetaloo Sub-basin Groundwater Map

Cover Photo: Korran (Bitter Springs), Elsey National Park, Mataranka

Glossary

Aquifer	a rock mass containing groundwater with a potential beneficial use to man
Karst	landscape shaped by the dissolution of layers of soluble bedrock
Strata	layers of rock in the ground
Unconformity	the contact between sedimentary rocks that are significantly different in age

Relative Geological Time

Youngest

Phanerozoic	Cenozoic	
	Mesozoic	Cretaceous
		Jurassic
		Triassic
	Palaeozoic	Permian
		Carboniferous
		Devonian
		Silurian
		Ordovician
		Cambrian
Proterozoic	Neoproterozic	
	Mesoproterozic	
	Palaeoproterozoic	

Oldest

1. Introduction

The Proterozoic Beetaloo Sub-basin is a subsurface sedimentary basin with no surface expression in the study area and a thickness of greater than 3000 m. Rocks of the Roper Group, which make the Beetaloo Sub-basin, are also present to the east of the study area (outside of the Beetaloo Sub-basin) where they outcrop. The Beetaloo Sub-basin comprises alternating sequences of sandstones and mudstones and is considered to have significant potential for both conventional and unconventional hydrocarbon accumulations, including shale gas (Ahmad and Munson, 2013). It is in this context that this study has been commissioned, to describe groundwater system overlying the Beetaloo Sub-basin.

1.1 Purpose of this report

This report is intended to act as the explanatory notes for a groundwater map (Appendix 1) created as part of this project to describe the groundwater systems associated with the Beetaloo Sub-basin in the Northern Territory. The focus of the report is not to describe the groundwater within the deep Beetaloo Sub-basin itself. Rather, the focus is the groundwater system and in particular the aquifers overlying and adjacent to the Beetaloo Sub-basin, but the potential for groundwater sourced within the Beetaloo Sub-basin for industrial use is introduced. Assessment of the potential for connectivity between aquifers and units that are prospective for petroleum production is beyond the scope of this report. The map depicts the groundwater systems within a nominal 25 km buffer outside of the approximate Beetaloo Sub-basin extent, as defined by DME (2016) and the report discusses aquifers in a broader context relative to their flows and potential discharge locations where this is considered appropriate.

1.2 Scope and limitations

GHD was commissioned in April 2016 to provide a rapid assessment of key publically available data to describe the groundwater systems and aquifers associated with the Beetaloo Sub-basin. This report has been prepared by GHD for Department of Land Resources Management (DLRM) and may only be used and relied on by DLRM for the purpose agreed between GHD and the DLRM as set out in section 1.1 of this report.

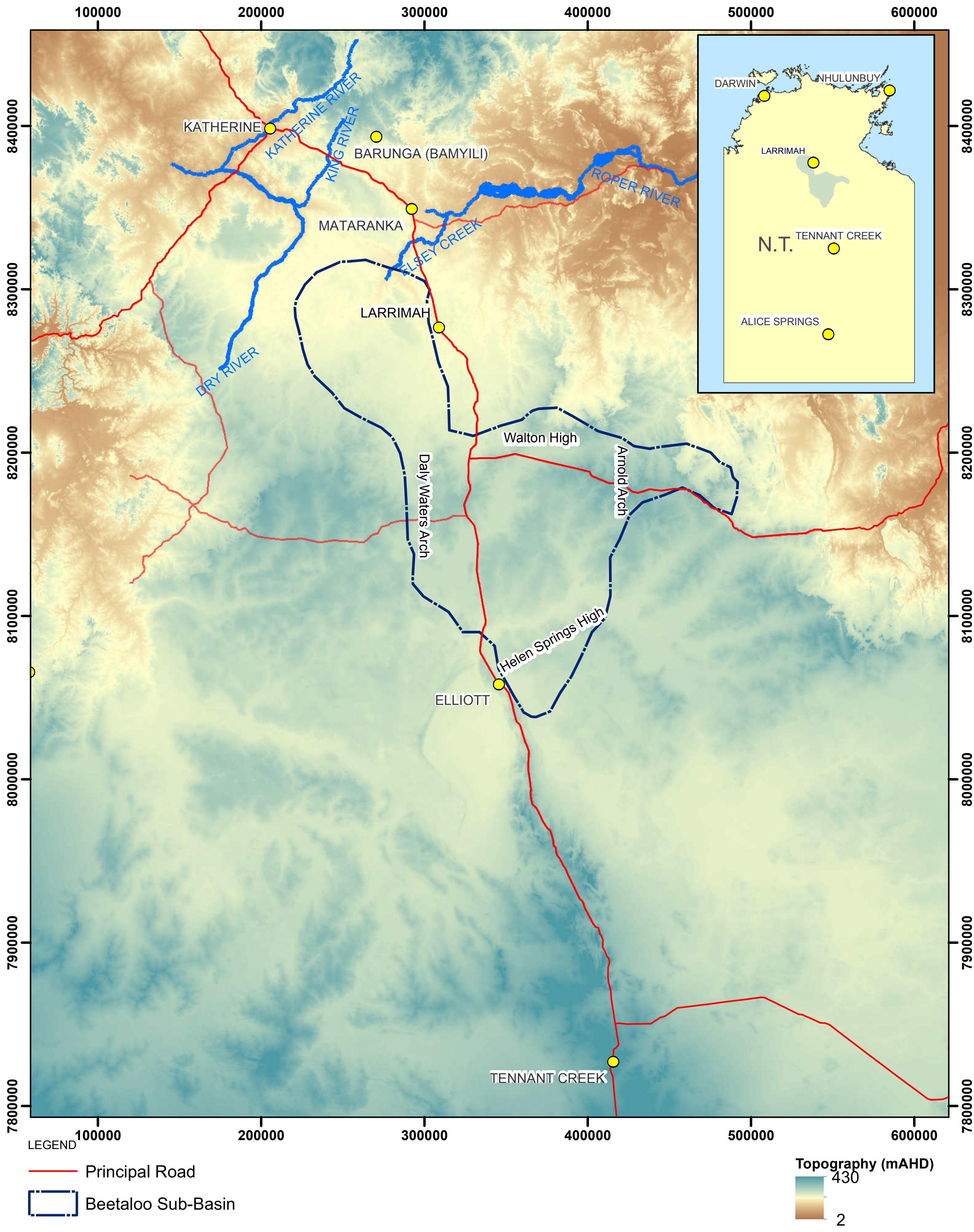
GHD otherwise disclaims responsibility to any person other than DLRM arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

GHD has prepared this report on the basis of information provided by DLRM and others including Government authorities who provided information to GHD, which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

Beyond the scope of this report are any consideration of information that is not available publically, as well as documentation of any gaps in information or required works by any parties.



Paper Size A4
0 5 10 20 30 40 50
Kilometers
Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 53

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Department of the Chief Minister
Beetaloo Sub-basin Groundwater

Job Number	32-12345
Revision	A
Date	20 May 2016

Site Location with Topography & Surfacewater Features

Figure 1

2 Salamanca Square Hobart TAS 7000 Australia T 61 3 6210 0600 F 61 3 6210 0601 E hbamail@ghd.com W www.ghd.com

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2. Physiography and Climate

The Beetaloo Sub-basin (Figure 1) is a sub-surface basin with no surface expression or local outcropping of the rocks within the study area. The majority of the Beetaloo Sub-basin is located beneath the Sturt Plain biogeographic region as delineated by ERIN (2012). The Sturt Plain biogeographic region is bounded to the north by the Daly Basin (in the vicinity of the northern extent of the Beetaloo Sub-basin), to the east by the Gulf Fall and Uplands, the Ord Victoria Plain to the west, the Tanami to the south west and the Mitchell Grass Downs to the south east (ERIN, 2012).

The Beetaloo Sub-basin has a thickness of greater than 3000 m below the overlying basins and Sturt Plain. The topographic range of the map area (including the 25 km buffer outside the Beetaloo Sub-basin) is from 115 to 319 mAHD (Australian height datum), a range of approximately 200 m. This is relatively flat country considering the Beetaloo Sub-basin extents of approximately 275 km east to west and 260 km north to south (an area of approximately 27,000 km^2). Including the 25 km buffer, the map area is approximately double (adding 24,000 km^2).

The low elevation points are associated with the drainage lines and tributaries that lead to:

- the Katherine River via Dry River and King River to the north of the study area; and
- the Roper River via Elsey Creek in the north-eastern corner of the study area near Mataranka (Figure 2).

The high elevation points of the study area are:

- the north western extent of the Barkly Tableland to the south east of the study area (Figure 3) and dissected by the Ashburton Range;
- towards the Tanami Desert to the south west of the study area.

Figure 2 Tributaries approaching the Roper River in the north of the study area

Figure 3 Mitchel Grass Downs of the Barkley Tablelands in the south west of the study area

The climate over the study area grades from dry tropical savannah climate, towards a warm desert climate inland (from the Gulf of Carpentaria) and towards the south. A strong wet season and dry season pattern is evident from the rainfall records. Daly Waters mean monthly rainfall and evaporation (Figure 4 and Figure 5 respectively) are provided as an example (BOM, 2016). The rainfall statistics presented are calculated from a dataset ranging from the years 1883 to 2013 (and for evaporation, from 1970 to 1986).

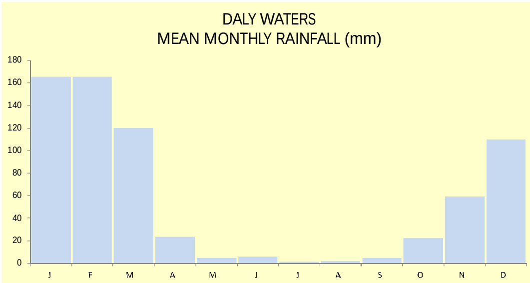

Figure 4 Rainfall (BOM, 2016)

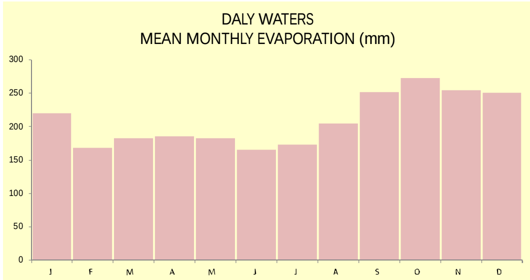

Figure 5 Evaporation (BOM, 2016)

3. Geology and Hydrogeology

3.1 Basins

The geology and hydrogeology of the study area are discussed in terms of basin settings and geological age (Figure 6). The deeper and older Proterozoic Beetaloo Sub-basin strata underlie an expansive sheet of flat-lying Palaeozoic volcanic strata. Overlying much of the Palaeozoic volcanic strata, Palaeozoic sedimentary basin strata of the Daly, Wiso and Georgina basins form the major aquifers in the area. On top of this, for the majority of the study area, are the youngest (Mesozoic) strata considered in this study; the sedimentary basin strata of the Carpentaria Basin.

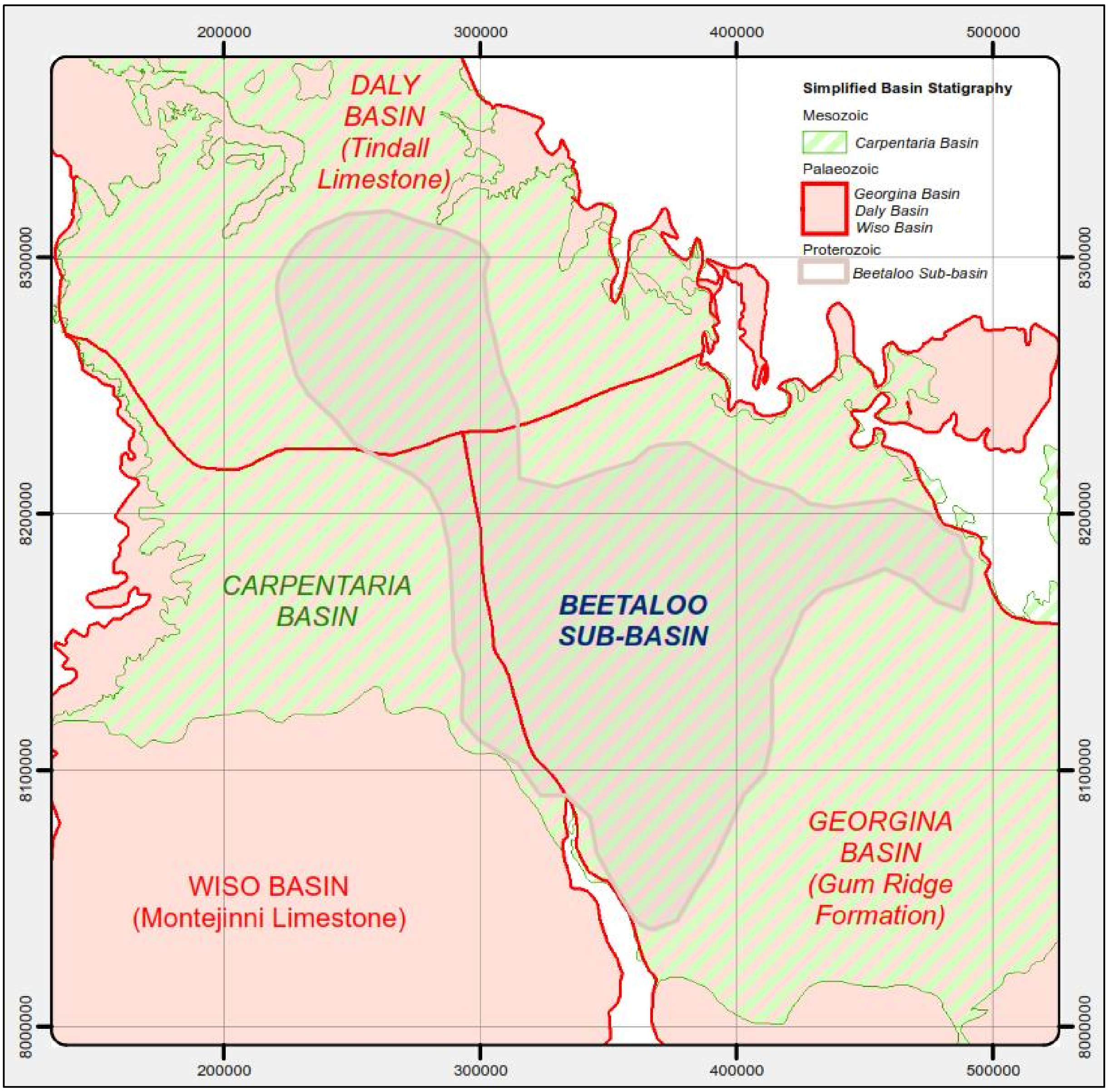

Figure 6 Basin Boundaries; Oldest-Proterozoic (Tan), Palaeozoic (Red), Youngest-Mesozoic (Green)

3.1.1 Proterozoic basins

The Proterozoic McArthur Basin includes, at its thickest (greater than 3000 m) and deepest point, the Beetaloo Sub-basin. The Beetaloo Sub-basin consists of at least three interconnected low points divided by the basement highs of the Daly Waters Arch and Arnold Arch. The main depocentre is bounded by basement highs, to the south, the Helen Springs High and to the north, the Walton High (Figure 7), and to the north east the Arnold Arch. The other smaller depocentres occur to the northwest of the Daly Waters Arch and to the east of the Arnold Arch (Ahmad et al. in Ahmad and Munson, 2013).

