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BIOREGIONAL ASSESSMENTS

CSIRO

Geology of the Isa GBA region

Technical appendix for the Geological and Bioregional Assessment: Stage 2

2020

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

The Geological and Bioregional Assessment Program

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

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

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Authorship is listed in relative order of contribution.

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

Cover photograph

The Burketown Bore, drilled in 1897 by the Queensland Government, is a naturally flowing bore that taps the artesian Gilbert River Formation aquifer at a depth of about 700 m below surface. Groundwater within this aquifer naturally contains a variety of dissolved chemical compounds that have deposited around the bore as the hot water (around 68 °C) has evaporated over the years, leading to the formation of a distinctive multi-coloured mound.

Credit: Steven Lewis, July 2018 Element: GBA-ISA-2-264

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Executive summary

This appendix reviews the geological setting, tectonic evolution, depositional environments and structural and stratigraphic framework of the Isa GBA region, part of the geological Isa Superbasin.

The Isa Superbasin is a Paleoproterozoic to earliest Mesoproterozoic superbasin, identified and described in Queensland from surface outcrop exposed on the Mount Isa Inlier and subcrop mapped from well and seismic data across the northern Lawn Hill Platform. Although the full extent of the Isa Superbasin remains undefined, its sequences extend under cover for potentially several hundred kilometres and they have been identified in the McArthur Basin in the NT.

The Isa GBA region is located over the northern Lawn Hill Platform, a relatively undeformed structural element of the superbasin where petroleum exploration has confirmed shale gas resource potential (Section 1). The Isa GBA region extents are based on both the availability of subsurface (well and seismic) data required for the shale gas resource assessment and geological criteria, such as where the sedimentary fill becomes deformed or exhumed, representing the limit of potentially prospective shale gas resources. To the west and south-west of the Isa GBA region, a broader region has been identified which may contain undeformed Isa Superbasin rocks, including organic-rich petroleum source rocks. However, this region currently has insufficient data available for inclusion in this assessment.

A review of existing open file geological, petroleum and environmental data and information was conducted for the Isa GBA region (Section 2). These include geographic and cultural datasets, detailing the location and nature of administrative boundaries, infrastructure and topography; and geological datasets such as surface geology, well and seismic data and other geophysical datasets. A range of public domain publications, reports and data packages for the Isa GBA region are also used to characterise the basin architecture and evolution.

Section 3 reviews the Isa Superbasin's geological setting and tectonostratigraphic evolution. The Isa Superbasin is considered to be part of the Archean to Paleoproterozoic North Australian Craton and overlies the Paleoproterozoic Leichhardt and Calvert superbasins. Isa Superbasin deposition began ca 1670 Ma and ended with the onset of the Middle Isan Orogeny at ca 1575 Ma. In the Isa GBA region, the Isa Superbasin succession comprises second-order supersequences (Gun, Loretta, River, Term, Lawn, Wide and Doom). The sediments include fluvial, coastal and shallow marine sandstone facies, to shallow and deep marine carbonate successions and deep water shale or fan facies. Shale gas intervals begin from the base of the River Supersequence in the Isa Superbasin and are associated with carbonaceous shales deposited as part of highstand systems tracts in anaerobic marine conditions. The Isa Superbasin succession in the Isa GBA region was not subjected to the full impact of the Isan Orogeny but it has been variably affected by Proterozoic hydrothermal activity.

The Isa Superbasin is directly overlain in the Isa GBA region by fluvial and shallow marine sediments of the Mesoproterozoic South Nicholson Basin and in the east by fluvial and marine sediments of both the Mesozoic Carpentaria Basin and Cenozoic Karumba Basin. Interpreted

erosion events occurred during the middle to late Mesoproterozoic, Carboniferous to Permian and after the mid-Cretaceous period. No mid-Mesoproterozoic to mid-Mesozoic rocks are preserved in the region.

A more detailed account of the structural and stratigraphic framework of Isa Superbasin and overlying basins in the Isa GBA region is in Section 4. Seismic interpretation was used to describe the region's major structural elements and a solid geology map was created delineating the maximum extent of the South Nicholson Basin and Isa Superbasin supersequences where they either outcrop at the surface or subcrop beneath the Carpentaria and Karumba basins. Three-dimensional depth-converted structure and isochore maps for key stratigraphic horizons of the Isa Superbasin, South Nicholson Basin, Carpentaria Basin and Karumba Basin further highlight key aspects of the Isa GBA region's structural architecture (Bradshaw et al., 2018c, 2018a). These maps show that sediment thickness varies from less than 1 km over a basement (i.e. pre-Isa Superbasin rocks) high in the north to approximately 9 km in the south.

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This technical product was reviewed by several groups:

- Internal Peer Review Group:
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- Technical Peer Review Group: Peter McCabe
- State Government Science Technical Review: This group includes scientists from the Queensland Government

Valuable comments were also provided by Justin Gorton, Laurie Hutton, Alison Troup (Geological Survey of Queensland) and Andrew Stacey (Department of the Environment and Energy)

Abbreviations and acronyms

Abbreviation/acronym	Definition
AGSO	Australian Geological Survey Organisation
AHD	Australian Height Datum
Ar/Ar	argon/argon
BMR	Bureau of Mineral Resources
ca	circa
C.I.	contour interval
DEM	digital elevation model
DW	deviated well
GAB	Great Artesian Basin
GBA	Geological and Bioregional Assessment
GIS	geographic information system
K-Ar	potassium-argon
Ma	millions of years before the present
mAHD	metres with respect to the Australian Height Datum
m MSL	metres with respect to mean sea level
MSL	mean sea level
My	million years
NABRE	North Australian Basins Resource Evaluation
NT	Northern Territory
NWQMEP	North-West Queensland Mineral and Energy Province
Qld	Queensland
QPED	Queensland Petroleum Exploration Data
SEEBASE®	Structurally Enhanced view of Economic BASEment
SHRIMP	Sensitive High-Resolution Ion Microprobe
TMI	total magnetic intensity
U-Pb	uranium-lead

Units

Unit	Description
Ma	millions of years before the present
MPa	megapascals
mW/m^2	milliwatts per square metre

The Geological and Bioregional Assessment Program

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

In consultation with state and territory governments and industry, three geological basins were selected based on prioritisation and ranking in Stage 1: Cooper Basin, Isa Superbasin and Beetaloo Sub-basin. In Stage 2, geological, hydrological and ecological data were used to define 'GBA regions': the Cooper GBA region in Queensland, SA and NSW; the Isa GBA region in Queensland; and the Beetaloo GBA region in NT.

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

The Program aims to:

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

The Program commenced in July 2017 and comprises three stages:

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

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

About this report

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

Technical appendices

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

- Bailey AHE, Bradshaw BE, Palu TJ, Wang L, Jarrett AJM, Orr ML, Hall LS, Evenden C, Skeers N, Woods M, Dehelean A and Hall LS (2020) Shale gas prospectivity of the Isa GBA region.
- Buchanan S, Dixon-Jain P, Martinez J, Raiber M, Kumar PR, Woods M, Arnold D, Dehelean A and Skeers N (2020) Hydrogeology and groundwater systems of the Isa GBA region.
- MacFarlane CM, Herr A, Merrin LE, O'Grady AP and Pavey C (2020) Protected matters for the Isa GBA region.
- Kear J and Kasperczyk D (2020) Hydraulic fracturing and well integrity review for the GBA regions.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D and Kookana R (2020) Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Isa GBA region.

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

1 Introduction

The Isa Superbasin is a Paleoproterozoic to earliest Mesoproterozoic superbasin (approximately 1670 to 1575 Ma), identified and described in north-west Queensland and the Northern Territory. The full spatial extent of the Isa Superbasin remains undefined, so is not shown on maps in this report. However, the superbasin likely extends under cover for potentially several hundred kilometres from the Isa GBA region into the NT. The superbasin is part of the North Australian Craton, which is distributed across the northern parts of WA, the NT and Queensland.

This study focuses on the Isa GBA region, the area of the Isa Superbasin in north-west Queensland containing identified shale gas plays, where future development of these resources could result in delivery of gas to the East Coast Gas Market within five to ten years. Geological data are sufficient to enable a baseline assessment to be undertaken (Table 1).

This technical appendix reviews the geological setting, tectonic evolution, depositional environments and structural and stratigraphic framework of the Isa GBA region. It provides a conceptual framework required for the shale gas prospectivity assessment outlined in the petroleum prospectivity technical appendix (Bailey et al., 2020) and the analyses of hydrostratigraphy and groundwater connectivity in the hydrogeology technical appendix (Buchanan et al., 2020).

Table 1 Geological summary table for the Isa Superbasin

Jurisdiction		Queensland, Northern Territory
Area (km²)		Undefined (>56,000 km²)
Maximum sediment thickness		~15,000 m
Age range		Paleoproterozoic–Mesoproterozoic (ca 1670 to 1575 Ma)
Basin	**Overlies**	Calvert Superbasin, Leichhardt Superbasin
	Underlies	South Nicholson Basin, Georgina Basin, Carpentaria Basin, Karumba Basin (in Queensland)
	Adjacent basins	McArthur Basin
Basin type		Intracratonic superbasin
Depositional setting		Fluvial, coastal, shallow marine, deep marine
Regional structure		Extensional, strike-slip and compressional events producing fault-bounded depocentres, inversion anticlines and thrust faults
Seismic line km		1,141 km of two-dimensional seismic reflection data
Number of petroleum wells		14 vertical, 1 horizontal (in/near Isa GBA region)

Number of petroleum wells above includes the stratigraphic wells BMR Westmoreland 1 and BMR Westmoreland 2; and the proximal Lawn Hill DDH 83-1, Lawn Hill DDH 83-2 and Lawn Hill DDH 83-5 wells located outside of the Isa GBA region. The petroleum exploration well Armraynald 1, located outside of the Isa GBA region, did not penetrate the Isa Superbasin succession and is not included in the total. See Figure 9 for well locations.

1.1 Aims and rationale of this appendix

A sound scientific understanding of a region's geology ideally underpins decisions on unconventional petroleum resource development. This appendix provides a geological review of the Isa GBA region and analyses relevant to understanding its structural and stratigraphic characteristics.

This assessment of the Isa Superbasin has been undertaken before the full spatial extents of the superbasin have been defined. Consequently, this review focusses on the Isa GBA region as the most likely part of the Isa Superbasin for future shale gas development, but places it in the context of the broader superbasin and highlights geological factors which underpin its relative prospectivity.

This appendix collates the current geological knowledge of the Isa GBA region relevant to the depositional and post-depositional history of the sedimentary rocks, and to the stratigraphic and structural framework of the region. It begins with an inventory of datasets broadly relevant to the assessment in Section 2. The rationale for the information provided in the regional geology (Section 3) and structural and stratigraphic framework (Section 4) sections is given below.

Several geological factors affect assessments of hydrocarbon prospectivity, groundwater distribution and aquifer connectivity. Many of these are controlled by the depositional and post-depositional history of the rocks. The depositional environment of shales has a direct influence on the type and amount of organic matter they contain, and hence their potential as source rocks for hydrocarbons. Depositional environments also influence the capacity of sedimentary rocks to hold hydrocarbons (as reservoirs) or water (as aquifers). Section 3.4 summarises the current geological knowledge of the depositional environments of the rocks within the Isa GBA region. A Proterozoic to Cenozoic stratigraphic chart, presented in Section 3.4, was compiled from published sources but further developed to integrate lithostratigraphy and hydrostratigraphy.

The post-depositional thermal evolution of the source rocks governs the generation of unconventional hydrocarbons. Basins are not timeless and static: thermal evolution is influenced by burial, uplift, erosion and hydrothermal activity in the basin over prolonged geological time frames. Temperature changes and generation of hydrocarbons may have occurred in any period since deposition of the organic-rich sediments: in the case of the Isa Superbasin's organic-rich rocks, this could have been at several intervals in the last 1.6 billion years. Section 3.3 reviews the tectonic evolution of the Isa GBA region and surrounds, including interpreted tectonothermal events. The information provides the background for the interpreted timing of hydrocarbon generation and for the burial and thermal history modelling component of the prospectivity technical appendix (Bailey et al., 2020).

Tectonic evolution affects also the degree of fracture porosity in indurated sedimentary rocks and strata displacements in fault systems, which can promote groundwater connectivity (Buchanan et al., 2020). Secondary porosity produced by fracturing, and structural offsets produced by faulting, can enhance connectivity between intervals and potentially permit inter-formational groundwater flow (Buchanan et al., 2020). The timing, distribution and degree of tectonic deformation is summarised in Section 3.3 to the current extent of knowledge, and further analysed in the context of the structural and stratigraphic framework in Section 4.

The structural and stratigraphic framework of the Isa GBA region is captured in Section 4 by a three-dimensional geological model created for the assessment. Three-dimensional depth and isochore maps for key Proterozoic and Phanerozoic stratigraphic horizons, based on the methods explained by Bradshaw et al. (2018c), and fault zone architecture are included in this section and available as a dataset (Bradshaw et al., 2018b). These are used to produce the conceptual models of hydrogeological connectivity presented in the hydrogeology technical appendix (Buchanan et al., 2020). In addition, the input parameter maps for the play fairway presence maps presented in the prospectivity technical appendix (Bailey et al., 2020) use the mapped depths and thicknesses of key stratigraphic horizons presented in Section 4.

1.2 Isa GBA region

The Isa GBA region is on the northern Lawn Hill Platform of the Isa Superbasin, where industry exploration for shale gas resources has previously occurred (Bailey et al., 2020). The data constraints in the broader frontier Isa Superbasin region currently preclude petroleum prospectivity assessments beyond the northern Lawn Hill Platform.

The Isa GBA region extents shown in Figure 1 are constrained by the following geological criteria and data considerations:

- the maximum extent of preserved and relatively continuous sedimentary deposits associated with the northern Lawn Hill Platform
- the limit for potentially prospective shale gas resources, defined where the sedimentary fill becomes extensively folded and faulted, with the potential shale gas intervals either brought closer to the surface, exhumed as outcrop or eroded
- the limit of available subsurface (well and seismic) data required as the basis for the assessment of shale gas resources
- the edge of sedimentary fill as mapped by the Geological Survey of Queensland, where seismic data coverage is insufficient for the interpretation of sedimentary deposit extents and deformation.

The northern boundary of the Isa GBA region represents the maximum extent of preserved and relatively continuous superbasin sediments. In the northern Lawn Hill Platform, the Isa Superbasin succession thins and onlaps a basement high in the north. Seismic data, of variable quantity and quality, are used to define the preserved limits of the Isa Superbasin here, based on interpretations presented in Bradshaw and Scott (1999) and further refined using the North West Queensland SEEBASE® grid (Frogtech Geoscience, 2018a) and Bradshaw et al. (2018c). In the north-west, the Isa Superbasin boundary represents the mapped outcrop limit.

The western boundary of the Isa GBA region marks the limit of available subsurface (well and seismic) data required for the shale gas prospectivity assessment. The eastern extent of the region is based on the Isa Superbasin edge mapped by the Geological Survey of Queensland (Geological Survey of Queensland, 2011b) due to the lack of seismic data coverage in this area.

The southern Isa GBA region boundary is defined where the Isa Superbasin sedimentary fill becomes extensively folded and faulted. As many of the potential shale gas intervals are either exhumed or outcrop at the surface, this boundary is interpreted to be the southern limit of potentially prospective shale gas resources. Key information used to map the southern boundary include the North West Queensland SEEBASE® grid (Frogtech Geoscience, 2018a) and interpretation of available seismic datasets.

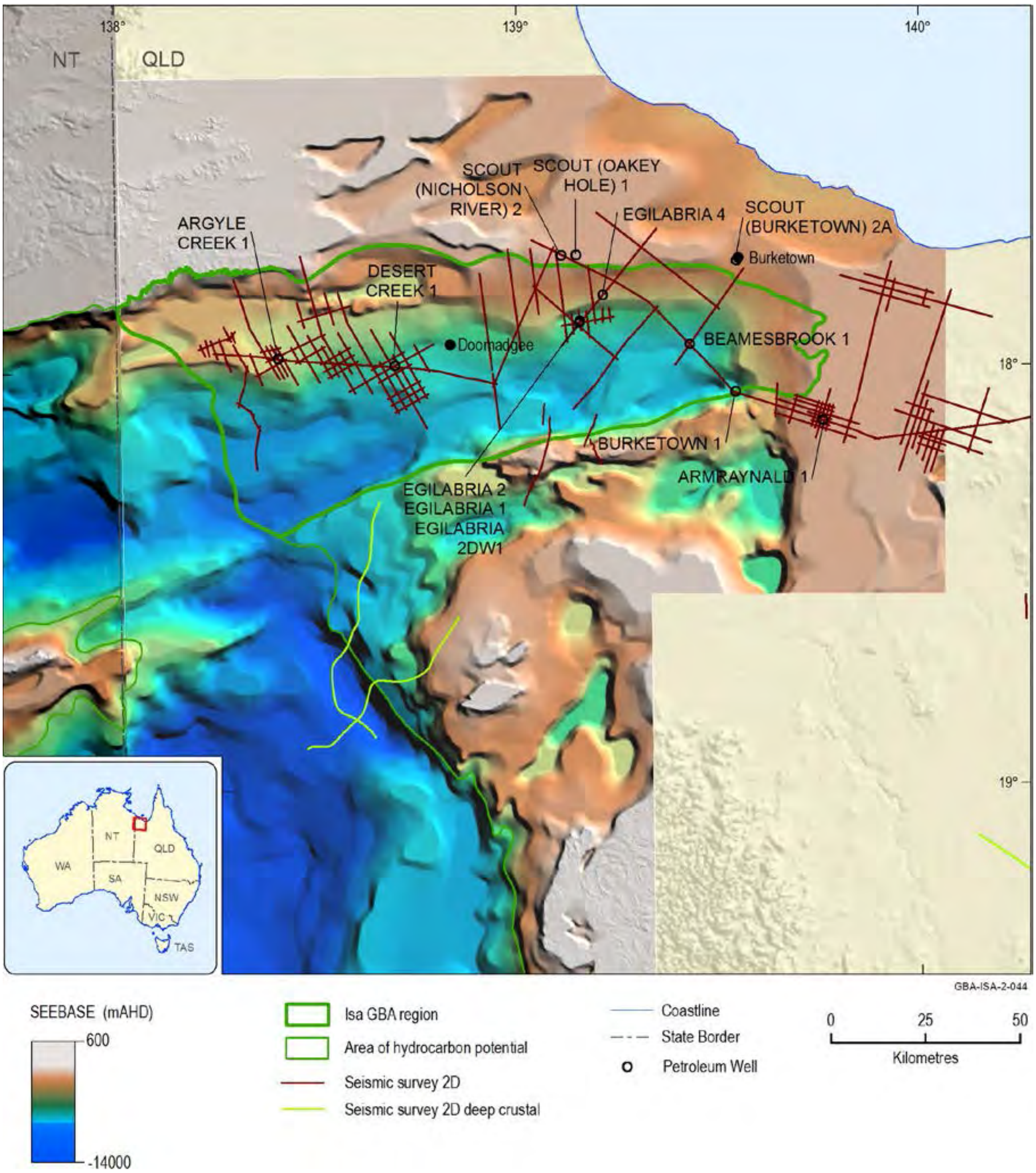


Figure 1 Isa GBA region in the northern Lawn Hill Platform superimposed over Frogtech Geoscience's SEEBASE® depth to basement image

Data: Queensland SEEBASE® image sourced from Frogtech Geoscience (2018a); NT SEEBASE® image sourced from Frogtech Geoscience (2018b); two-dimensional seismic survey line locations from Department of Natural Resources (2017b), deep crustal seismic line locations from Department of Natural Resources (2017c), petroleum well locations from Department of Natural Resources (2017a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-044

1.3 Broader area of hydrocarbon potential

The Isa Superbasin extends beyond the limits of the Isa GBA region. The Isa Superbasin strata are either known or inferred to extend to the south and west of the Isa GBA region beneath the younger Karumba, Carpentaria, Georgina and South Nicholson basins (Figure 2) and this succession has the potential to contain organic-rich source rocks. Although other areas of the superbasin may be prospective for shale gas resources, there is presently insufficient data coverage outside the region to undertake meaningful analysis for the purposes of this assessment.

Isa Superbasin rocks in some areas outside the Isa GBA region are deformed and variably metamorphosed due to post-depositional tectonic events. These deformational events have constrained the likely extent of any petroleum system to the basin sequences that overlie basement terranes resistant to deformation. A region west and south-west of the Isa GBA region (Figure 3) has been identified that may contain undeformed Isa Superbasin sediments, including organic-rich petroleum source rocks, although it has insufficient data available for assessment (at the time that this review was undertaken). This region is delineated based on the modelled depth to basement in the North West Queensland SEEBASE® grid (Frogtech Geoscience, 2018a), which indicates the Isa Superbasin may be present in this region. Supporting evidence for the presence of strata of this age comes from the Lawn Hill DDH 83-2 (Amoco 83/2) and Morstone 1 (Figure 3) well data. In addition, seismic data interpretation by Gibson et al. (2016) show that relatively undeformed superbasin strata may be present along the eastern margin of this area (Figure 3; Figure 4).