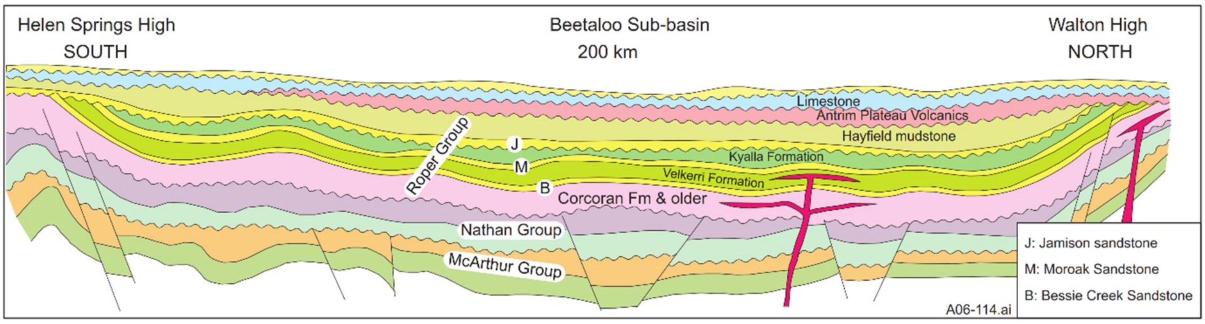

Figure 7 Schematic cross section through the main depocentre of the Beetaloo Sub-basin (modified after Silverman et al., 2007) with dolerite intrusions depicted in pink

The Beetaloo Sub-basin contains three sandstone to mudstone successions, the lower two of which are assigned to the Mesoproterozoic Roper Group (Ahmad et al. in Ahmad and Munson, 2013). Ahmad et al. in Ahmad and Munson (2013) state "the sub-basin is successively overlain by volcanic rocks of the late early Cambrian Kalkarindji Large Igneous Province (Kalkarindji Province) and by Neoproterozoic–Palaeozoic Georgina Basin and Mesozoic Carpentaria Basin strata". In addition to this the Beetaloo Sub-basin at the south-eastern and northern extents are also overlain by Palaeozoic strata of the Wiso Basin and Daly Basin respectively.

3.1.2 Palaeozoic basins

The Cambrian Kalkarindji Suite erupted over a vast area of the continent (Figure 8) extending into what is now Western Australia, Queensland and South Australia (GA, 2016 and Glass et al. in Ahmad and Munson, 2013). The Kalkarindji Suite are unconformably overlain by strata deposited during the Cambrian and Ordovician (Palaeozoic) over a vast set of interconnected sedimentary basins (Figure 9) that were simultaneously deposited in what is referred to as the Centralian B Superbasin (Munson et al. in Ahmad and Munson, 2013).

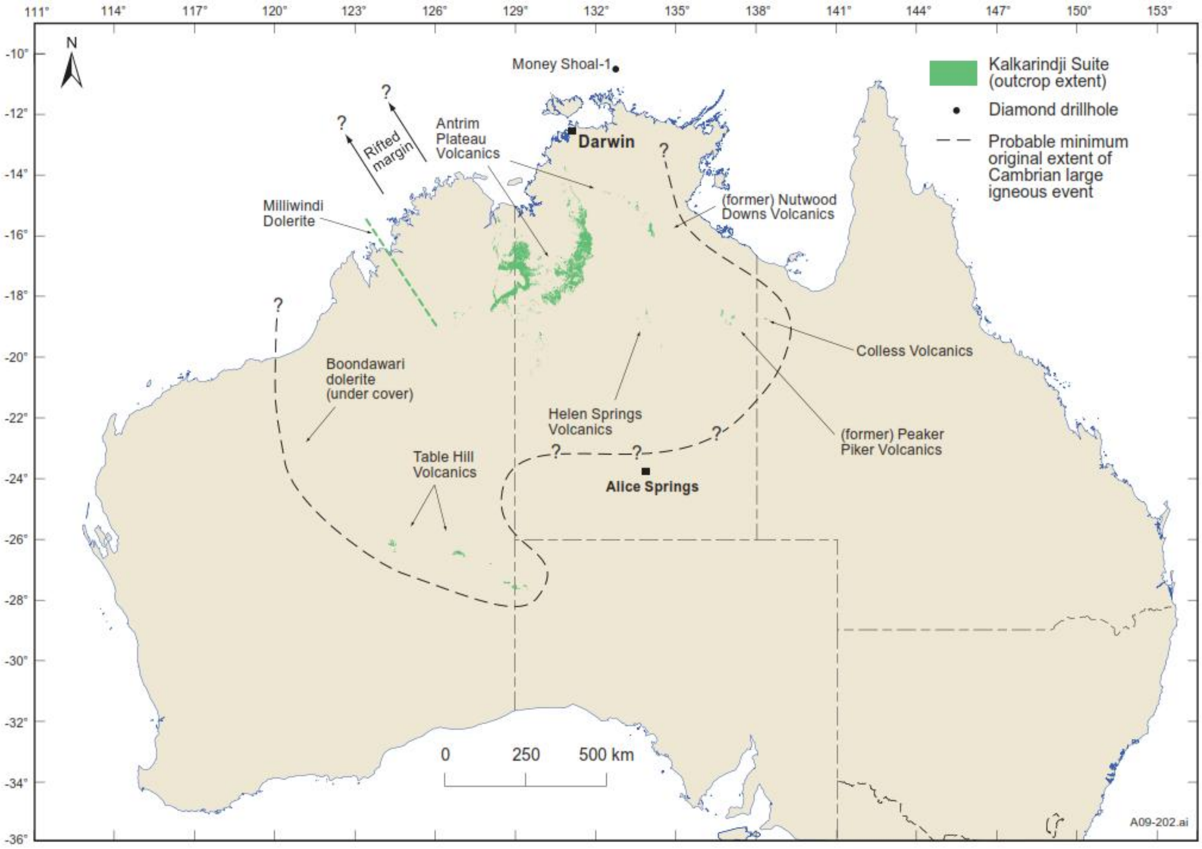

Figure 8 Distribution of the Kalkarindji Suite outcrop and probable minimum original extent of the Cambrian Kalkarindji Large Igneous Province (Glass et. al. in Ahmad and Munson, 2013)

The Centralian B Superbasin in the study area is divided into three basins, the Daly Basin, the Wiso Basin and Georgina Basin, the nexus of which is situated directly above the Beetaloo Sub-basin. The deposits of these basins were deposited as essentially flat-lying beds on a shallow seabed, primarily on the relatively flat volcanic rocks. Tickell (2009) describes that mild tectonic forces caused sagging of the crust and the rocks are now preserved in the three basin structures. The divide between the basins is not dictated by modern day flow directions, rather represents the highpoints or dividing ridges of the basin floors. This nexus therefore represents a local highpoint in the volcanic rocks or underling strata.

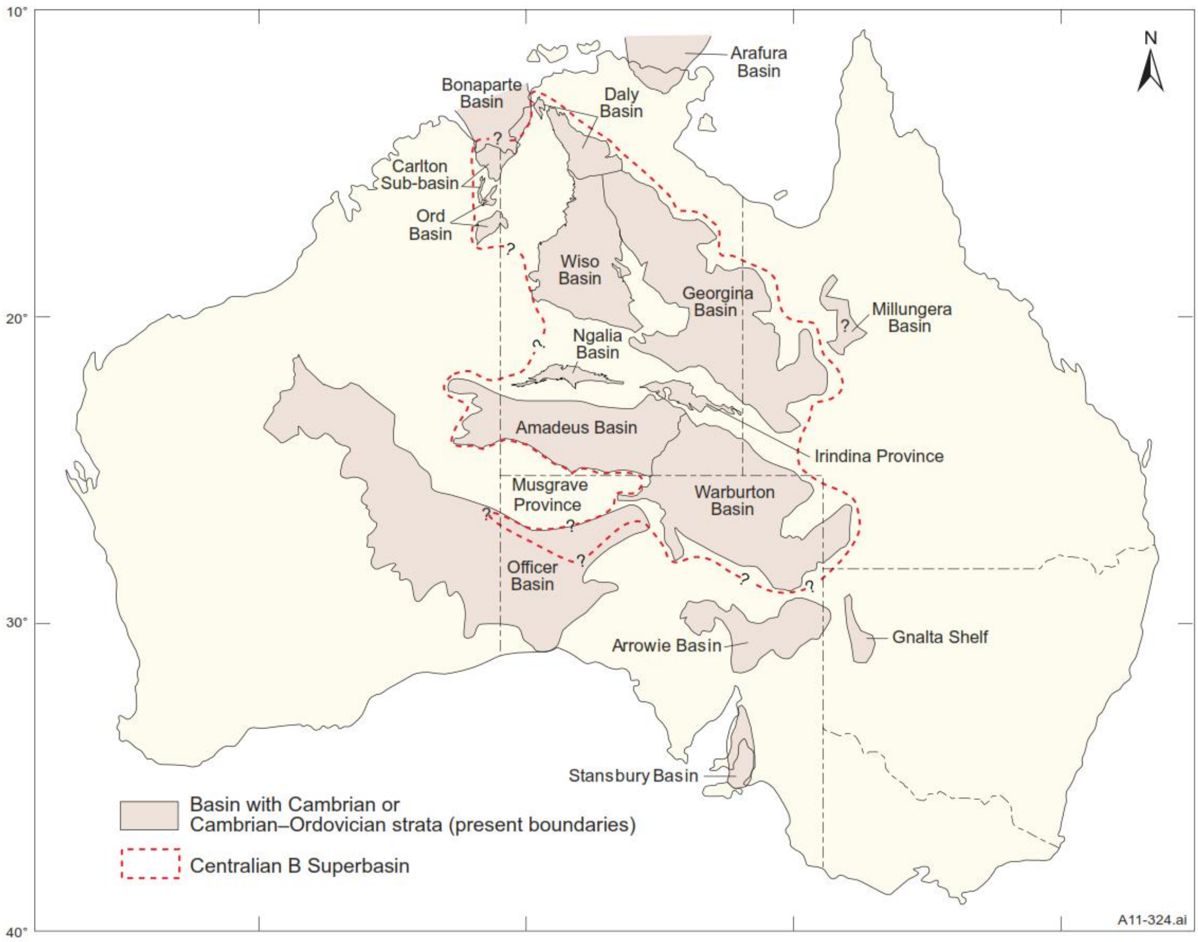

Figure 9 Distribution of Australian cratonic Cambrian and Cambrian–Ordovician basins comprising Centralian B Superbasin (Munson et al. in Ahmad and Munson, 2013)

3.1.3 Mesozoic basins

Jurassic to Cretaceous strata were deposited on an erosional surface of the Proterozoic strata, the Cambrian volcanics, and the Cambrian to Ordovician basin strata in the study area. The onshore component of the Mesozoic Carpentaria Basin covers much of the study area (Figure 6) with the sedimentary strata of the McArthur (Beetaloo Sub-basin), Georgina, Wiso and Daly basins underlying this basin. Munson et al.(b) in Ahmad and Munson (2013) presents a graphical representation (Figure 10) following on from numerous studies which demonstrates extent of the Cretaceous (Aptian and Albian) cover, demonstrating the extent of the study area in the marine depositional environment.

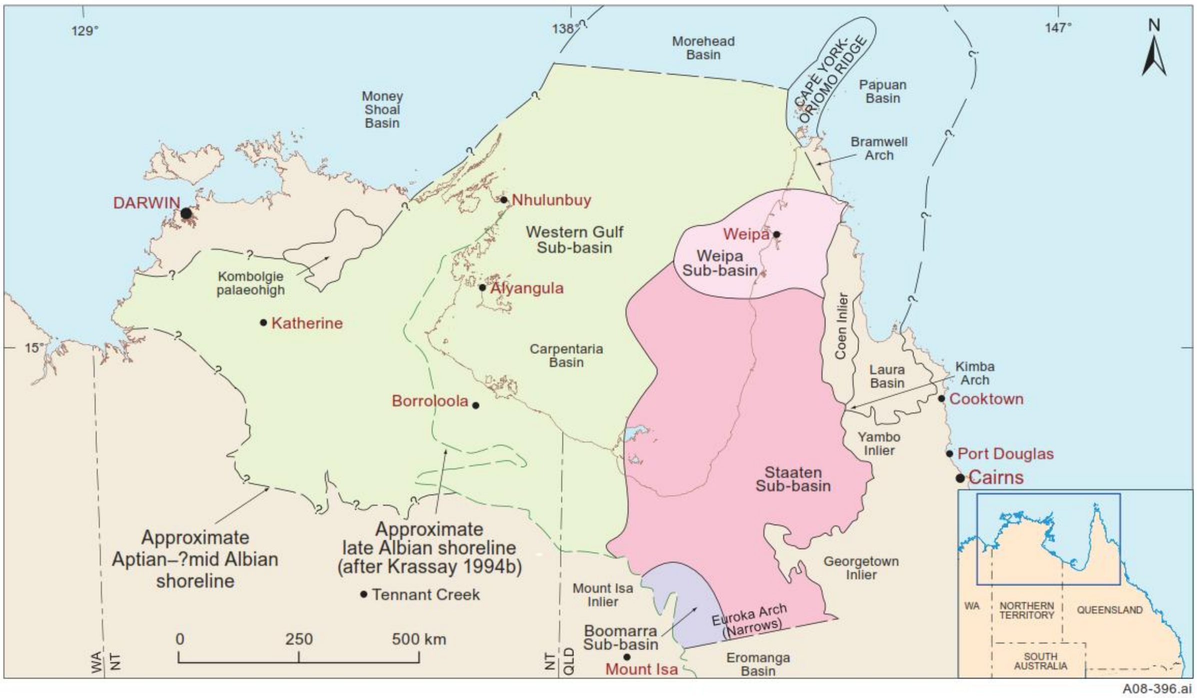

Figure 10 Schematic map showing extent of Carpentaria Basin and sub-basins. Maximum extent of Cretaceous deposition (Aptian) and approximate late Albian regional shoreline (Munson et al.(b) in Ahmad and Munson, 2013).

3.2 Stratigraphy

The stratigraphy of the Beetaloo Sub-basin and overlying basins are described in this section. A summary of the stratigraphy is presented below (Table 2). An example drillhole interpretation is presented as Figure 11.

3.2.1 Beetaloo Sub-basin Stratigraphy

For the purposes of this study, the Beetaloo Sub-basin stratigraphy is limited to the Maiwok Subgroup of the Roper Group and younger. The Roper Group comprises a cyclic succession of mudstone alternating with sandstone, deposited in a variety of shallow-marine, nearshore to shelf environments (Munson, 2014).

In the Beetaloo Sub-basin the formations include, but may not be limited to, from oldest to youngest (Munson, 2016):

- Corcoran Formation;
- Bessie Creek Sandstone;
- Velkerri Formation;
- Moroak Sandstone;
- Sherwin Formation;
- Kyalla Formation;
- Bukalorkmi Sandstone;
- Derim Derim Dolerite;
- Chambers River Formation;
- Jamison Sandstone; and
- Hayfield Mudstone.

The above also represents the deepest to shallowest strata with the exception of the Derim Derim Dolerite, an intrusive that intersects at least the Corcoran Formation, the Bessie Creek Sandstone and Velkerri Formation.

Ahmad et al. in Ahmad and Munson (2013) discuss the inclusion the Jamison Sandstone and Hayfield Mudstone as part of the Beetaloo Sub-basin succession, despite potentially being as young as Neoproterozoic and therefore not strictly of the part of the McArthur Basin. For consistency, this report continues this approach. The stratigraphy relevant to this study is presented as Table 2.

The Geoscience Australia (GA) descriptions for each of these units are provided in Table 1.