This broader area of hydrocarbon potential is currently under investigation by Geoscience Australia as part of the Exploring for the Future Program, which aims to understand the extent of Proterozoic sedimentary basins in the region (Henson et al., 2018). Although new seismic data were acquired over the southern area of hydrocarbon potential in late 2017, interpretations were not available at the time of this assessment. Publication of the L210 South Nicholson Deep Crustal Seismic Reflection Survey data interpretation is expected in 2020.

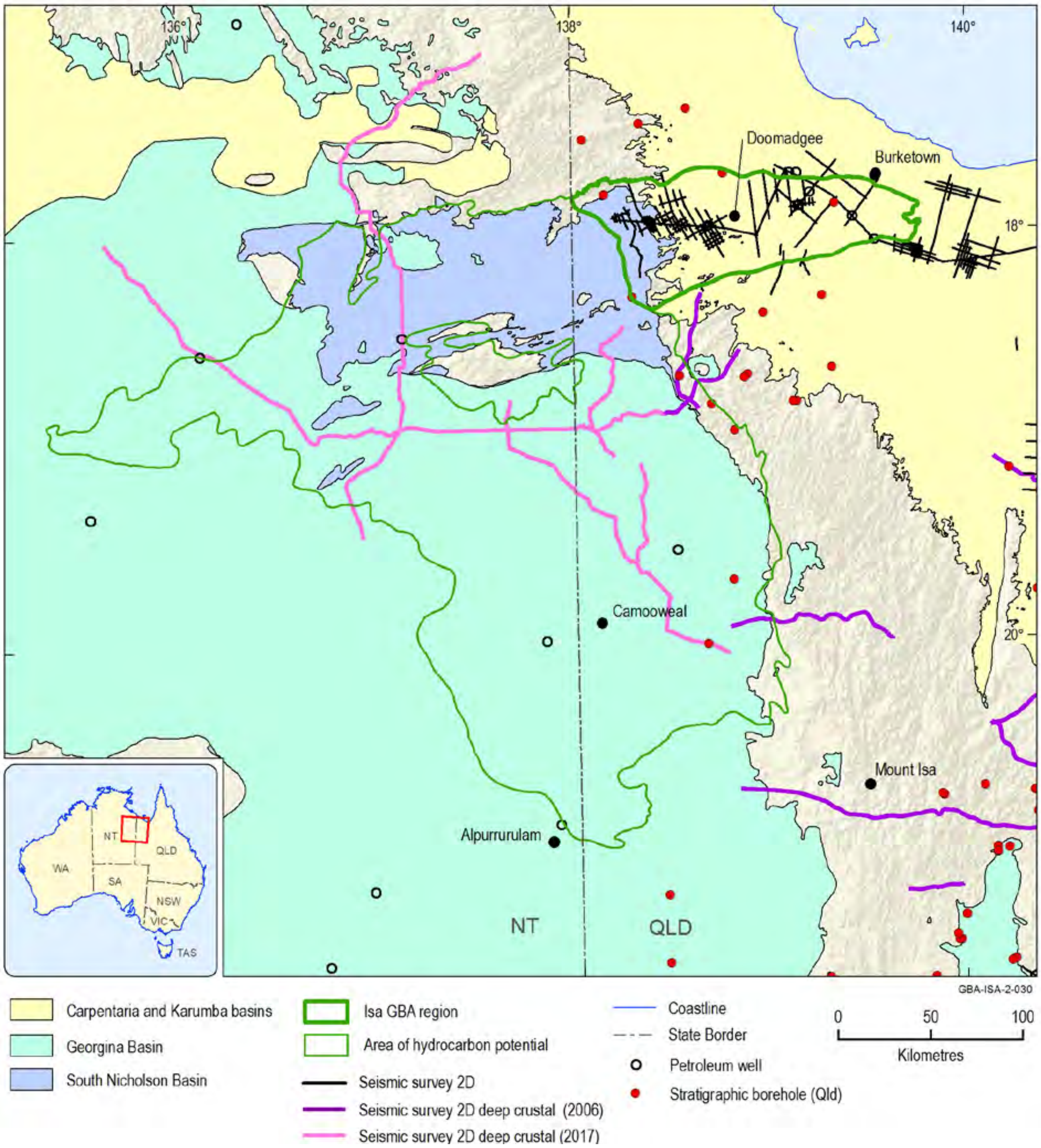


Figure 2 Area of hydrocarbon potential surrounding the Isa GBA region, and simplified extents of overlying basins

Data: Carpentaria Basin distribution from Ransley et al. (2015) and Department of Primary Industry and Resources (NT) (2018b), Georgina and South Nicholson basins distribution from Raymond et al. (2018), Queensland two-dimensional seismic survey line locations from Department of Natural Resources (2017b), deep crustal seismic line locations (2006) from Department of Natural Resources (2017c), deep crustal seismic line locations (2017) from Frogtech Geoscience (2018a), Queensland well and borehole locations from Department of Natural Resources (2017a), NT petroleum well locations from Department of Primary Industry and Resources (NT) (2018a), Isa GBA region and area of hydrocarbon potential outlines from Geological and Bioregional Assessment Program (2018). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-030

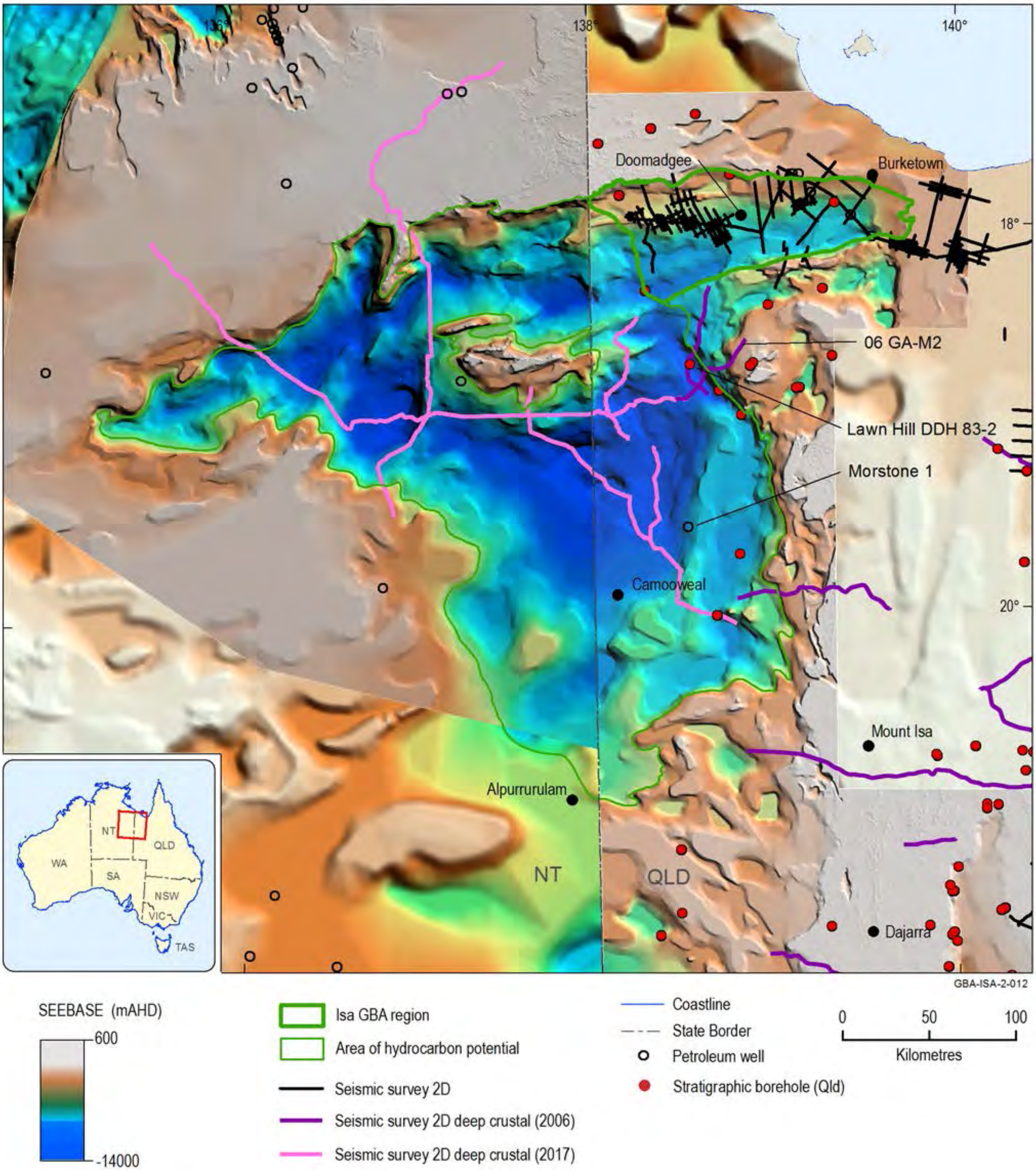


Figure 3 Area of hydrocarbon potential for shale gas resources surrounding the Isa GBA region superimposed over Frogtech Geoscience's SEEBASE® depth to basement image

Data: SEEBASE® image from Frogtech Geoscience (2018a) and Frogtech Geoscience (2018b), Queensland two-dimensional seismic survey line locations from Department of Natural Resources (2017b), deep crustal seismic line locations (2006) from Department of Natural Resources (2017c), deep crustal seismic line locations (2017) from Frogtech Geoscience (2018a), Queensland well and borehole locations from Department of Natural Resources (2017a), NT petroleum well locations from Department of Primary Industry and Resources (NT) (2018a), Isa GBA region and area of hydrocarbon potential outlines from Geological and Bioregional Assessment Program (2018)
Element: GBA-ISA-2-012

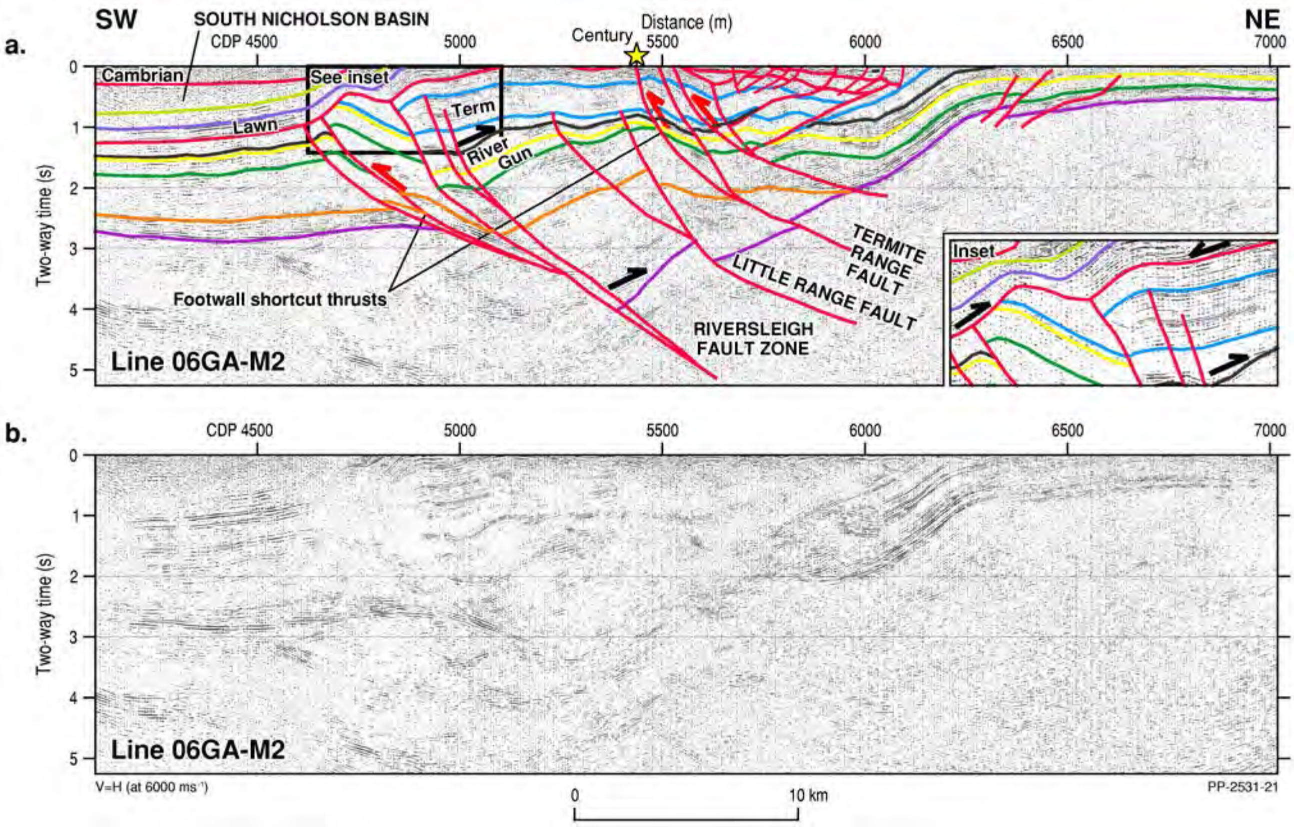


Figure 4 Interpreted and uninterpreted images of seismic section 06GA-M2 over the north-eastern margin of the area of hydrocarbon potential shown in two-way time

Location of line 06GA-M2 is shown in Figure 3. Interpreted horizons (coloured lines) include the base Isa Superbasin (green, base of Gun Supersequence), the Isa Superbasin top Gun Supersequence (yellow), top River Supersequence (black), Term Supersequence phases (blue) and base Lawn Supersequence (crimson), below the South Nicholson Basin and Cambrian sedimentary rocks (see Section 3 for an explanation of these terms). Also shown is the position of the Century base metal mine adjacent to seismic line 06GA-M2.

Source: Gibson et al. (2016)

Element: GBA-ISA-2-111

2 Data inventory

2.1 Introduction

This section reviews the available geological and petroleum data and information for the Isa GBA region. The datasets considered as part of this assessment are limited to those in the public domain and considered by the authors as fit for purpose as of October 2018.

2.2 Culture, hydrography and relief

2.2.1 Administrative boundaries and infrastructure

Administrative boundaries, centres of population and infrastructure such as road and rail (Figure 5) shown on maps created for the Isa GBA were sourced from the GEODATA TOPO 250K Series 3 dataset (Geoscience Australia, 2017). The dataset is a vector representation of the major features appearing on 1:250,000 scale NATMAPs in Shape file format

The National Oil and Gas Infrastructure datasets (Petrosys Pty Ltd, 2019) present the spatial locations of onshore pipelines for the transmission of oil and gas within mainland Australia. They also present the location of oil and gas infrastructure facilities for the extraction, processing and/or storage of oil and natural gas. The construction of a new 622 km gas pipeline (Northern Gas Pipeline) (Figure 5) connecting Tennant Creek in the Northern Territory to Mount Isa in Queensland was completed in 2018 and is now operational. There are currently no oil or gas processing facilities in the Isa GBA region or surrounds.

2.2.2 Topographic and remote sensing data

Remotely sensed radiometric, satellite and photographic data have been used in previous studies (Geological Survey of Queensland, 2011a) to understand the surface geology of the Isa Superbasin. These data have also been used for the mapping and assessment of surface geomorphology and soils, which are useful for an assessment of environmental risks of gas extraction.

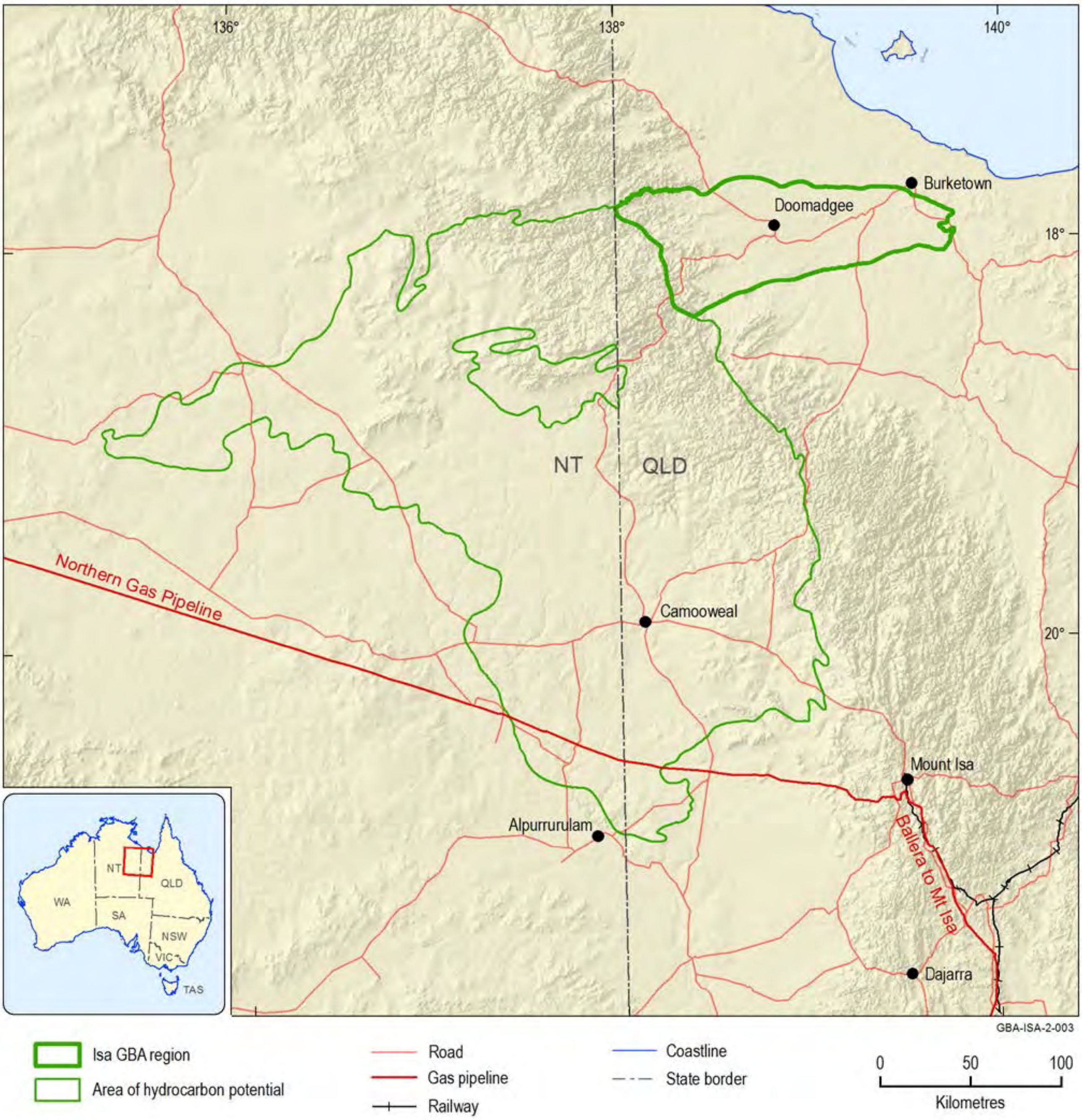


Figure 5 Administrative boundaries, road infrastructure and gas pipelines

Data: GEODATA TOPO 250K Series 3 dataset (Geoscience Australia, 2017), pipeline from GPInfo by Petrosys Pty Ltd (2019), Isa GBA region and area of hydrocarbon potential outlines from Geological and Bioregional Assessment Program (2018). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-003

2.2.2.1 Digital elevation data

The GEODATA 9-second digital elevation model (DEM-9S) Version 3 is a grid of ground level elevation points covering the whole of Australia with a grid spacing of 9 arc-seconds in longitude and latitude (approximately 250 metres) in the GDA94 coordinate system (Figure 6) (Hutchinson et al., 2008). This is the best available open access topography data for the Isa GBA region.