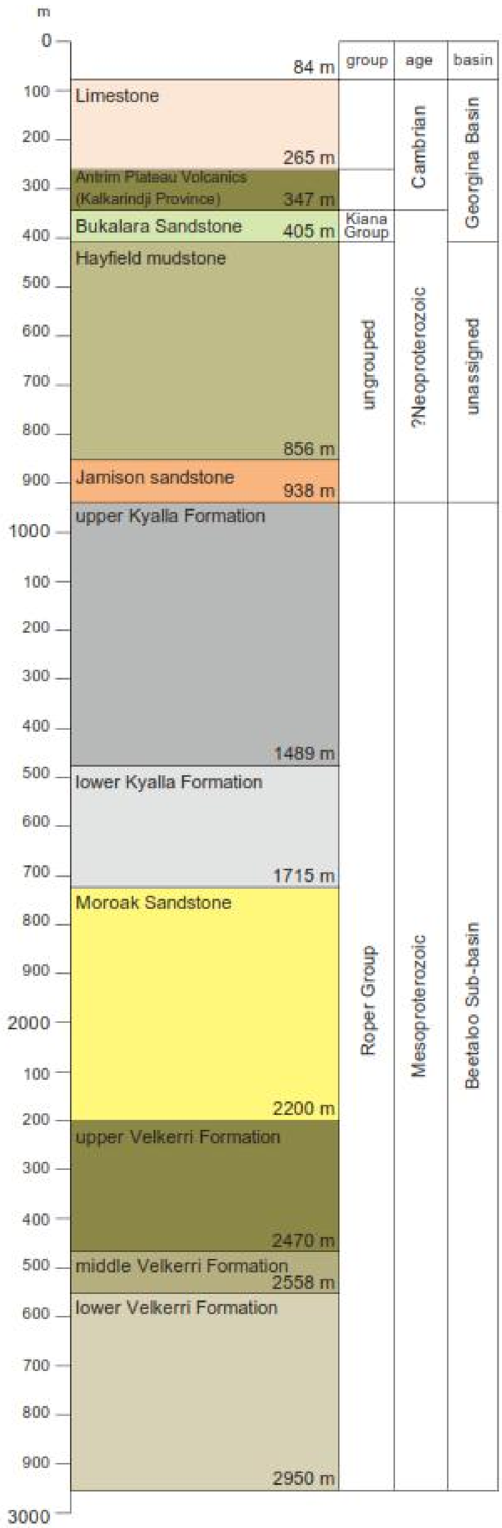

Figure 11 Example drillhole (Shenandoah-1) interpretation of formation tops from (modified after Munson, 2014)

Table 1 Beetaloo Sub-basin Descriptions

Unit	Descriptions (GA, 2016)
Bukalara Sandstone	Red-brown thin- to thick-bedded, fine- to very coarse-grained quartz sandstone, often feldspathic; minor shale and conglomerate. Cross-bedding, ripples and slumping common.
Hayfield mudstone	Regional, thick, organic-poor shale and siltstone. Massive to fissile, well indurated. Glauconite is a common, but minor component.
Jamison Sandstone	Light to medium-grey sandstone, very fine- to medium-grained, and moderately to well sorted. Generally coarsens upwards.
Bukalorkmi Sandstone	Quartz sandstone: thin to medium bedded, trough cross stratified, fine grained, ripple marks.
Kyalla Formation	Interbedded siltstone, mudstone and very fine grained quartz sandstone.
Sherwin Formation	Interbedded coarse to fine grained ferruginous sandstone, siltstone, mudstone, pisolitic ironstone
Moroak Sandstone	Thinly to medium bedded, medium to fine quartz sandstone with coarse, quartz-granule-rich intervals up to 1 m thick near base. Cross-stratification, symmetric ripples, interference ripples, moulds of rip-up clasts, and synaeresis cracks are common.
Velkerri Formation	Grey and black (carbonaceous) mudstone and siltstone, and minor fine sandstone. Rocks are laminated, but intervals that are structureless or characterised by abundant convoluted laminae are common. Calcite nodules and veins, and pyrite are present.
Bessie Creek Sandstone	Quartz sandstone: fine to medium and locally coarse grained, tough cross-stratification, ripple marks.
Corcoran Formation	Red laminated siltstone and mudstone in upper part; interbedded fine grained quartz sandstone and laminated siltstone in lower part.

Table 2 Stratigraphy

Eon	Era	Age	Basin	Group or Suite	Formations
Carpentaria Basin					
Phanerozoic	Mesozoic	Jurassic to Cretaceous	Carpentaria Basin		Walker River Formation
Centralian B Superbasin					
Phanerozoic	Palaeozoic	Ordovician to Cambrian	Georgina Basin	Barkly Group	Anthony Lagoon Formation Gum Ridge Formation
Phanerozoic	Palaeozoic	Ordovician to Cambrian	Daly Basin	Daly River Group	Jinduckin Formation Tindall Limestone
Phanerozoic	Palaeozoic	Ordovician to Cambrian	Wiso Basin		Hooker Creek Formation Montejinni Limestone
Phanerozoic	Palaeozoic	Cambrian	Kalkarindji Igneous Province	Kalkarindji Suite	Antrim Plateau Volcanics Helen Springs Volcanics
Beetaloo Sub-basin					
Proterozoic			McArthur Basin (Beetaloo Sub-basin)	Kiana Group	Bukalara Sandstone
				Roper Group	Hayfield mudstone Jamison Sandstone Derim Derim Dolerite Maiwok Subgroup Bukalorkmi Sandstone Kyalla Formation Sherwin Formation Moroak Sandstone Velkerri Formation Bessie Creek Sandstone Corcoran Formation

3.2.2 Palaeozoic Basin Stratigraphy

Kalkarindji Province

The Kalkarindji Suite (Glass et al. in Ahmad and Munson, 2013) includes the relatively flat-lying Antrim Plateau Volcanics, which covers much of the study area, and the Helen Springs Volcanics at the southern extent. The Kalkarindji Suite comprises “tholeiitic basalt, dolerite and andesite: partly vesicular or amygdaloidal; minor trachyte, microdolerite, basaltic flow breccia, peperite, pyroclastic deposits, quartz sandstone, siltstone, sedimentary breccia, limestone and chert” (GA, 2016).

Georgina Basin

The key units of the Georgina Basin are part of the Barkly Group (Kruse et al. in Ahmad and Munson, 2013). In the study area, the Barkly Group comprises (GA, 2016):

- Anthony Lagoon Formation; and
- Gum Ridge Formation.

The Anthony Lagoon Formation is recognised within the study area adjacent to the steeply dipping Gum Ridge Formation, south of the northern boundary of the Georgina Basin (Bruwer and Tickell, 2015). The Anthony Lagoon Formation is described as “Dolomudstone/ dolosparstone, dolomitic-siliciclastic siltstone and mudstone, dolomitic sandstone-siltstone interbeds; evaporites, chert concretions; minor intraclast and oncoid dolostone, microbial dololaminite, dolomitic quartz sandstone” (GA, 2016).

The Gum Ridge Formation in the study area occurs from the northern boundary of the Georgina Basin. The Gum Ridge Formation is described as “Grey, partially dolomitised massive, ribbon, bioclast, lithoclast and minor oncoid limestone, minor cryptomicrobial dololaminite and grey siliciclastic mudstone; brown-maroon siltstone at base; recessive outcrop pervasively chertified and lateritised” (GA, 2016).

Daly Basin

The Daly Basin (Kruse and Munson in Ahmad and Munson, 2013) contains rocks of the Daly River Group, which are equivalents of the Barkly Group (GA, 2016) which in the study area comprises:

- Tindall Limestone; and
- Jinduckin Formation.

The Tindall Limestone conformably underlies the Jinduckin Formation. The Tindall Limestone is described as “Partially dolomitised limestone with silt laminations, interbedded calcilutite and marl; bioclastic limestone, mudstone, siltstone; minor stromatolitic boundstone, cryptalgal laminate; local bioclastic calcarenite, arkosic sandstone, conglomerate” (GA, 2011).

The Jinduckin Formation contrasts the Oolloo Dolostone and Tindall Limestone as it is dominantly siltstone with minor limestone and sandstone beds (Tickell, 2009).

The maximum recorded thickness of the rocks in the Daly Basin is 709 m and the maximum recorded thicknesses of the individual formations are: Tindall Limestone 204 m and Jinduckin Formation 356 m (Tickell, 2009).

Wiso Basin

Key units within the Wiso Basin include, but may not be limited to, the Hooker Creek Formation and Montejinni Limestone (Kruse and Munson (b) in Ahmad and Munson, 2013). The

Montejinni Limestone is the lateral correlative of Tindall Limestone and Gum Ridge Formation (GA, 2016).

The Hooker Creek Formation and Montejinni Limestone are described as “Fine to medium crystalline dolomite, dolomitic siltstone, siltstone, gypsum veins. Red-brown, laminated, micaceous, dolomitic siltstone, siltstone, silty dolomite” (GA, 2016)

3.2.3 Mesozoic basins

The Walker River Formation (previously known as the Mullaman Beds) covers much of the study area at surface (Munson et al.(b) in Ahmad and Munson, 2013). The Walker River Formation is described as “Variably ferruginous and clayey, medium-grained sandstone; some fine to coarse-grained sandstone; massive claystone and siltstone; minor conglomerate and breccia; marine fauna including pelecypods and ammonites” (GA, 2016).

3.3 Basin Visualisation

The Department of Mines and Energy (DME, 2016) provided 3D interpretations of the basin geometry which were examined to make graphical representations of the basins (Figure 12 to Figure 16).

Respectively Figure 12 and Figure 13 display a fence diagram and the key section which depict:

- The Beetaloo Sub-basin (the base of the Velkerri Formation to the base of the lower Cambrian sediments and volcanics) in light tan;
- The Cambrian volcanics in a textured darker pink;
- The key aquifers within the Cambrian sedimentary basins (the Daly, Wiso and Georgina basins) in lighter pink; and
- The overlying Mesozoic Carpentaria Basin in light green.

The elevation of the base of the Mesozoic Carpentaria Basin (the top if the key aquifers) is displayed in Figure 14. The elevation of the base of the Cambrian sedimentary basins (the Daly, Wiso and Georgina basins) and base of the key aquifers is displayed in Figure 15.

The Middle Velkerri Formation is the most prospective unit for shale gas and Figure 16 displays the elevation base of the Velkerri Formation.

Cambrian sediments and volcanics overlying the Beetaloo Sub-basin occur to depths varying from 61 m to 686 m based on the DME (2016) datasets. The base of the Velkerri Formation within the Beetaloo Sub-basin varies from 394 m to 3637 m below ground level based on the DME (2016) datasets.

GHD understand that these or similar datasets also exist in gOcad-SKUA® format contained within the Digital Information Package DIP 012 (Bruna and Dhu, 2016).

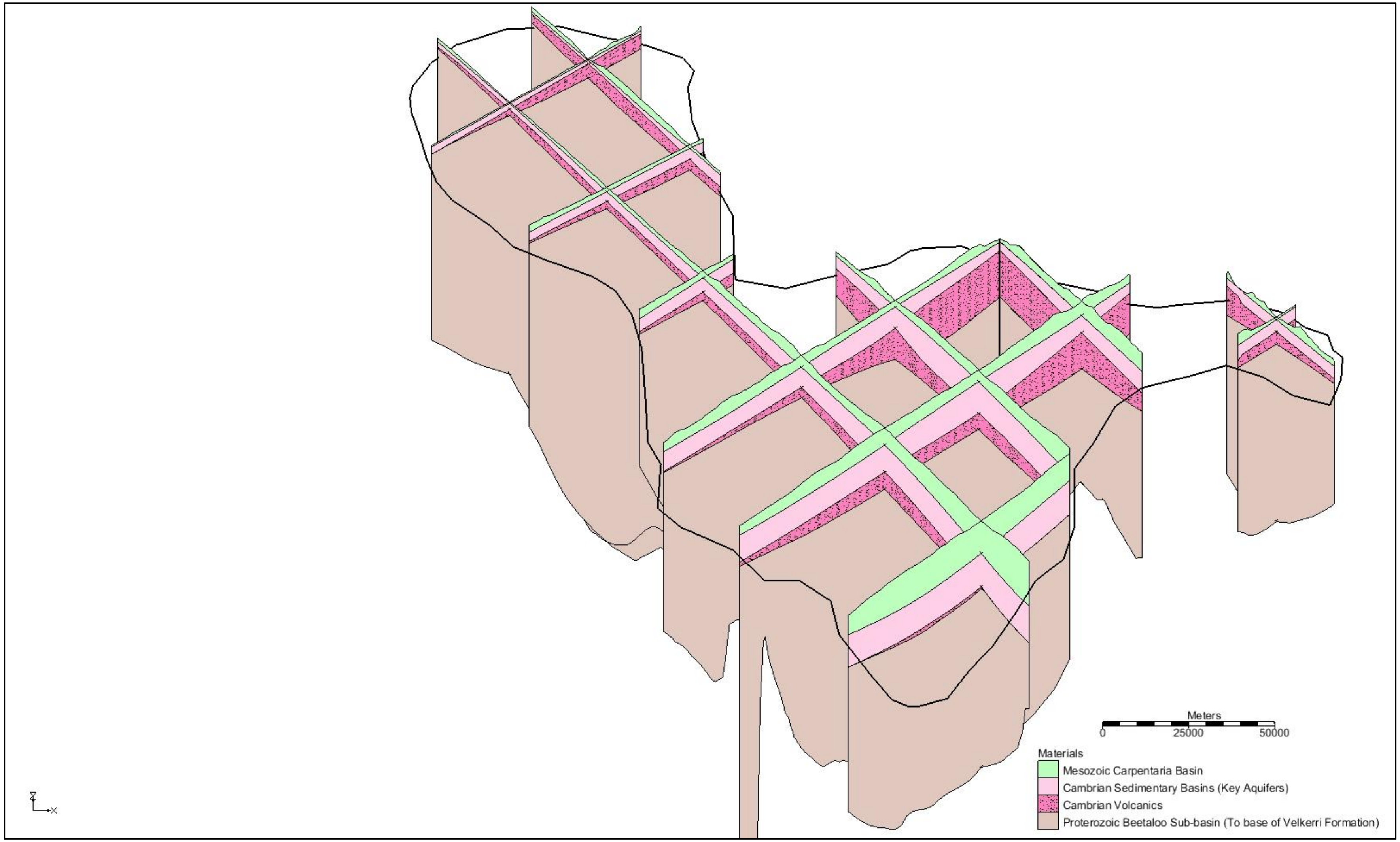

Figure 12 Fence Diagram (after DME, 2016 data), vertical exaggeration of 50, orthogonal view looking north at looking down at 45 degrees

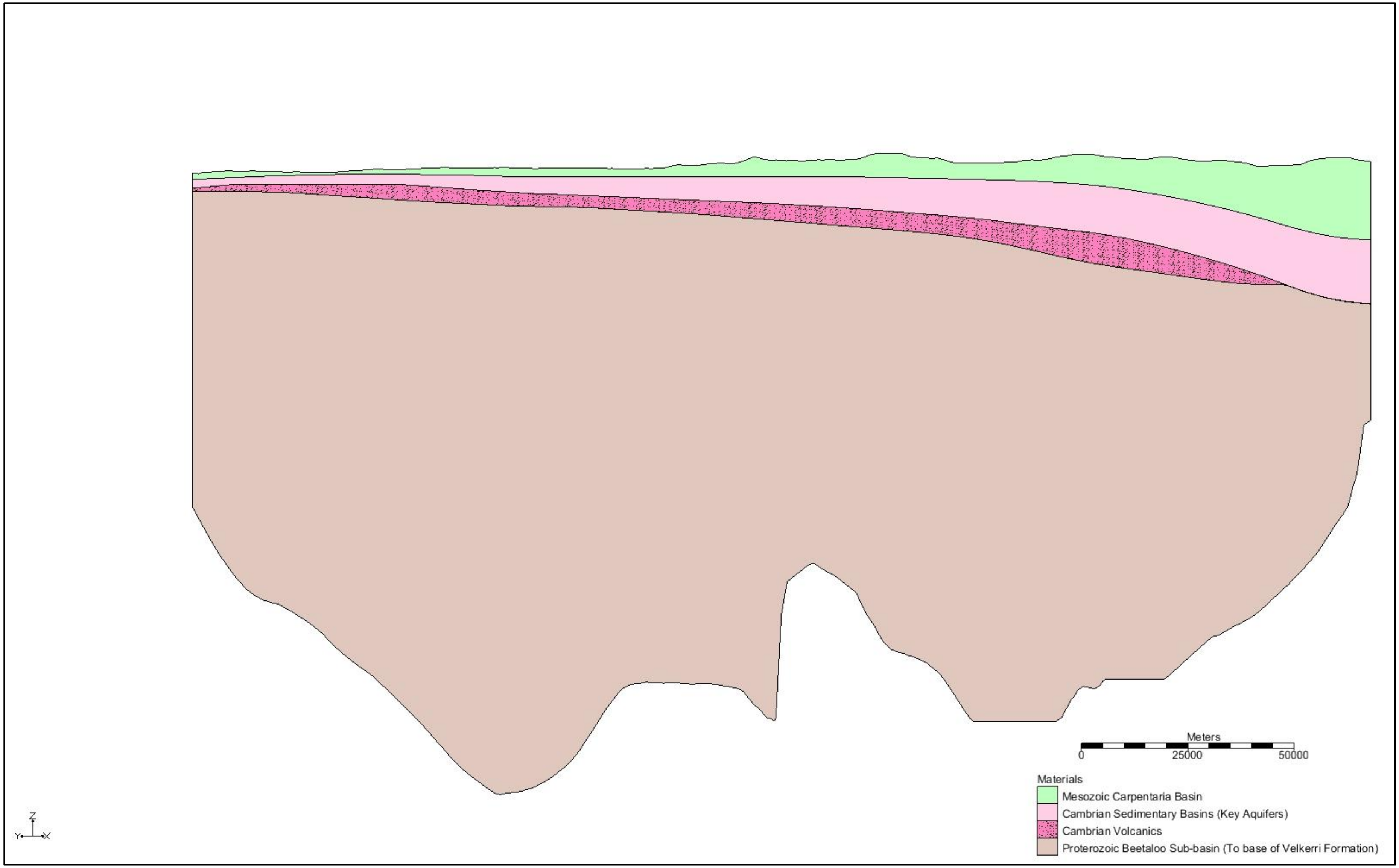

Figure 13 Basin Long Section (after DME, 2016 data), vertical exaggeration of 50 looking north east