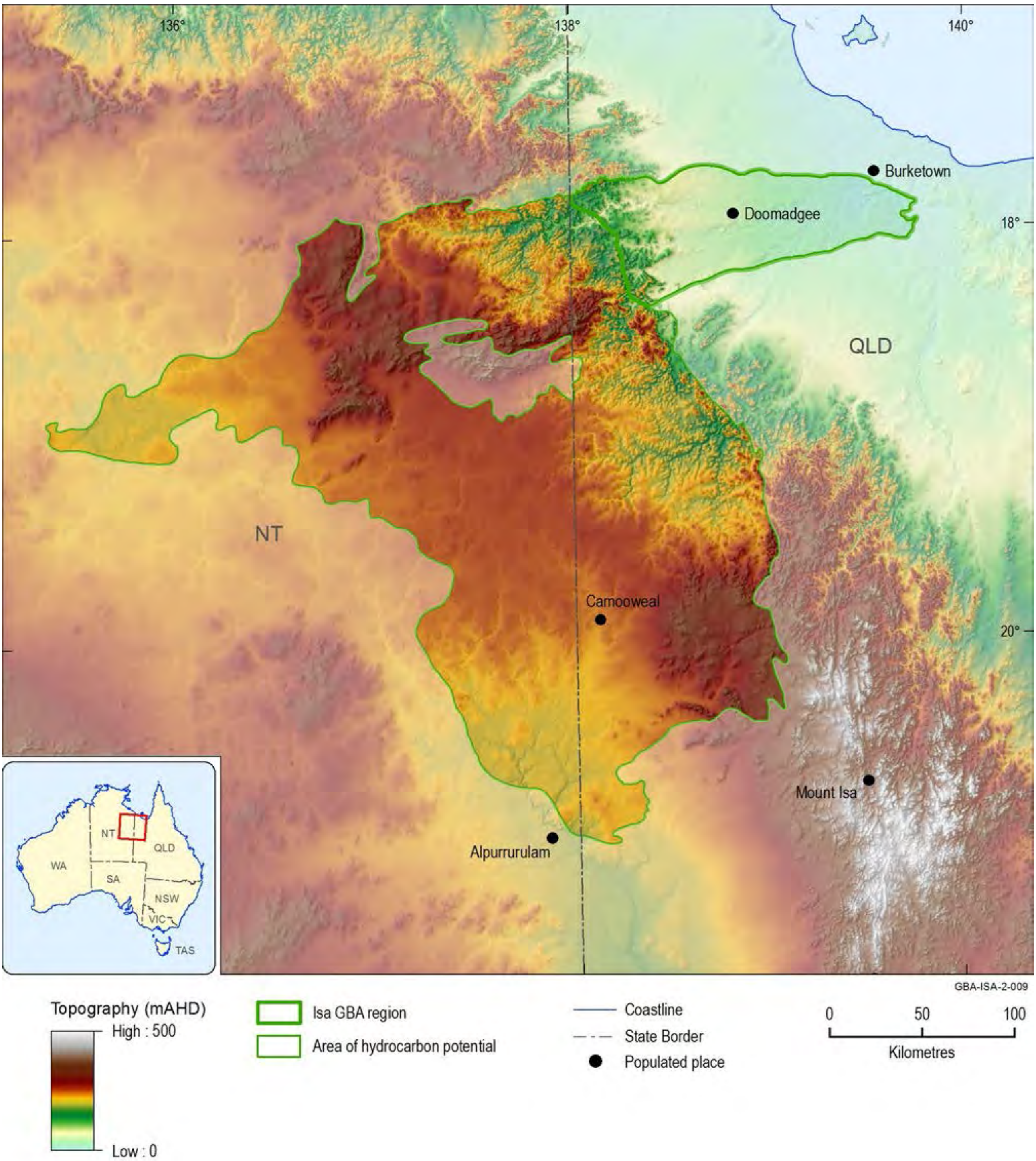


Figure 6 Isa GBA regional surface topography

Data: GEODATA 9 second DEM and D8 (Hutchinson et al., 2008), Isa GBA region and area of hydrocarbon potential outlines from Geological and Bioregional Assessment Program (2018)
Element: GBA-ISA-2-009

2.2.2.2 Remote sensing data

The North West Queensland Mineral and Energy Province study revised the Mount Isa Inlier surface geology with the aid of remote sensing datasets, including aerial photography, Landsat and ASTER satellite data, new field observations, SHRIMP U-Pb zircon geochronology and seismic, potential field and radiometric data (Geological Survey of Queensland, 2011b).

Airborne radiometric and magnetic surveys have been flown with maximum line separation of 400 m over north-western Queensland (Figure 12). Radiometric techniques measure the amount of gamma ray radiation emitted from the decay of potassium, thorium and uranium isotopes in the upper 30 cm (approximate) of the surface regolith and is used for surface geological and regolith mapping, as well as to trace sediment pathways in the landscape. Imaged radiometrics and other remote sensing datasets of north-west Queensland are provided in a GIS dataset associated with this study—see the hydrogeology technical appendix (Buchanan et al., 2020).

Remote sensing data in the form of airborne magnetic datasets are discussed in Section 2.3.4.3.

2.3 Geological datasets

This data inventory describes the geological datasets relevant to basin evaluation, shale gas prospectivity assessment and hydrogeology of the Isa GBA region.

2.3.1 Surface geology

The surface geology maps used in this study are sourced from the Surface Geology of Australia 1:1,000,000 scale dataset, 2012 edition (Figure 7) (Raymond et al., 2012b), or 1:2,500,000 scale dataset, 2012 edition (Raymond et al., 2012a). These are seamless national coverages of outcrop and surficial geology, which show areas of outcropping bedrock geology and unconsolidated, or poorly consolidated, regolith. Geological units are represented as polygons and lines, and are attributed with information regarding stratigraphic nomenclature and hierarchy, age, lithology and primary data source. The dataset also contains geological contacts, structural features such as faults and shear zones, and miscellaneous features such as the boundaries of surface water bodies.

Figure 8 presents the index of the spatial extents of scanned images of all 1:250,000 scale geological maps of Australia from Geoscience Australia's Web Map Service (Geoscience Australia, 2016). The service contains information on the edition, publication date and map publisher, and has links to map images.

2.3.2 Geological provinces

Geological province boundaries, including sedimentary basin outlines, are sourced from the Australian Geological Provinces dataset (Raymond et al., 2018). The Isa Superbasin boundary has yet to be formally identified (see Section 1), so is not currently defined within the database.

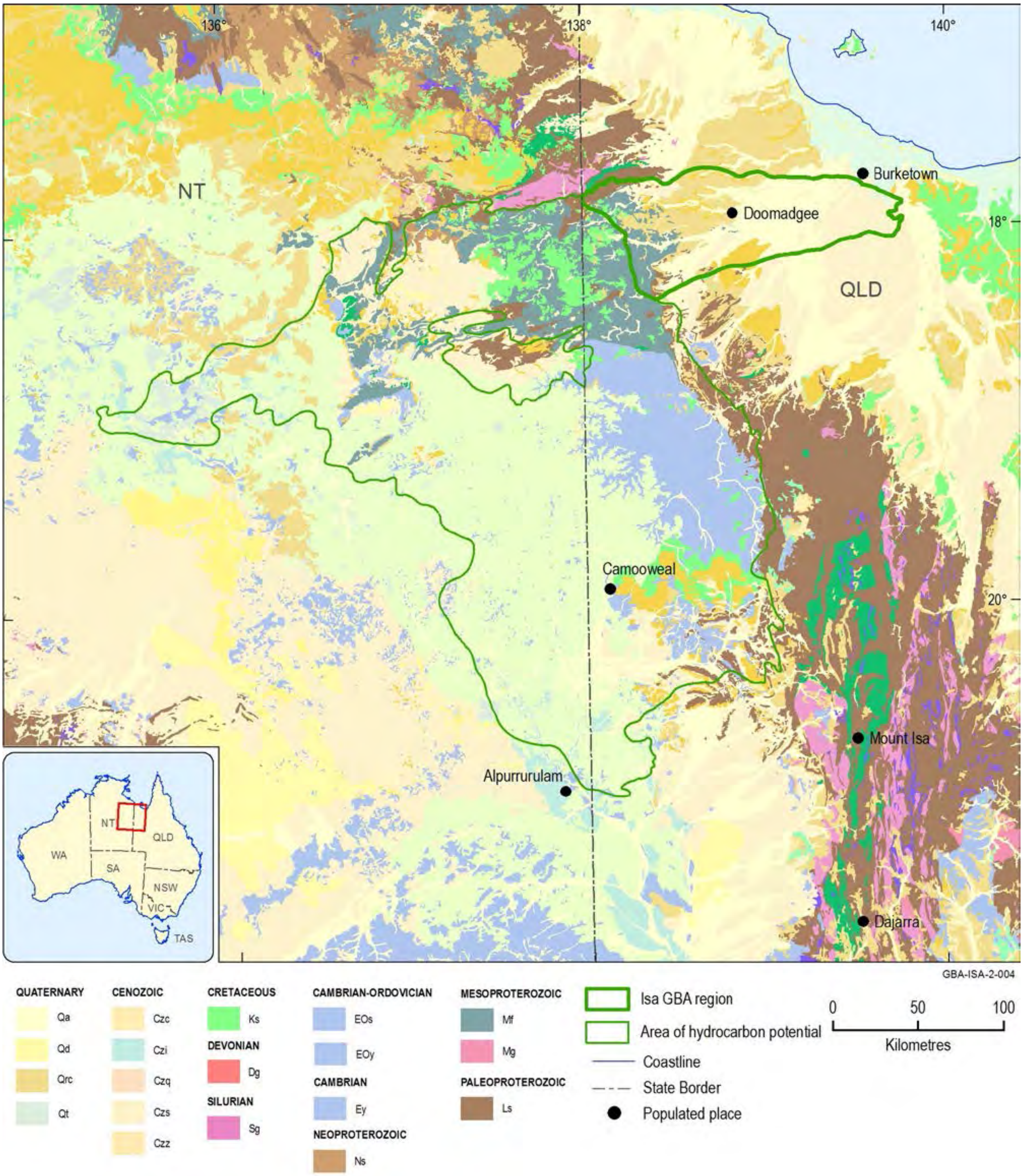


Figure 7 Isa GBA region surface geology derived from the 1:1,000,000 scale dataset

Data: Surface Geology of Australia 1:1 million scale dataset 2012 edition (Raymond et al., 2012b), Isa GBA region and area of hydrocarbon potential outlines from Geological and Bioregional Assessment Program (2018)
Element: GBA-ISA-2-004

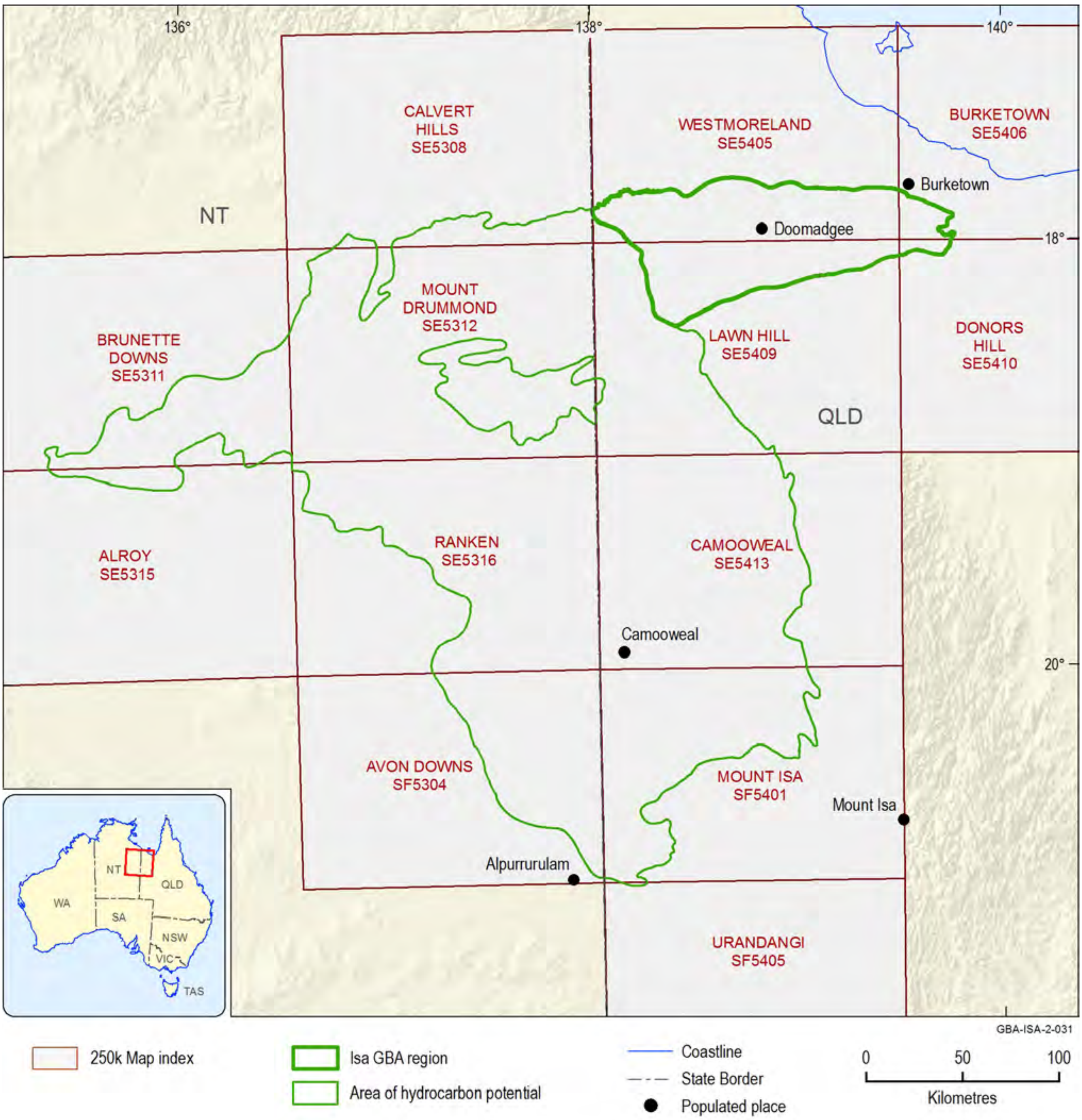


Figure 8 Index of the scanned 1:250,000 scale geological map sheets

Data: Scanned 250K geological map index (Geoscience Australia, 2016), Isa GBA region and area of hydrocarbon potential outlines from Geological and Bioregional Assessment Program (2018). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-031

2.3.3 Well data

Data and information extracted from Queensland well reports are available from the Queensland Petroleum Exploration Data (QPED) downloadable dataset (Geological Survey of Queensland, 2018). The data are derived from petroleum wells, coal seam gas wells, stratigraphic boreholes and mineral drillholes. Well history (header) information, and compilations that include formation tops, biostratigraphy, hydrocarbon indications, and petrophysical and geochemical data, are provided as thematic datasets (Geological Survey of Queensland, 2018). Well completion reports and log data are available online from the Queensland Government's QDEX Reports and Data (Department of Natural Resources, 2019b, 2019a).

Fourteen vertical petroleum and stratigraphic wells (and one horizontal well) have been drilled within or very close to the boundary of the Isa GBA region. The distribution of these and other wells in the surrounding area, classified according to their depth of penetration, is shown in Figure 9. The maximum well depth in the Isa GBA region is 2337 m (true vertical depth) at Desert Creek 1 (Figure 9).

Much of the well log data in the Isa GBA region comes from four petroleum wells drilled by Comalco Aluminium Limited in 1988 and 1992: Beamesbrook 1 (Dunster et al., 1989), Argyle Creek 1 (Dunster et al., 1993b), Desert Creek 1 (Dunster et al., 1993c) and Egilabria 1 (Dunster et al., 1993a). The wells Argyle Creek 1, Desert Creek 1 and Egilabria 1 include a comprehensive set of wireline logs that can be confidently tied to seismic data.

Additional well data are available from three wells drilled by Armour Energy in 2013. Egilabria 2 is a step-out well drilled 0.5 km north-east of Egilabria 1 and was completed in a similar stratigraphic section (the Lawn 4 sequence) as Egilabria 1 (Longdon, 2014a). Egilabria 2 DW 1 is a horizontal sidetrack well that kicked off from Egilabria 2 in the Lawn Supersequence and has not been used in this study. Egilabria 4 was drilled 9.7 km north-east of Egilabria 1 to test the extension of the Lawn 4 shale gas fairway, and the potential of the deeper River Supersequence shale gas play (Longdon, 2014b). Egilabria 4 penetrates the oldest stratigraphic section in the eastern part of the Isa GBA region, and provides important stratigraphic data that was not available for this area during previous studies (Bradshaw and Scott, 1999).

Four petroleum wells, drilled in the late 1950s to the mid-1960s, are also located either within, or in the immediate vicinity of, the Isa GBA region: Burketown 1, Scout (Oakey Hole) 1, Scout (Nicholson River) 2, and Scout (Burketown) 2A (Figure 9). A well completion report is available for Burketown 1 (Perryman, 1964). However, the wireline log suite does not include gamma ray or sonic data and was therefore not interpreted. The remaining boreholes are shallow wells that were completed within the Carpentaria and Karumba basins and were therefore not included in this assessment. Several shallow stratigraphic wells and measured outcrop sections from previous work (Bradshaw and Scott, 1999) are located around the Isa GBA region, and have also been used to help define the zero edges for mapped intervals.

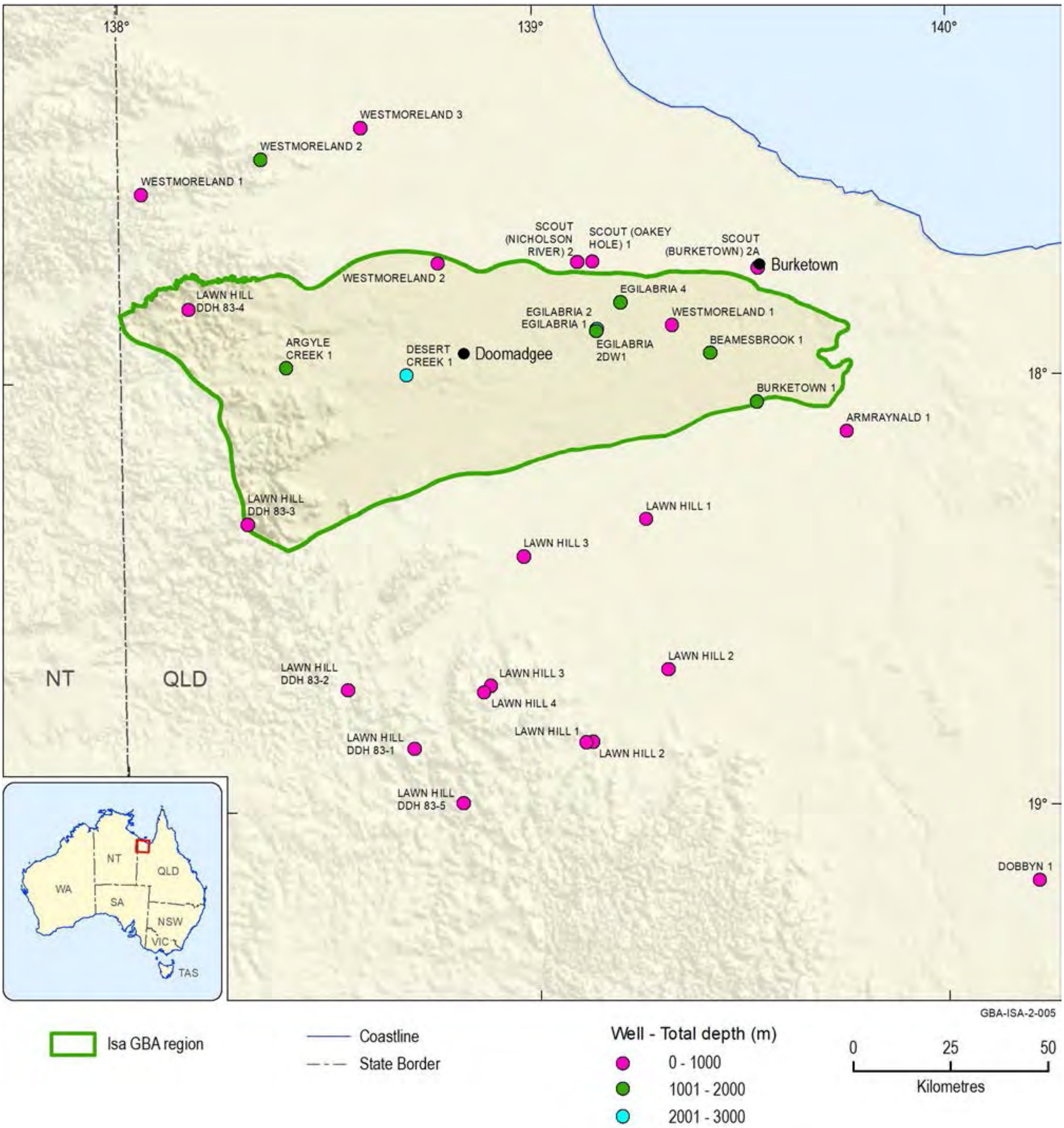


Figure 9 Distribution of stratigraphic and petroleum exploration wells across the Isa GBA region and surrounds, classified according to depth of penetration

Egilabria 2 DW1 is a lateral well. The Westmoreland 1 and Westmoreland 2 wells to the north of the Isa GBA region are stratigraphic wells drilled by the Geological Survey of Queensland in 1984; those of the same name within the Isa GBA region, and Westmoreland 3 to the north, are stratigraphic wells drilled by the Bureau of Mineral Resources in 1970 and 1972.