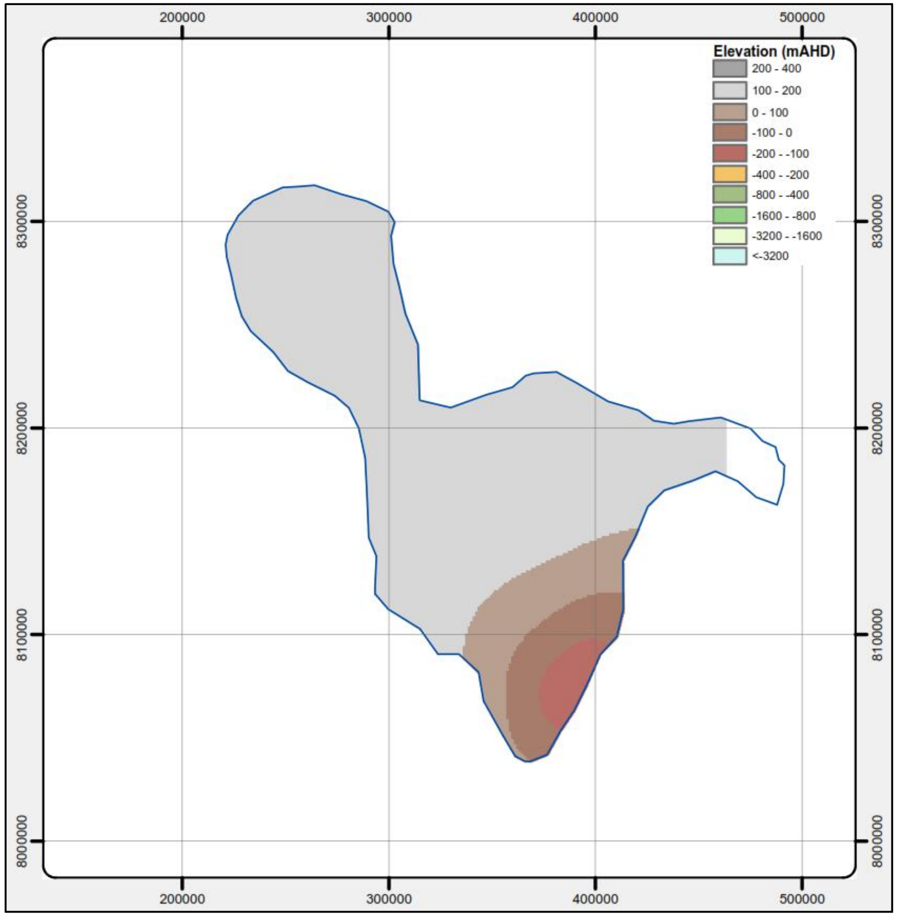

Figure 14 Base of the Carpentaria Basin Elevation/Top of Key Aquifers (after DME, 2016 data)

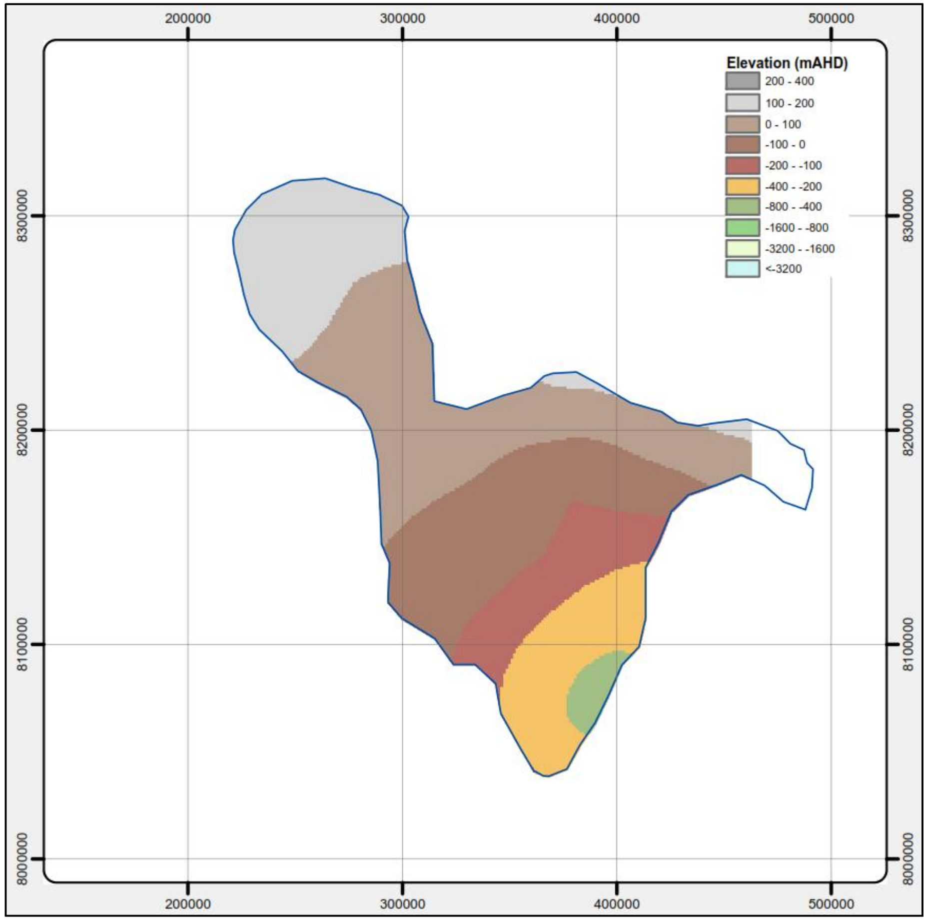

Figure 15 Base of the Cambrian Sedimentary Basins Elevation/Base of Key Aquifers (after DME, 2016 data)

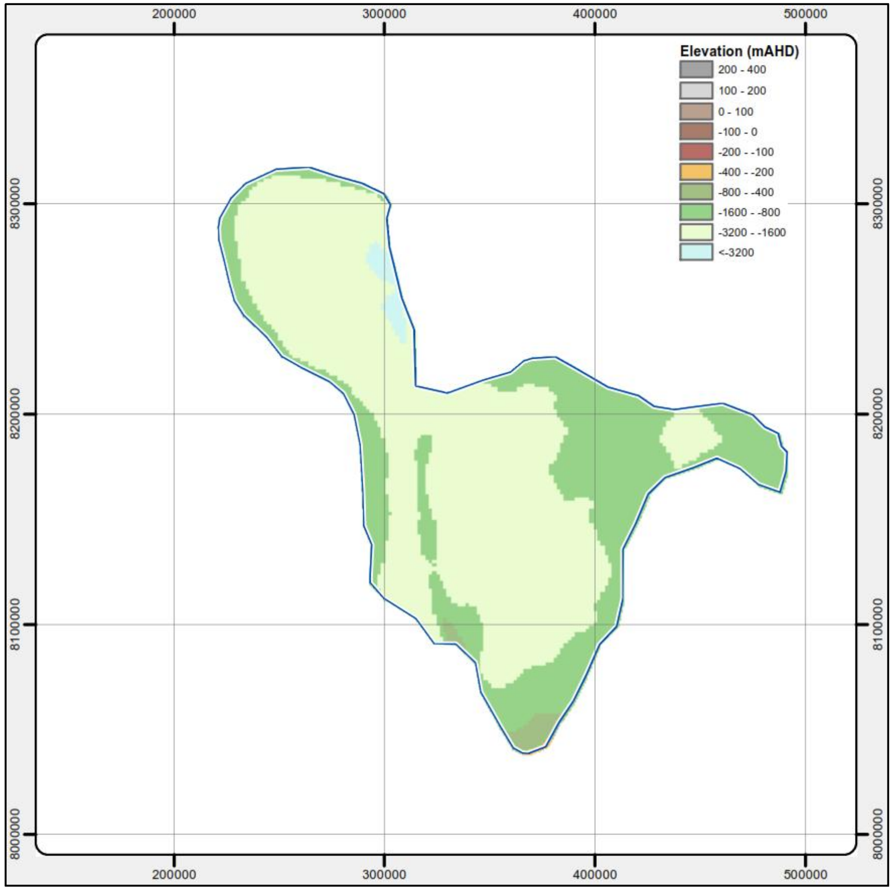

Figure 16 Base of the Velkerri Formation Elevation (Beetaloo Sub-basin) (after DME, 2016 data)

3.4 Petroleum Potential

The Beetaloo Sub-basin area has had relatively limited faulting, folding and intrusion since the deposition of the flat lying sediments during the Mesoproterozoic, with further periods of sedimentation leading to burial to depths and pressures suitable for oil and gas generation. Close et al. (2016) describes this unique geological history stating that the Beetaloo Sub-basin has "preserved source rocks that have been subject to relatively limited tectonic activity while still burying and maintaining them within the gas window". The Beetaloo Sub-basin has good source rocks and potential reservoirs in a number of siliciclastic and carbonate units (Ahmad and Munson, 2013) and these are summarised in Figure 17 reproduced here from Munson (2014).

The Beetaloo Sub-basin is considered to be one of the most prospective regions in Australia for shale gas and liquids (Munson, 2014). This is due to the presence of thick, flat-lying, organic-rich shale units that are mature for gas over extensive areas (Close et al., 2016). The most of important of these shales units the middle Velkerri Formation, which is up to 400 m thick and has produced significant gas shows in exploration wells. Studies have shown that the middle Velkerri shale has most or all of the necessary geological characteristics necessary for a productive shale gas play (Close et al., 2016 and Revie, 2016). In the centre of the Beetaloo Sub-basin, the most prospective shale within the middle Velkerri Formation (known as the B-shale) is at a depth of around 2400 m, and is around 30 m thick (Close et al., 2016). The depth of the prospective shale varies from 1000-1500 m in the northwest, to more than 3000 m in the deepest parts of the sub-basin (Scrimgeour, pers. comm., 2016). A second shale unit higher in the stratigraphy, the Kyalla Formation, is considered less prospective that the middle Velkerri Formation, but may have potential for shale gas and liquids where it occurs at depths of more than 1000 m (Scrimgeour, pers. comm. 2016).

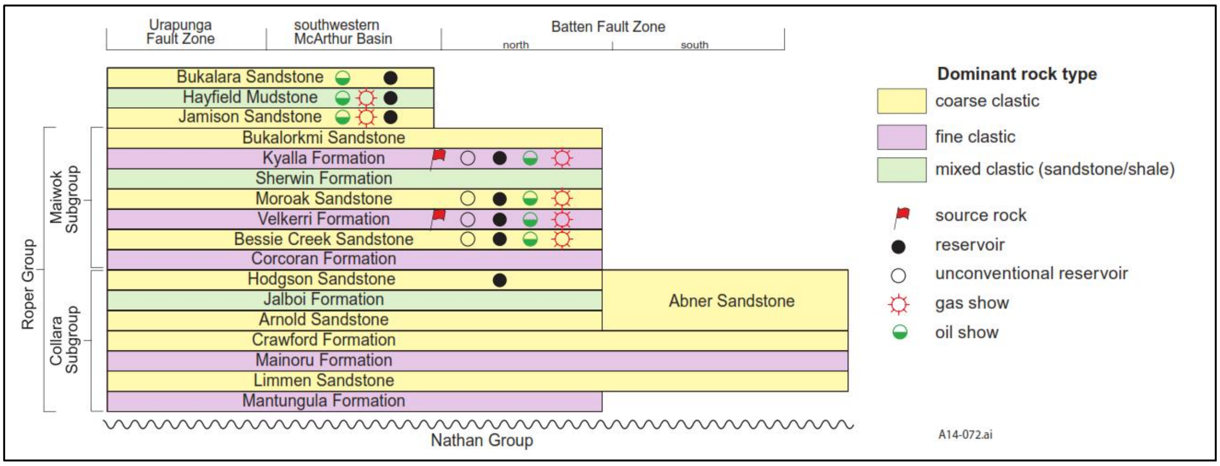

Figure 17 Petroleum potential showing source, reservoirs and petroleum shows (Munson, 2014)

3.5 Groundwater and Aquifers

3.5.1 Key Aquifers

The key aquifers in the area are the Tindall Limestone within the Daly Basin and its correlatives the Montejinni Limestone and Gum Ridge Formation within the Wiso Basin and Georgina Basin respectively. Together, these aquifers could be considered a single aquifer as they are interconnected at the basin boundaries. In addition to the Tindall Limestone, the Oolloo Dolostone is a major aquifer in the Daly Basin, however, it is believed to only occur to the north of the study area.

Other units also form significant aquifers over the area, including but not limited to:

- the Antrim Plateau Volcanics as either fractured aquifers or from primary porosity, particularly in vesicular basalt flows;
- other units within Barkly Group, notably isolated beds within the Anthony Lagoon Beds have been identified drilling across the study area (Munson, 2014); and
- potentially the fractured rocks of the Hooker Creek Formation.

The Antrim Plateau Volcanics provide an important aquifer, although usually outside the extent of the sedimentary basins or where faulting has limited the vertical extent of the overlying aquifer (i.e. in the west of the study area).

The overlying rocks of the Carpentaria Basin (previously referred to as the Mullaman Beds) are not considered to be an aquifer and the base of the Mullaman Beds has historically been a target to determine the top of the aquifer (Randall, 1973).

Beetaloo Sub-basin Aquifers

At depth, the rocks of the Beetaloo Sub-basin have the potential to contain significant groundwater resources. For the purposes of this study, it is reasonable to assume that the primary targets for these potential aquifers are the sandstone units and the most likely aquitards are the mudstone units of the succession. It is recognised that there are mixed units (Figure 17) and there are likely to be both permeable units within the units named 'mudstone' and aquitards within the units named 'sandstone'.

Permeability and porosity interpretations are routinely collected as part of the petroleum exploration process using core, in-situ geophysics and physical testing. Permeability and porosity of the sandstone units of the Beetaloo Sub-basin has been published in petroleum exploration-related document including:

- Moroak Sandstone permeability up to 100 milliDarcies (mD) (Burgess, 2010);
- Jamison Sandstone core porosity of up to 12.4% (Silverman et al, 2007);
- Jamison Sandstone permeability up to 121 mD (Silverman et al, 2007);
- Moroak Sandstone core-derived permeability from under 0.01 up to approximately 200 mD (Silverman and Ahlbrandt, 2011); and
- Jamison Sandstone core porosity from approximately 4% to 18% (Silverman and Ahlbrandt, 2011).

Likewise, the mudstone (shale) units Kyalla Formation and Velkerri Formation also have a range of published permeability and porosity interpretations (i.e. Law et al., 2010).

GHD also understand that a significant dataset exists in the Digital Information Package DIP 013 (Hallett, 2016).

3.5.2 Aquifer Types

The groundwater map (Appendix A) presents the aquifers in terms of aquifer type based on Tickell (2013). The three aquifer types within the study area are:

- Regional-Scale Fractured and Karstic Rocks (the key aquifers discussed above);
- Intermediate-Scale Fractured and Karstic Rocks (which indicates the presence of the Jinduckin Formation, but notably is underlain by the regional scale aquifer, the Tindall Limestone); and
- Local-Scale Fractured and Weathered Rocks (discussed below).

The local-scale fractured and weathered rocks include the basalts of the Antrim Plateau Volcanics to the east, west and in the centre of the map area (Appendix A). To the east, they also include rocks of the McArthur Basin. To the south, they include the Helen Springs Volcanics and Tomkinson Creek Beds.