Data: Queensland wells from Department of Natural Resources (2017a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-005

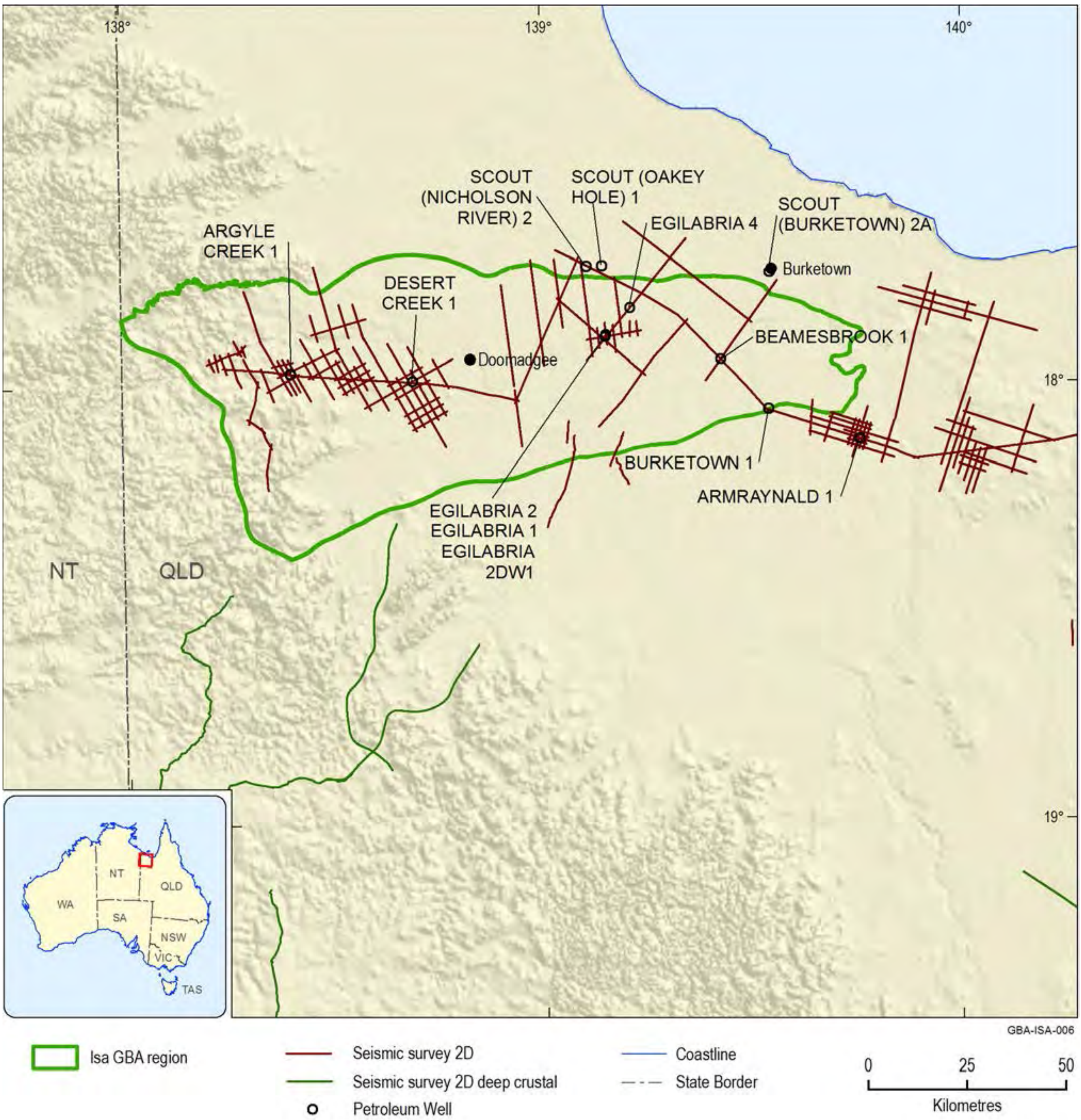


Figure 10 Two-dimensional seismic reflection data coverage across the Isa GBA region and surrounds

Data: Queensland two-dimensional seismic survey line locations from Department of Natural Resources (2017b), deep crustal seismic line locations from Department of Natural Resources (2017c), Queensland petroleum well locations from Department of Natural Resources (2017a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-006

2.3.4 Geophysical data

Geophysical data are available over the Isa GBA region, including seismic, gravity and magnetics (discussed in this section), and radiometrics. Seismic, gravity and magnetic datasets provide valuable insight into the subsurface architecture of the Isa Superbasin.

2.3.4.1 Seismic

The Isa GBA region and surrounds has a sparse coverage of two-dimensional reflection seismic data of varying vintage and quality (Figure 10) (Department of Natural Resources, 2017b, 2017c). Most petroleum wells in the Isa GBA region are intersected by this two-dimensional seismic data.

Comalco Limited acquired approximately 1000 km of two-dimensional vibroseis seismic data over the northern Lawn Hill Platform as part of their Burketown and Burketown-Normanton surveys between 1986 and 1991 (Department of Natural Resources, 2017b). The Comalco seismic data ranges from a series of closely spaced (2 to 5 km) lines around the Argyle Creek 1, Desert Creek 1, Egilabria 1 and Egilabria 2 wells, to widely spaced lines (up to 20 km) elsewhere (Figure 10).

Seismic data quality is highly variable across the Isa Superbasin. Good quality seismic lines with well ties, allowing seismic horizons to be confidently interpreted, extend from east of Argyle Creek 1 to west of Beamesbrook 1. The area around Argyle Creek 1 extending up to the northern Isa GBA region boundary (Figure 10) has poor quality seismic data, thereby reducing the confidence in seismic interpretation. Seismic data quality also deteriorates in the area around Beamesbrook 1.

Two-dimensional, including deep crustal, seismic line locations for Queensland were sourced directly from the state website (Department of Natural Resources, 2017b, 2017c). There are no deep crustal seismic surveys across the Isa GBA region, although several lines occur to the south-west of the region (Figure 10).

2.3.4.2 Gravity

The Australian National Gravity Database contains data from more than 1.5 million point gravity observations on the Australian mainland, over the continental margins, on the Australian Antarctic Territory and other external territories of Australia. These data have been collected from more than 1700 gravity surveys dating back to 1937 (Wynne and Bacchin, 2009). A full coverage of ground-based gravity is available over the Isa GBA region (Geoscience Australia, 2018b) at generally a 2 to 4 km station spacing (Figure 11), with spacing as low as 100 m in some locations. The most recent survey data included in the database from the Isa GBA region was acquired in 2009.

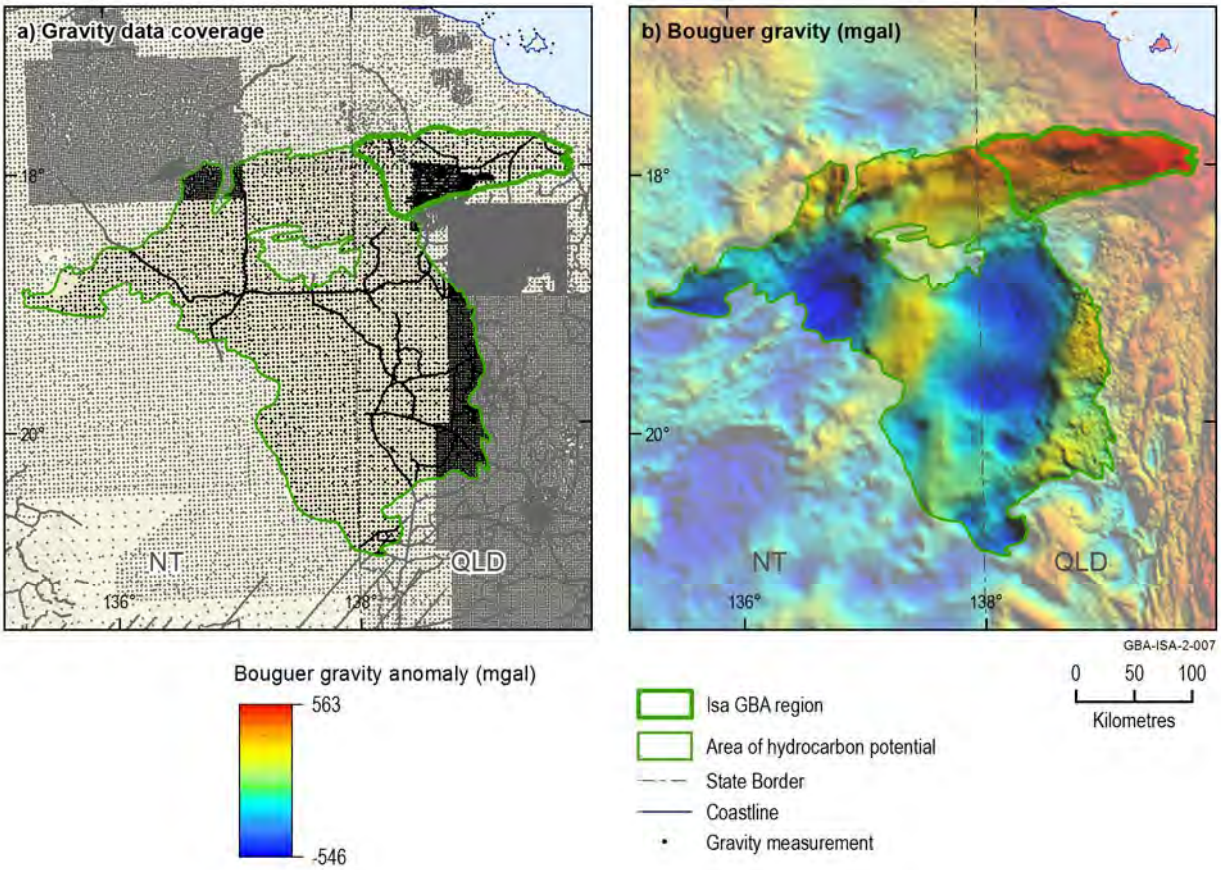


Figure 11 a) Distribution of point gravity data observations; b) Regional Bouguer gravity coverage

Data: a) Australian National Gravity Database (Wynne and Bacchin, 2009); b) Bouguer Gravity Anomaly Grid of Onshore Australia (Nakamura, 2016)
Element: GBA-ISA-2-007

2.3.4.3 Magnetics

The sixth edition of the total magnetic intensity (TMI) anomaly grid of Australia with Variable Reduction to Pole (VRTP) covers all of Australia with a grid cell spacing of approximately 3 seconds of arc (approximately 80 m) (Nakamura and Milligan, 2015). Details of the specifications of individual airborne surveys can be found in the Fourteenth Edition of the Index of Airborne Geophysical Surveys (Percival, 2014). Airborne magnetic data are available across the Isa GBA region at flight-line spacing of 500 m or less (Figure 12).