It is recognised that the map (Appendix A) presents a 'flat' depiction of the aquifers present and that Beetaloo Sub-basin rocks beneath these key aquifers may also provide suitable conditions for the extraction of groundwater for beneficial use. It is understood that a potential use of the deeper groundwaters from within the Beetaloo Sub-basin may be for industrial use within the petroleum industry.

Karst

The key aquifers type discussed above fractured and karstic rocks. Karst is term associated with a landscape shaped by the dissolution of layers of soluble bedrock such as limestone. The solution of the rock mass results in cavernous material which contributes to the aquifers capacity to both store and transmit groundwater. Terrestrial karst features are present to the north of the study area where rocks associate to the key aquifers outcrop at surface (i.e. Figure 18 and Figure 19). In addition, the widespread presence of sinkholes across the study area (Tickell, 2014) is also typical of the karst terrain.

Figure 18 Terrestrial karst features of the Tindall Limestone outcropping to the north of the study area

Figure 19 Tindall Limestone outcropping to the north of the study area displaying exceptionally high permeability due to karstified solution cavities

3.6 Groundwater Flow

The groundwater map (Appendix A) presents the groundwater contours and flow direction in the key aquifers. Groundwater flow across the study area is broadly from south to north. Groundwater contours are more tightly spaced (steeper hydraulic gradients) to the north and almost flat (10 m in 100 km or a hydraulic gradient of 0.0001) in the south of the study area. This thought to be due to the overlying Mullaman Beds limiting recharge to the aquifer but also due to lower rainfall in the south (Yin Foo, pers. comm., 2016). To the north, steeper hydraulic gradients are associated with groundwater being able to discharge (and potentially also due to aquifer use, i.e. in the Mataranka and Katherine areas) at springs and into rivers.

The basalt in the centre of the north of the study area effectively divides the aquifer flow in two. Likely discharge locations for groundwater in the aquifer to the east of the basalt include (Tickell, 2014) Elsey Creek, the Roper River and the springs and wetlands associated with Elsey National Park (Figure 20). Likewise, based on the groundwater elevation and chemistry data, the majority of the groundwater from the south of the study area (mostly the Georgina Basin) is also expected to take this path.

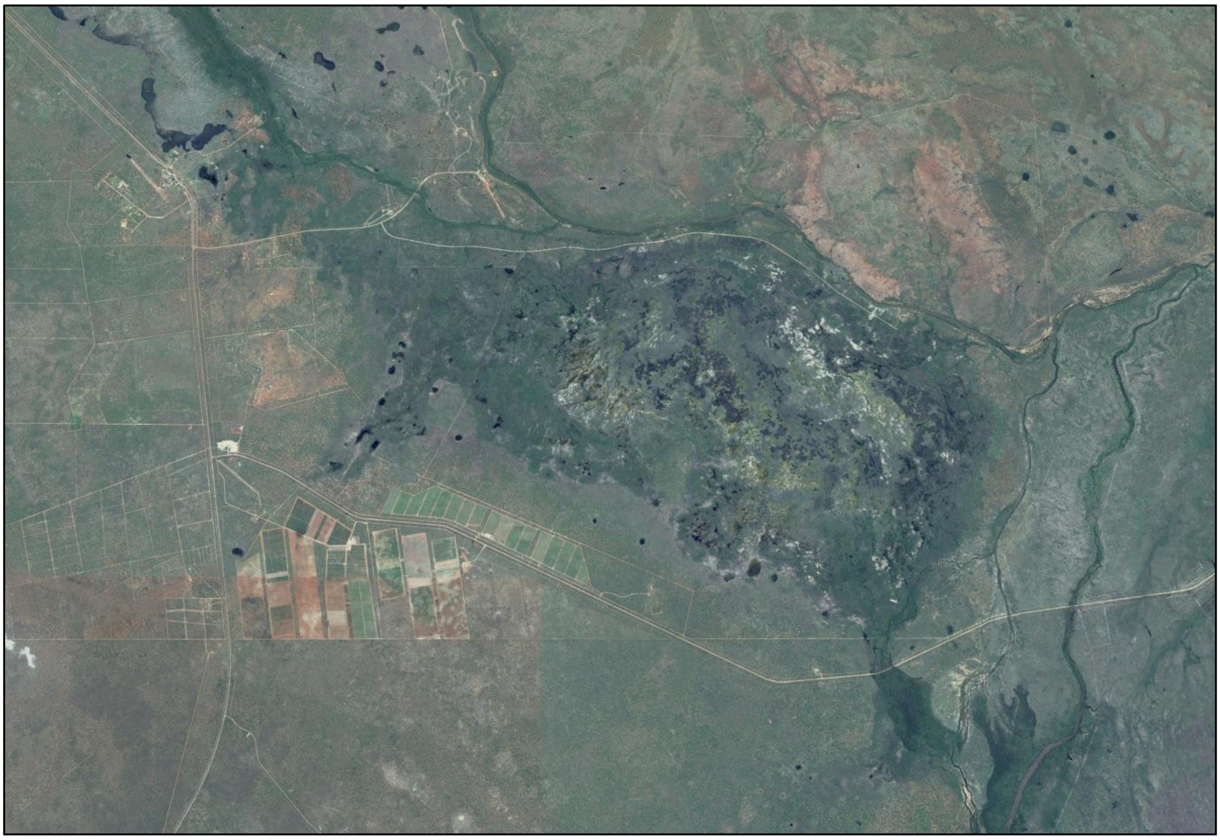

Figure 20 Wetlands associated with Elsey National Park, also visible are the nearby town of Mataranka to the NW of the image and associated agriculture to the centre to SW of the image (Google Earth, 2016)

Likely discharge locations for groundwater in the aquifer to the west of the basalt include the Flora River and associated springs to the north west of the study area.

No publically available information exists on the groundwater flow systems in the underlying rocks within the Beetaloo Sub-basin.

3.6.1 Standing Water Levels

The standing water levels are presented for three bores across the study area representing the key aquifers:

RN029012 (Figure 21) in the Tindall Limestone (Daly basin);

RN028087 (Figure 21) in the Montejinni Limestone (Wiso Basin); and

RN036471-1 (Figure 22) in Gum Ridge Formation (Georgina Basin).

In addition the standing water levels from RN036471-2 in the Anthony Lagoon Beds (overlying the Gum Ridge Formation at the same locations are presented in Figure 22.

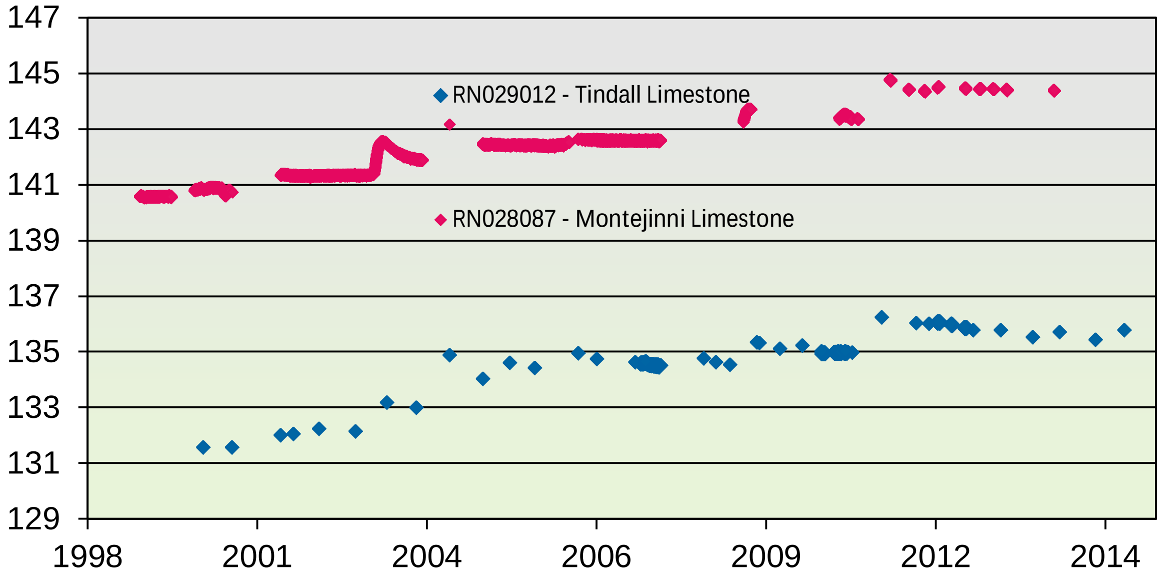

Figure 21 Example standing water levels in the Daly and Wiso basins (mAHD)

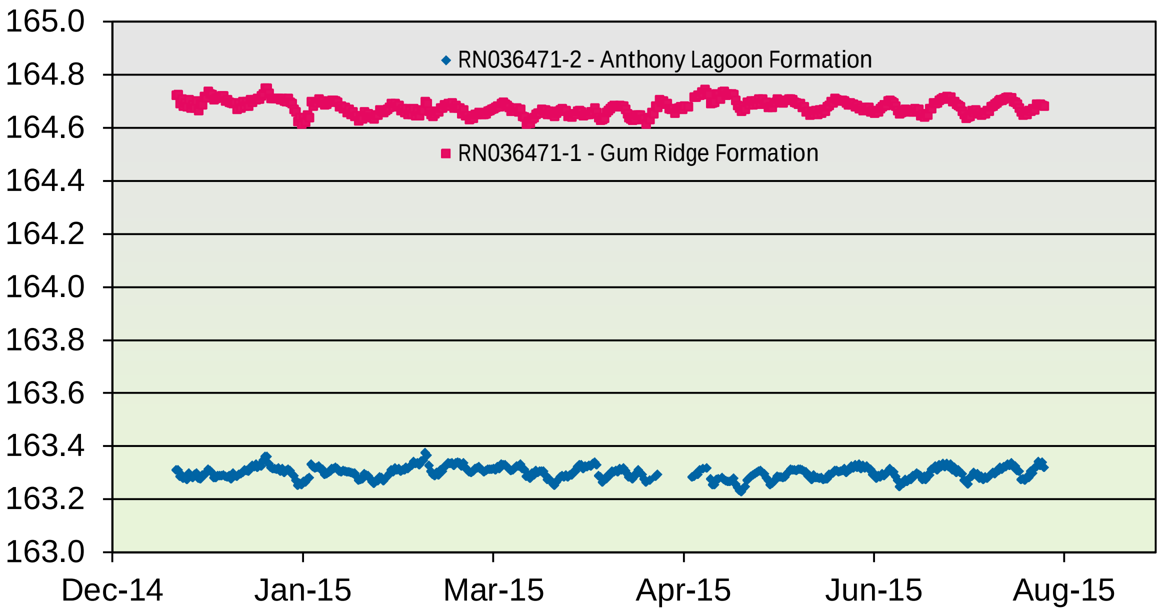

Figure 22 Example standing water levels in the Georgina Basin (mAHD)

3.7 Groundwater Quality

Groundwater quality (Figure 23) is presented on the map (Appendix A) in terms of total dissolved solids (TDS) for multiple aquifers. TDS is a measure of 'freshness' or 'salinity'. It also provides an indication of the rate of recharge (and age) and the material the groundwater has come into contact with, as older groundwaters have more time to weather and dissolve aquifer minerals and groundwater in contact with marine sediments may pick up salt deposited with the sediments. Over the study area, the general trend is that groundwaters are generally fresher in the Wiso Basin and eastern portion of Daly Basin. In the Georgina Basin and western portion of the Daly Basin, TDS generally increases towards the south with the majority of samples classified as fresh but with an increased abundance of samples classified as fair, brackish or saline and less samples classified as very fresh.

Based on the above logic, any deeper groundwater contained in the units of the of the Beetaloo Sub-basin is likely to be more saline with depth. This is due to limited recharge, longer residence time (age) and interaction with the rock mass. Whilst not currently considered aquifers, the potential for use as industrial water within the petroleum industry could change this. Given the expected quality of such aquifers, it is likely that this use may be the only beneficial use for such groundwater.

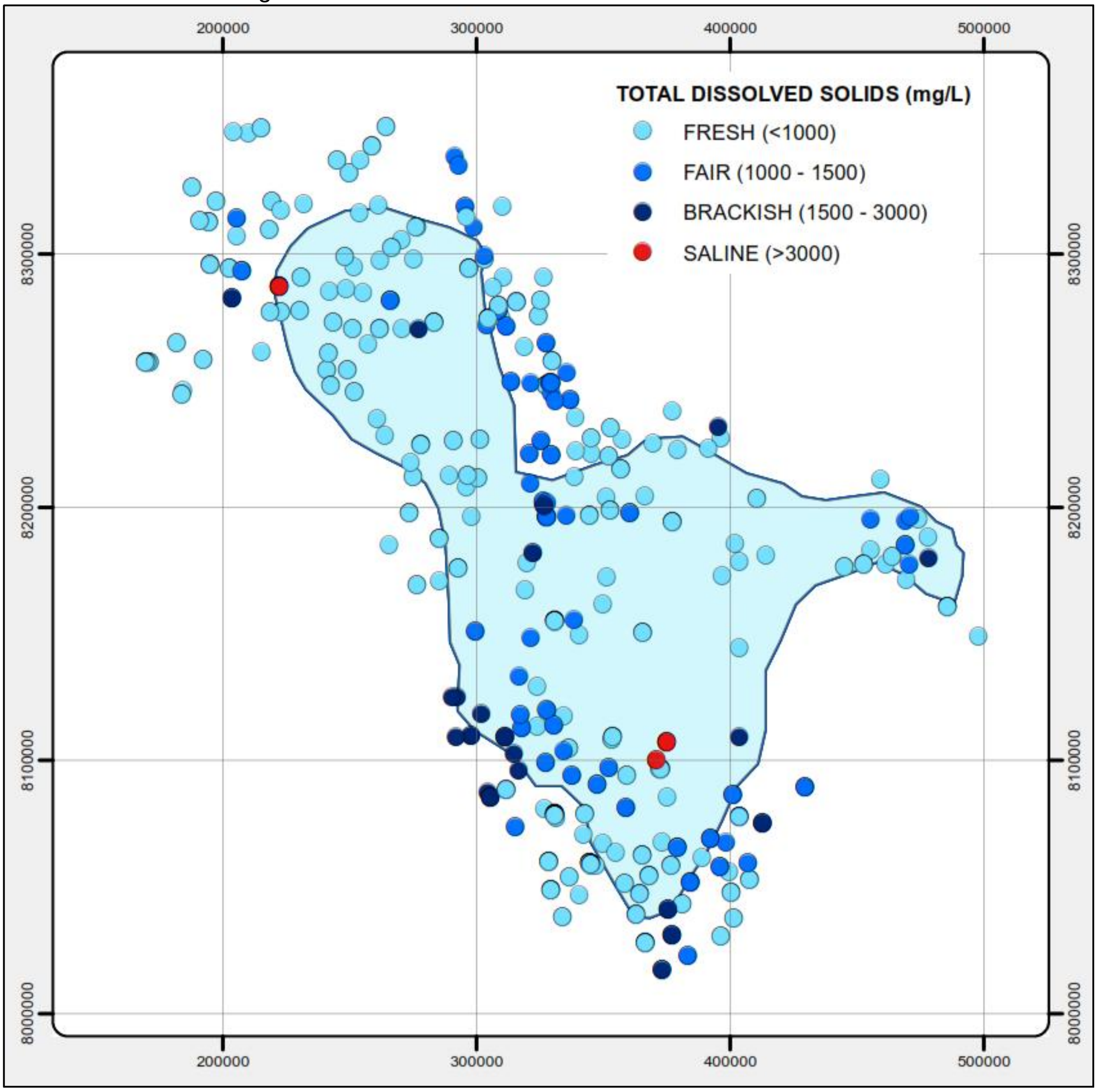

Figure 23 Multiple aquifer total dissolved solids (mg/L) from DLRM dataset

4. Groundwater Use

Key groundwater uses include stock water, domestic water supply, agriculture, springs, baseflow for perennial rivers and potentially the petroleum industry.

Much of this groundwater use is associated with the key aquifers discussed above. Due the high yields and good quality of the aquifers, prior to petroleum exploration, there has been little motivation to drill deeper into the Proterozoic Beetaloo Sub-basin.

4.1 Domestic water supply

The Larrimah Study (Bruwer and Tickell, 2015) determined the groundwater quality south of Mataranka to be suitable for human consumption but stated that it was considered to be of "poor palatability". It is understood that the Power and Water Corporation (PWC) use groundwater to provide town water supplies at:

- Mataranka;
- Larrimah;
- Daly Waters;
- Newcastle Waters; and
- Elliot (PWC, 2016).

4.2 Agriculture

Groundwater is used for irrigation at Mataranka (Figure 20) and Larrimah (at least one pivot) as well as towards Katherine from the key aquifers discussed above. The potential use of additional groundwater for irrigation was a focus of the Larrimah Study (Bruwer and Tickell, 2015) between the King River (north of Mataranka) and Daly Waters. The Larrimah Study modelling "indicated that over the past 30 years, the average groundwater recharge is approximately 330 GL/year" and that "given that NT Water Allocation Framework allows for 20% of recharge (or 66 GL/year) to be available for allocation, and that current groundwater entitlements in the region total approximately 26 GL/year, a further 40 GL/year could be available for allocation".

4.3 Stock water

Groundwater is used for stock water, primarily for cattle, across much if not the majority of the study area. Groundwater bores, fitted with either windmills, diesel or electric pumps, provide water to surface watering points, which can be seen across the landscape of the Sturt Plain.

4.4 Petroleum

It is understood that a potential use of the deeper groundwaters from within the Beetaloo Sub-basin is for industrial use within the petroleum industry. As discussed above, for the purposes of this study, it assumed that the sandstone units of the succession could be targeted for such potential use.

4.5 Ecosystems

Perennial rivers, creeks, wetlands, springs and the ecosystems they support are considered in this report collectively. As discussed above in the groundwater flow section (Section 3.6), likely discharge points for groundwaters in the key aquifer are:

- the perennial rivers, creeks, wetlands and springs (including Rainbow Spring [Figure 24], Bitter Spring [Figure 25], Fig Tree Spring and Botanic Walk Spring) associated with the Elsey National Park and start of the Roper River area near Mataranka; and
- the perennial rivers and springs associated with Giwining (Flora River National Park) to the north west of the study area.

In addition, to the north, the key aquifer is also associated with discharges to the Katherine and Daly rivers.

Additional springs are also associated with the fringe of the map area (Appendix A) where discharge occurs at or beyond the margins of the basins. These include springs:

- in the Hot Springs Valley area (i.e. Lagoon Creek Spring and Beauty Creek Spring) in the east of the study area where the Sturt Plain drops away to the Gulf Fall and Uplands; and
- to the west of Old Birrimba (i.e. Mud Spring, Green Spring and Brian Spring).

4.6 Cultural Significance

For the purpose of this study, it is assumed that all water and in particular water associated with the ecosystems above, has cultural significance.

Figure 24 Groundwater upwelling at Rainbow Springs, Mataranka

Figure 25 Groundwater dependent ecosystem (and a place of cultural significance) Bitter Springs (Korran)

5. Groundwater Map

This report is intended to act as the explanatory notes for a groundwater map created to describe the groundwater systems associated with Beetaloo Sub-basin in the Northern Territory. The Beetaloo Sub-basin Groundwater map is provided as Appendix 1.

The primary map displays groundwater elevation and flow direction within the key (limestone) aquifers. It also presents for reference: key basement highs within the Beetaloo Sub-basin referenced in the schematic section insert, those boreholes with standing water levels presented on the map, place names (towns/domestic water supply), tracks, roads, railways, cadastre, aquifer types, known irrigation graphed on the map insert, drainage lines, springs, the approximate Beetaloo Sub-basin extent and a 25 km buffer.

The elevation of the base of the Mesozoic Carpentaria Basin (the top if the key aquifers) is displayed in the top left sub-map. The elevation of the base of the Cambrian sedimentary basins (the Daly, Wiso and Georgina basins) and base of the key aquifers is displayed in middle left sub-map. The Middle Velkerri Formation is the most prospective unit for shale gas and the bottom left sub-map displays the elevation base of the Velkerri Formation. The Kyalla Formation is less prospective but may have potential for shale gas and liquids where it occurs at depths of more than 1000 m.

The top right sub-map displays the basin boundaries and key aquifers (within the Palaeozoic basins). The middle right sub-map displays the multiple aquifer groundwater quality using total dissolved solids as the key measure for quality. The bottom right sub-map displays the surface topography.

The relevant stratigraphy is present on the schematic and in tabular form with reference to the sub-maps and cross sections.

Mean monthly rainfall and evaporation are provided for Daly Waters as an example which display higher evaporation than rainfall. Seasonal rainfall results in seasonal recharge which is reflected as season increases in standing water level in the Tindall Limestone (Daly Basin) and Montejinni Limestone (Wiso Basin) hydrographs presented.

6. Acknowledgements

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- Darryl Day, Department of Land Resource Management
- Quinton Bruwer, Department of Land Resource Management
- Joanne Townsend, Department of Land Resource Management
- Charles Dack, Department of Mines and Energy; and
- Ian Scrimgeour, Department of Mines and Energy

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Approximate Beetaloo Sub-Basin Extent (Beetaloo.TAB,*.MAP,*.ID,*.DAT),
Base of the Velkerri Fm (BessieCreekCorcoran_RM02_GRD.TAB,*.MAP,*.ID,*.DAT),
Top of the Mid Cambrian (TopMidCam_GDA94Z53_GRD. TAB,*.MAP,*.ID,*.DAT),
Top of the Lower Cambrian (TopLowCam_GDA94Z53_GRD.TAB,*.MAP,*.ID,*.DAT).

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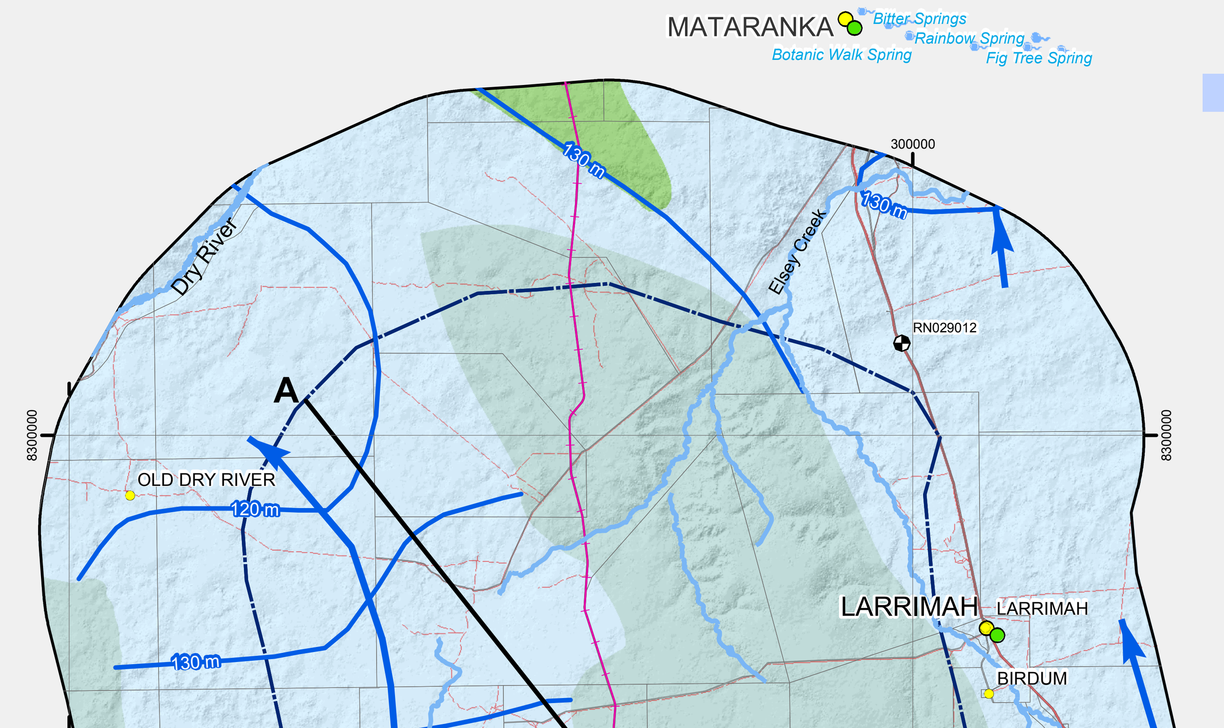
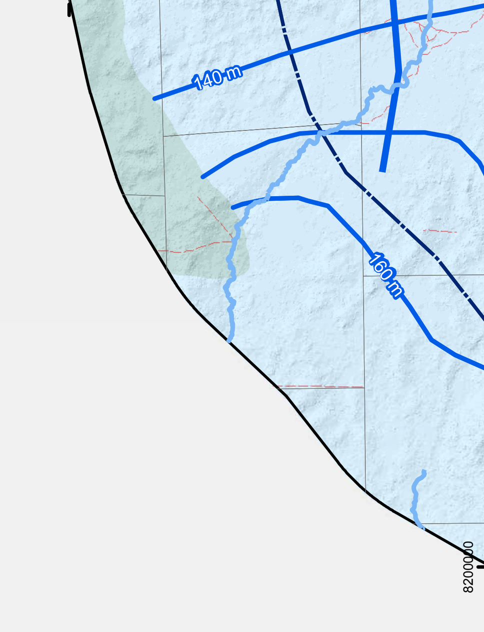
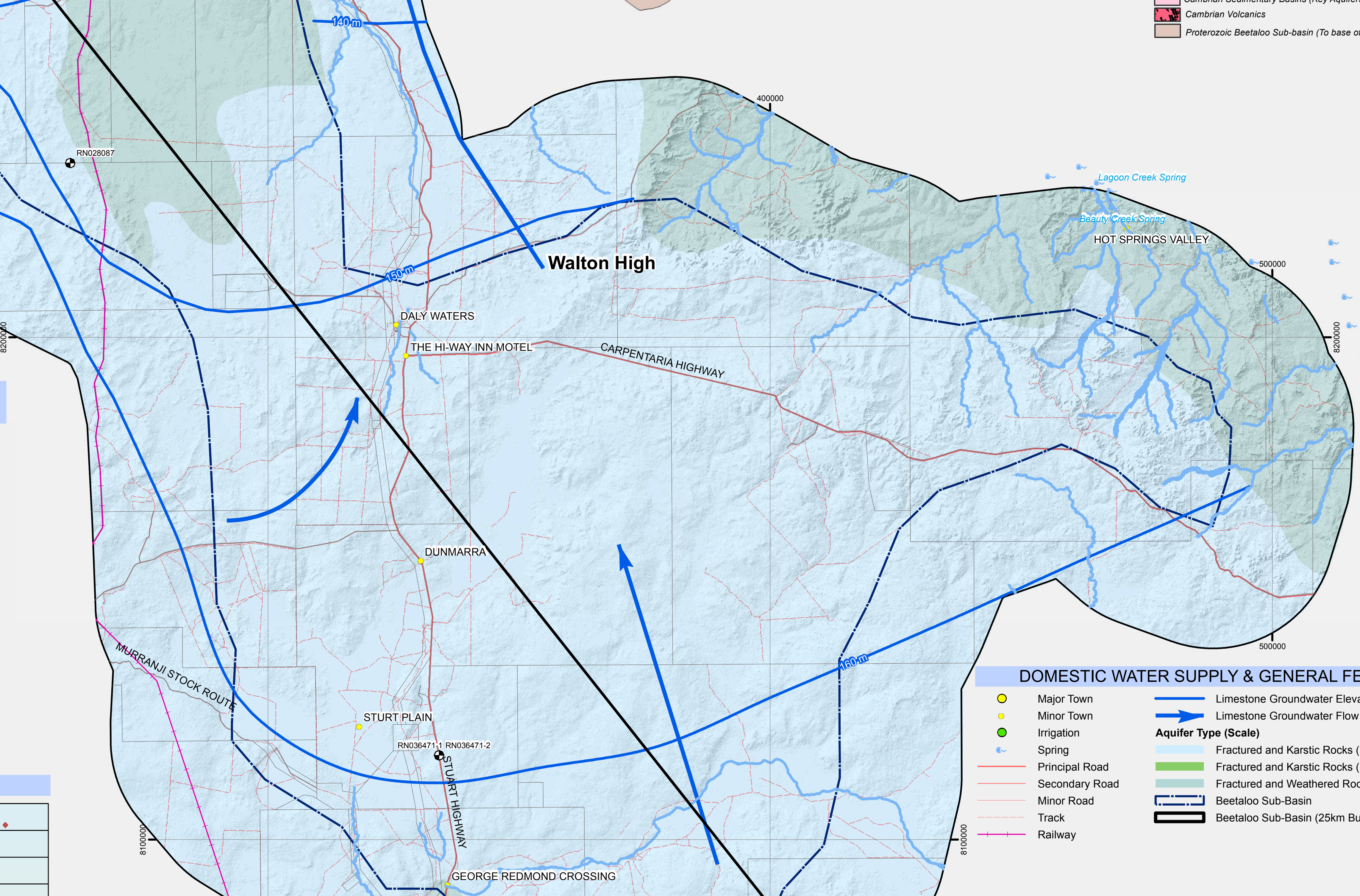
Appendices

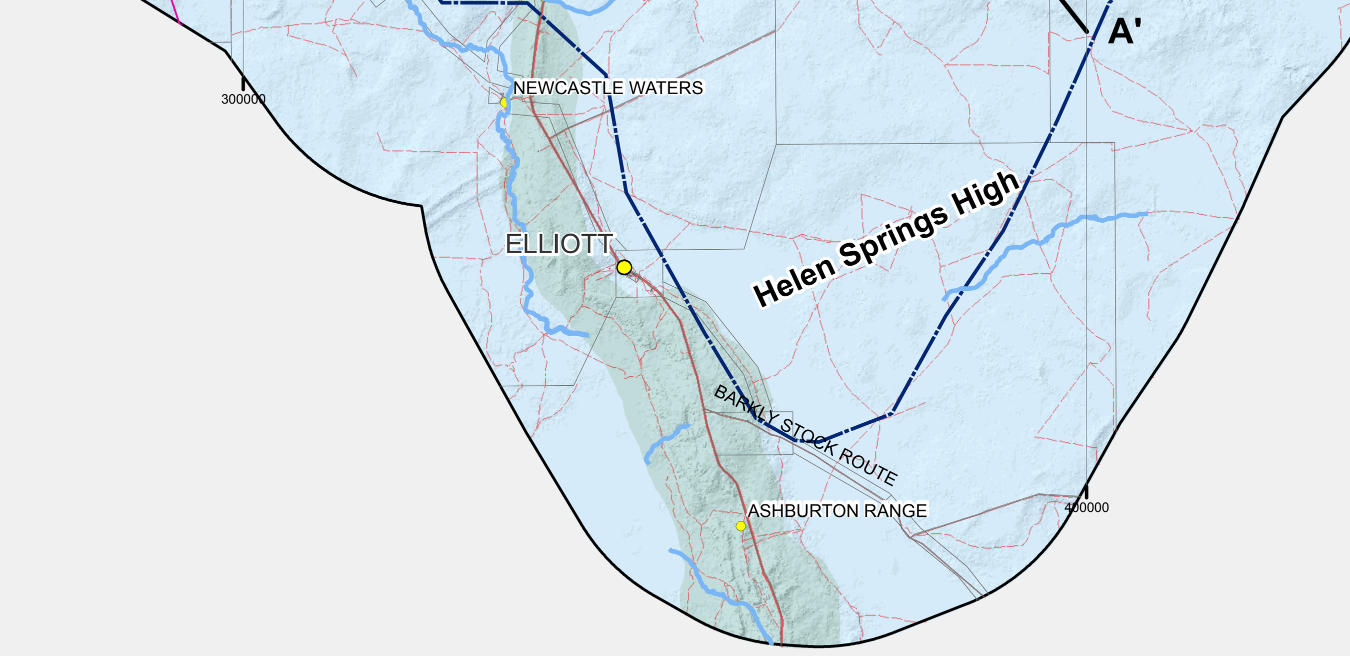
Appendix A – Beetaloo Sub-basin Groundwater Map

GHD





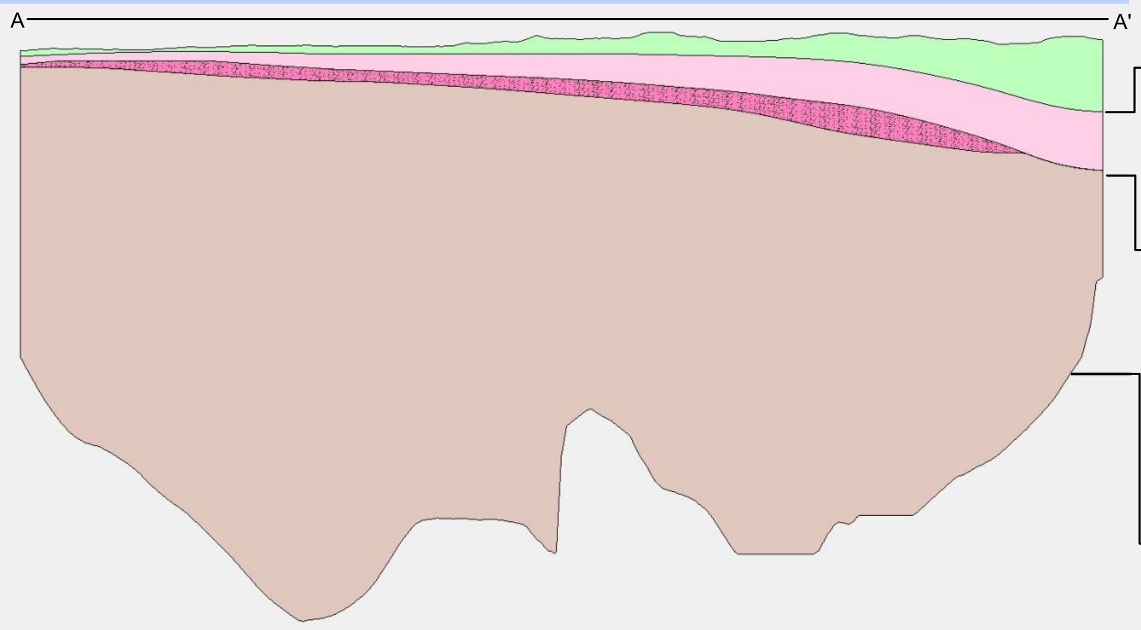




DOMESTIC WATER SUPPLY & GENERAL FEATURES

Major Town
Minor Town
Irrigation
Spring
Principal Road
Secondary Road
Minor Road
Track
Railway
Limestone Groundwater Elevation Contour (m AHD84)
Limestone Groundwater Flow Direction
Aquifer Type (Scale)
Fractured and Karstic Rocks (Regional)
Fractured and Karstic Rocks (Intermediate)
Fractured and Weathered Rocks (Local)
Beetaloo Sub-Basin
Beetaloo Sub-Basin (25km Buffer)

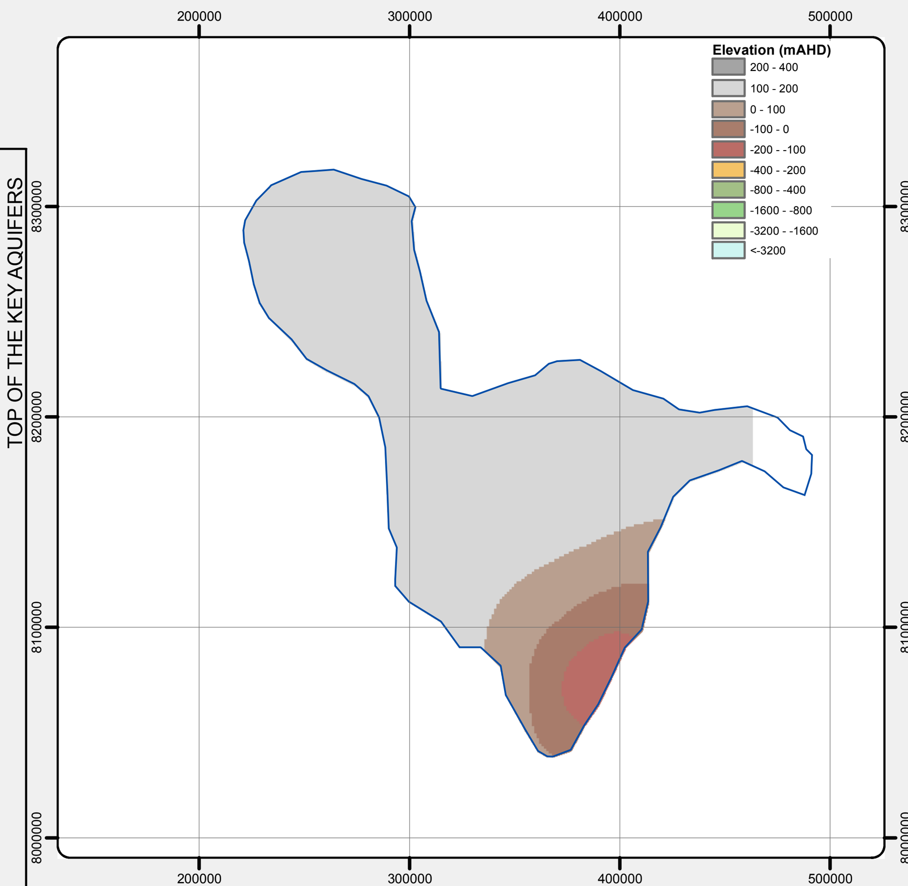
BEETALOO SUB-BASIN CROSS SECTION (50X VERTICAL EXAGERATION)



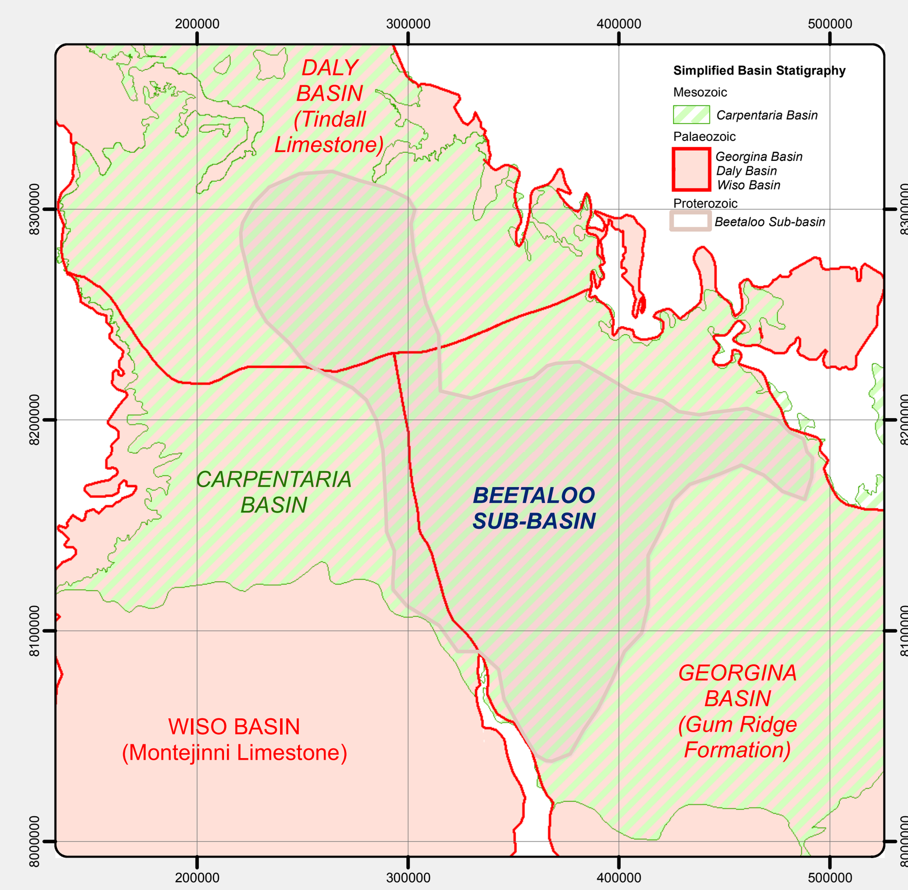
Eon	Era	Age	Basin	Group or suite	Formations
Carpentaria Basin					
Phanerozoic	Mesozoic	Jurassic to Cretaceous	Carpentaria Basin		Walker River Formation
Centralian B Superbasin					
Phanerozoic	Palaeozoic	Ordovician to Cambrian	Georgina Basin	Barkly Group	Anthony Lagoon Formation Gum Ridge Formation
Phanerozoic	Palaeozoic	Ordovician to Cambrian	Daly Basin	Daly River Group	Jinduckin Formation Tindall Limestone
Phanerozoic	Palaeozoic	Ordovician to Cambrian	Wiso Basin		Hooker Creek Formation Montejinni Limestone
Phanerozoic	Palaeozoic	Cambrian	Kalkarindji Igneous Province	Kalkarindji Suite	Antrim Plateau Volcanics Helen Springs Volcanics
Beetaloo Sub-basin					
Proterozoic			McArthur	Kiana	Bukalara Sandstone Hayfield mudstone Jamison Sandstone Derim Derim Dolerite
				Roper	Maiwok Subgroup Bukalorkmi Sandstone Kyalla Formation Sherwin Formation Moroak Sandstone Velkerri Formation Bessie Creek Sandstone Corcoran Formation

Mesozoic Carpentaria Basin
Cambrian Sedimentary Basins (Key Aquifers)
Cambrian Volcanics
Proterozoic Beetaloo Sub-basin (To base of Velkerri Formation)

TOP OF THE KEY AQUIFERS

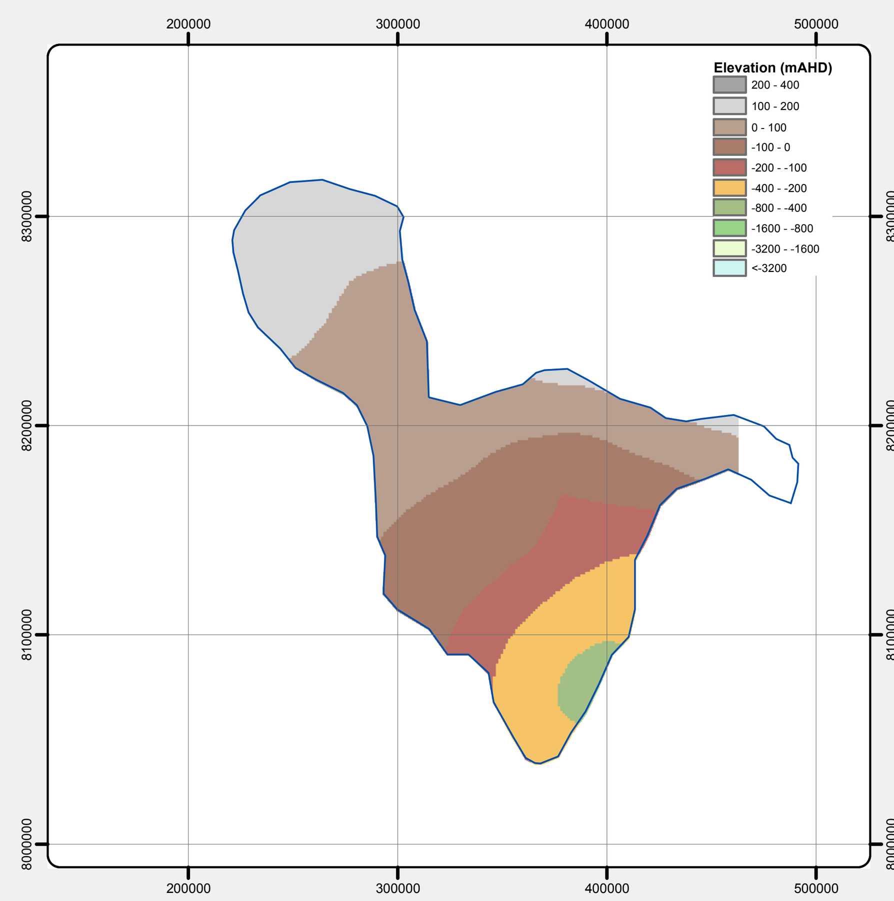


BASE OF THE CARPENTARIA BASIN

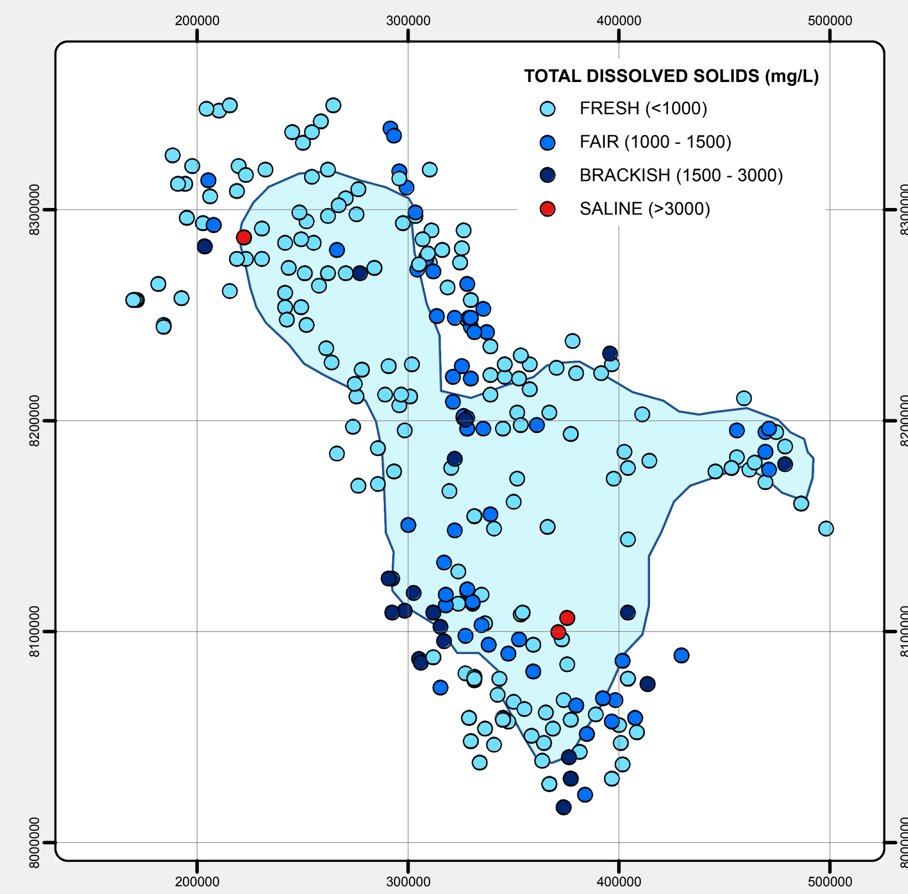


BASIN BOUNDARIES (Key Aquifers)

BASE OF THE KEY AQUIFERS

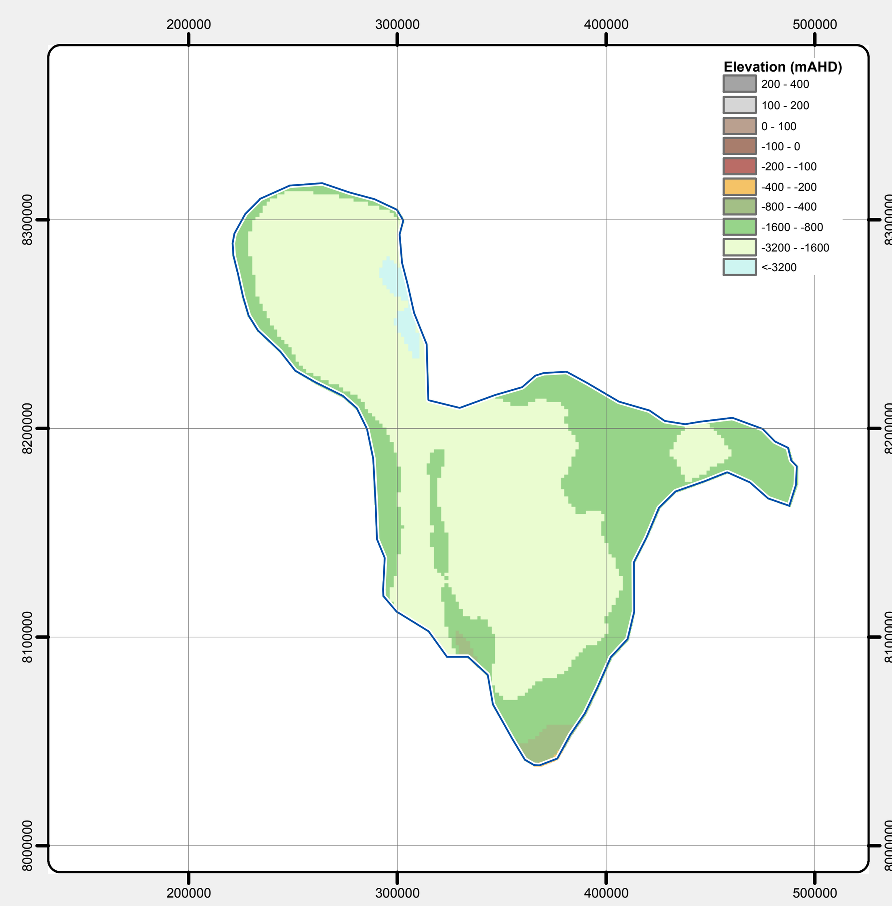


BASE OF THE LIMESTONES

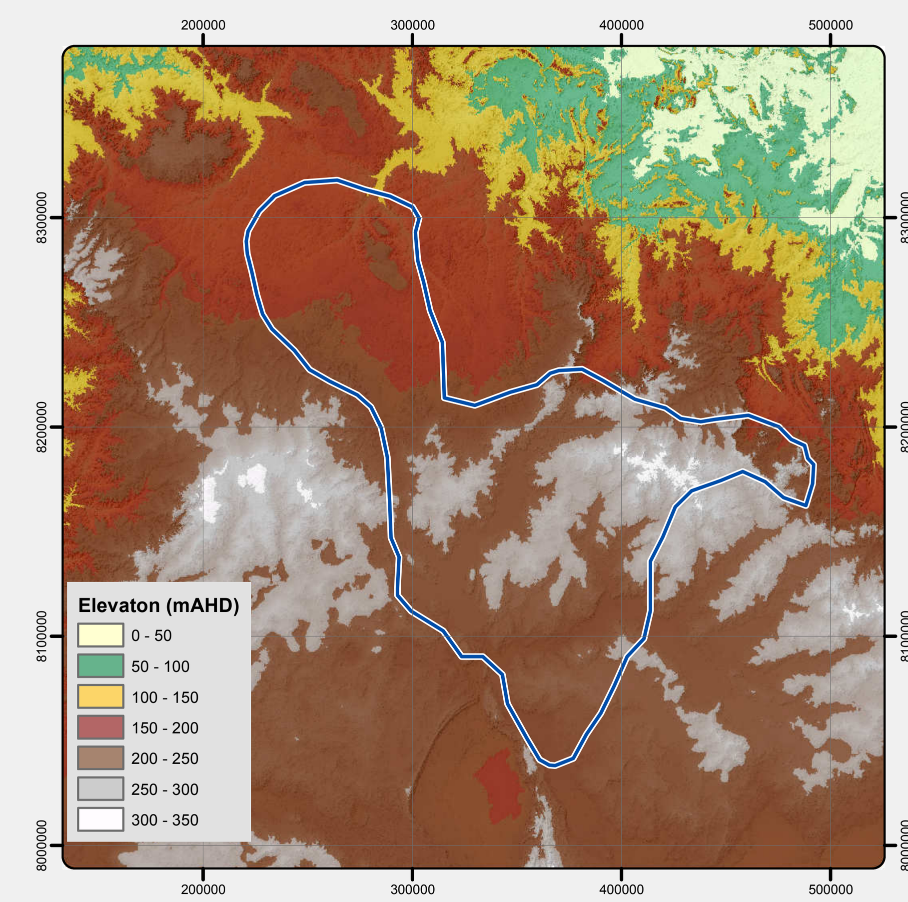


MULTIPLE AQUIFER GROUNDWATER QUALITY

BASE OF THE MOST PROSPECTIVE SHALE GAS FORMATION

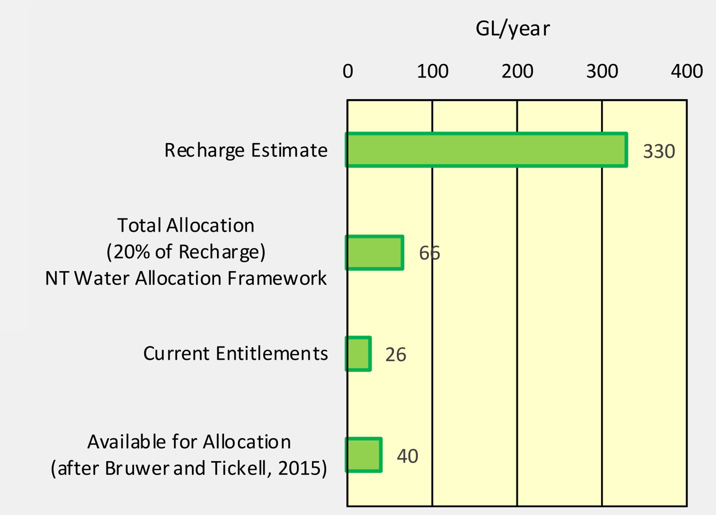


BASE OF THE VELKERRI FORMATION

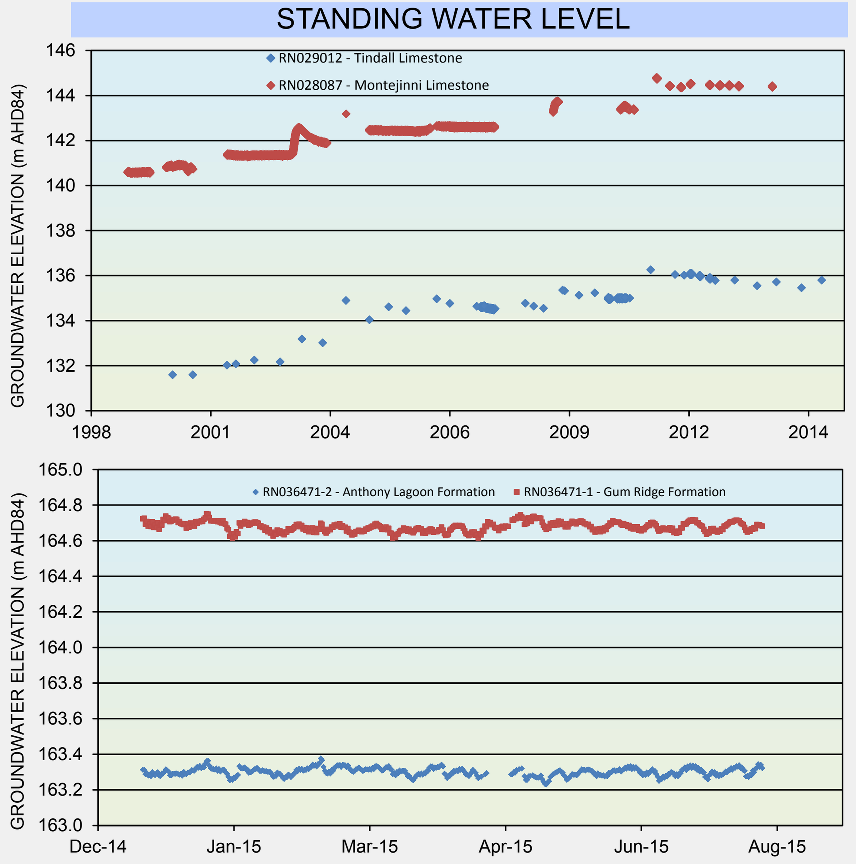


TOPOGRAPHY

NORTH MATARANKA TO DALY WATERS GROUNDWATER AVAILABILITY



STANDING WATER LEVEL



The primary map displays groundwater elevation and flow direction within the key (limestone) aquifers and aquifer types overlying the Beetaloo Sub-basin. For reference it also presents key basement highs within the Beetaloo Sub-basin referenced in the schematic section insert, those boreholes with standing water levels presented, place names (towns/domestic water supply locations), known irrigation locations, tracks, roads, railways, cadastre, drainage lines, springs, the approximate Beetaloo Sub-basin extent and a 25 km buffer.

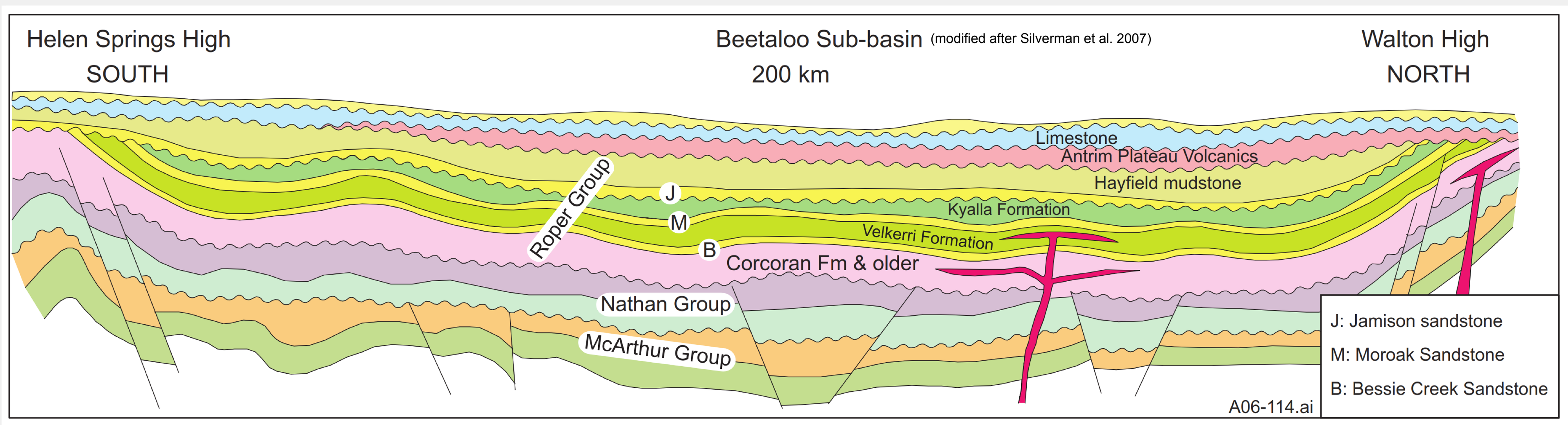
The elevation of the base of the Mesozoic Carpentaria Basin (the top if the key aquifers) is displayed in the top left sub-map. The elevation of the base of the Cambrian sedimentary basins (the Daly, Wiso and Georgina basins) and base of the key aquifers is displayed in middle left sub-map. The Middle Velkerri Formation is the most prospective unit for shale gas and the bottom left sub-map displays the elevation base of the Velkerri Formation. The Kyalla Formation is less prospective but may have potential for shale gas and liquids where it occurs at depths of more than 1000m. Cambrian sediments and volcanics overlying the Beetaloo Sub-basin occur to interpreted depths varying from 61 m to 686 m. The interpreted base of the Velkerri Formation within the Beetaloo Sub-basin varies from 394 m to 3637 m below ground level.

The top right sub-map displays the basin boundaries and key aquifers (within the Palaeozoic basins). The middle right sub-map displays the multiple aquifer groundwater quality using total dissolved solids as the key measure for quality. The bottom right sub-map displays the surface topography.

The relevant stratigraphy is present on the schematic and in tabular form with reference to the sub-maps and cross sections.

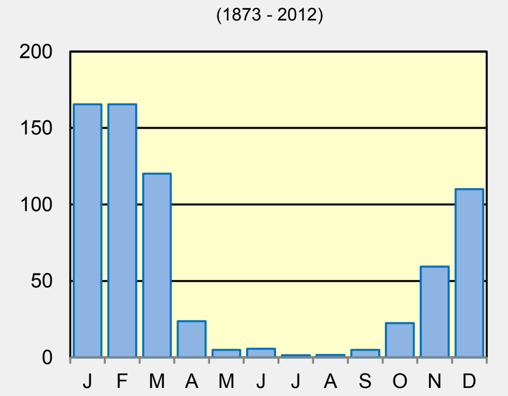
Mean monthly rainfall and evaporation are provided for Daly Waters as an example which display higher evaporation than rainfall. Seasonal rainfall results in seasonal recharge which is reflected as season increases in standing water level in the Tindall Limestone (Daly Basin) and Montijinni Limestone (Wiso Basin) hydrographs presented.

SCHEMATIC - BEETALOO SUB-BASIN CROSS SECTION



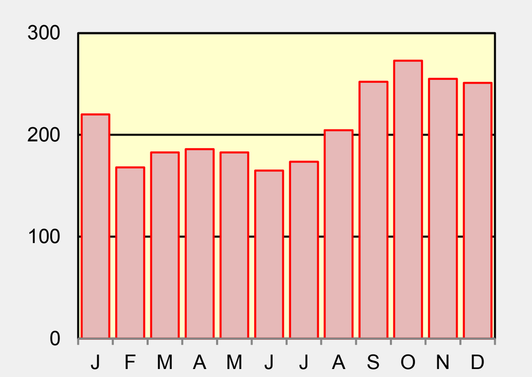
RAINFALL

DALY WATERS - MEAN MONTHLY RAINFALL (mm) (1873 - 2012)



EVAPORATION

DALY WATERS - MEAN MONTHLY EVAPORATION (mm)



N

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 53

Paper Size A1

Main Map Scale 1:750,000

0 10 20 40 60 80

Kilometers

GROUNDWATER OVERLYING THE BEETALOO SUB-BASIN

Data Sources:

Beetaloo Basin outline,"Munson TJ, 2014. Petroleum geology and potential of the onshore Northern Territory, 2014. Northern Territory Geological Survey, Report 22" Carpentaria Basin outline,"Munson TJ, 2014. Petroleum geology and potential of the onshore Northern Territory, 2014. Northern Territory Geological Survey, Report 22" "Wiso, Georgina, Daly Basins outlines","Munson TJ, 2014. Petroleum geology and potential of the onshore Northern Territory, 2014. Northern Territory Geological Survey, Report 22 Water course lines,"Geoscience Australia, 2006. GEODATA TOPO 250K Series 3 Topographic Data. Commonwealth of Australia, Canberra" Water course areas,"Geoscience Australia, 2006. GEODATA TOPO 250K Series 3 Topographic Data. Commonwealth of Australia, Canberra "Springs,"Department of Land Resource Management 2016, Northern Territory Government" Monitoring bore locations,"Department of Land Resource Management 2016, Northern Territory Government" Groundwater contours,"Tickell, S. 2014. Daly Basin Aquifers. Water Resources Division, Department of Land Resource Management." Towns,"Geoscience Australia, 2006. GEODATA TOPO 250K Series 3 Topographic Data. Commonwealth of Australia, Canberra"Railway,"Geoscience Australia, 2006. GEODATA TOPO 250K Series 3 Topographic Data. Commonwealth of Australia, Canberra"Roads,"Geoscience Australia, 2006. GEODATA TOPO 250K Series 3 Topographic Data. Commonwealth of Australia, Canberra"DEM/Topography,"CSIRO, 2010. One-second Digital Elevation Model for Australia" Ntaq 2M gw – Aquifer type,"Department of Land Resource Management 2016, Northern Territory Government"Limestone groundwater chemistry,"Department of Land Resource Management 2016, Northern Territory Government" Hydrograph data,"Department of Land Resource Management 2016, Northern Territory Government"Rainfall,Bureau of Meteorology 2016 Evaporation,Bureau of Meteorology 2016 Beetaloo Sub-Basin Cross Section,"Ahmad M and Munson TJ (compilers), 2013. Geology and mineral resources of the Northern Territory. Northern Territory Geological Survey, Special Publication 5"Base of Carpentaria, Base of Cambrian basins,Base of Beetaloo, Cadastre,"Department of Lands, Planning and the Environment 2007, Northern Territory Government"

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Document Status

Revision	Author	Reviewer		Approved for Issue		
		Name	Signature	Name	Signature	Date
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