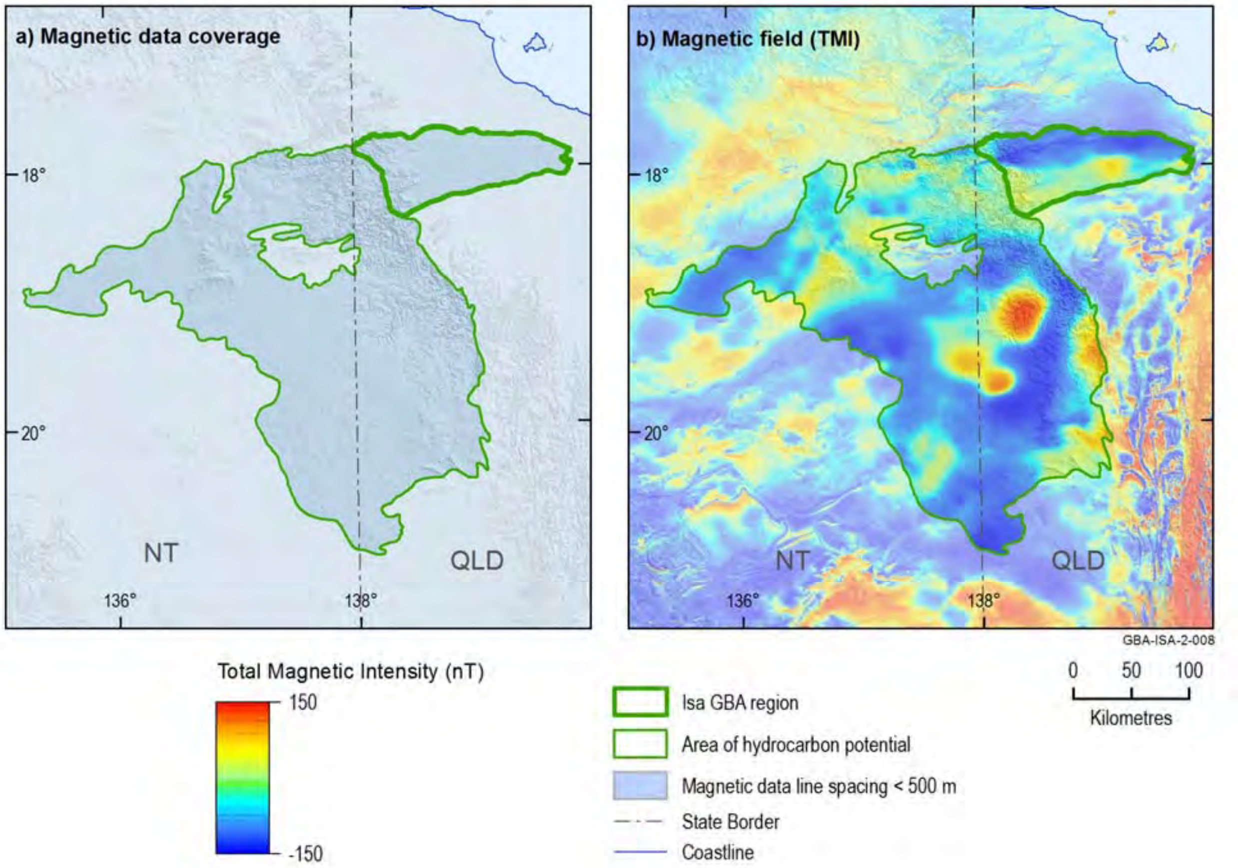


Figure 12 a) Distribution of magnetic survey by resolution; b) Regional TMI (total magnetic intensity) coverage

Data: a) ARGUS (Airborne Geophysical Surveys) metadata database (Richardson, 2018); b) Total Magnetic Intensity (TMI) Anomaly Grid of Australia (Nakamura and Milligan, 2015)
Element: GBA-ISA-2-008

2.3.4.4 Other geophysical surveys

The Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) is a collaborative, national survey that acquires long-period magnetotelluric (MT) data across the Australian landmass (Geoscience Australia, 2018c). The ongoing program, which commenced in 2013, aims to acquire data from portable stations located on a half-degree (about 55 km) grid. AusLAMP, by measuring the electrical conductivity–resistivity structure of the deep subsurface below 10 km, will image broad geological features as three-dimensional structures within the lithosphere and, thereby, provide information on the architecture of the deep crust and upper mantle.

The Australian Airborne Electromagnetic Project (AusAEM) is a series of airborne electromagnetic surveys conducted at a line spacing of 20 km across a large region of northern Australia (Geoscience Australia, 2018a). An AusAEM survey across north-west Queensland and the north-east Northern Territory was completed in 2018 (Geoscience Australia, 2018a). The analysis of subsurface electrical conductivity to several hundreds of metres will be used to map sedimentary and regolith cover, as well as to assess the potential for groundwater resources.

2.4 *Published geological studies*

Previous federal and state government research programs in northern Australia reflect the frontier status of the Proterozoic superbasins for hydrocarbon exploration. These programs had an emphasis on expanding the geological knowledge of the broad regions under cover and apply broadly to both mineral and energy exploration. Outlined below are those published studies relevant to the Isa Superbasin included in this data inventory.

2.4.1 Northern Australian Basins Resource Evaluation (NABRE)

The Australian Geological Survey Organisation (AGSO), now Geoscience Australia, undertook the North Australian Basins Resource Evaluation (NABRE) program in the period 1995 to 2000 (see Section 3.2.2.1). The NABRE program combined mineral and petroleum exploration techniques, referred to as integrated basin analysis, in recognition that mineral exploration advances would require the subsurface interpretation approaches used in hydrocarbon exploration, in addition to near-surface strata interpretation (Bradshaw and Scott, 1999; Southgate, 2000). The program produced a detailed Proterozoic chronostratigraphic basin framework for part of northern Australia, which included the identification of the Isa Superbasin. Data types used included SHRIMP zircon age and paleomagnetic determinations, potential field data, seismic, drillcore, wireline and outcrop datasets (Bradshaw and Scott, 1999; Southgate, 2000; Southgate et al., 2000a).

2.4.2 North West Queensland Mineral and Energy Province

The Geological Survey of Queensland completed the North West Queensland Mineral and Energy Province study and mapping program from 2006 to 2009. This study synthesised the surface geology of the Mount Isa Inlier to support future mineral and energy resource exploration, including hydrocarbon and geothermal energy (Geological Survey of Queensland, 2011a). This study used publications and integrated public domain geological, geochemical and potential field datasets to classify the structurally complex north-west Queensland region into geological domains of similar structural grain and metamorphic grade. The domains are discussed further in sections 3.1 and 4, and the extent of the study area is shown in Figure 18.

2.4.3 Concurrent programs

The Queensland Government is undertaking the Strategic Resources Exploration Program in north-west Queensland from 2017 to 2021 (Knight, 2018) to help expand resource exploration and development of gas and minerals in north-west Queensland. One completed output of the program is the North West Queensland SEEBASE® update, described in Section 2.4.4.

From 2016 to 2020, Geoscience Australia is undertaking the Exploring for the Future program, in partnership with state and territory government agencies, CSIRO and universities (Henson et al., 2018). The program includes the South Nicholson Seismic Survey, which was acquired between the southern McArthur Basin and the western part of the Mount Isa Province (Figure 2). Acquisition of five seismic lines, covering about 1100 km, was completed in early August 2017 (Henson et al., 2018). Seismic interpretations are expected to be published in 2020.

2.4.4 North West Queensland SEEBASE® update

The North West Queensland SEEBASE® data release, which includes the Isa Superbasin, is a revised depth to basement model of the region (Figure 3), recently developed for the Geological Survey of Queensland (Frogtech Geoscience, 2018a). The revised model used post-2006 acquisition of potential field data in north-west Queensland, deep two-dimensional seismic data and well data. The data release includes an assessment of basement geology and structural evolution of the area.

2.4.5 North Australian Basins Resource Evaluation (NABRE) update

A recent update to the NABRE program (Bradshaw and Scott, 1999) was undertaken by Geoscience Australia in mid-2018 (Bradshaw et al., 2018c). Results included a series of depth-structure and isochore (vertical thickness) maps over the Isa GBA region, which are based primarily on seismic and well log interpretations by the NABRE project (Bradshaw and Scott, 1999; Krassay et al., 1999). The update by Bradshaw et al. (2018c) also includes new interpretations of recently acquired well data by Armour Energy (Egilabria 2 and Egilabria 4). A summary of the results from Bradshaw et al. (2018c) is included in Section 4.2.

Bradshaw et al. (2018c) selected eight seismic horizons originally interpreted by Bradshaw and Scott (1999) for depth-structure and isopach gridding, based on their relevance to exploration for shale gas resources over the northern Lawn Hill Platform, including:

- Base Carpentaria Basin (base Mesozoic groundwater systems)
- Base South Nicholson Basin (top Isa Superbasin)
- Base Doom Supersequence (potential tight gas play)
- Base Wide Supersequence (top of the Lawn 4 shale gas interval)
- Base Lawn 4 Sequence (base of the Lawn 4 shale gas interval)
- Base Lawn Supersequence (base proven shale gas play)
- Base Term Supersequence (top of deepest potential shale gas play)
- Base River Supersequence (base of deepest potential shale gas play).

Deeper Isa Superbasin horizons from the Base Loretta Supersequence and Base Gun Supersequence were not included in the update of Bradshaw et al. (2018c) as these lack organic-rich shales and are therefore assumed to not be prospective for shale gas.

3 Regional geology

3.1 Overview

The Isa Superbasin is a Paleoproterozoic to earliest Mesoproterozoic superbasin considered to be part of the Archean to Proterozoic North Australian Craton. It has been primarily identified and described from the exposed rocks of the Mount Isa Inlier and from well and seismic data on the northern Lawn Hill Platform. However, the superbasin has the potential to extend for several hundred kilometres beyond these regions (Betts et al., 2006; Scott et al., 2000) and its sequences have been identified in the McArthur Basin in the NT (Abbott et al., 2001; Jackson and Southgate, 2000; Page et al., 2000; Southgate et al., 2000a).

Petroleum source rocks were first identified in Proterozoic-aged sediments of the North Australian Craton in the 1980s with the retrieval of oil from the BMR Urapunga 4 stratigraphic hole in the NT (Jackson et al., 1986). Not all Proterozoic superbasin rocks of the North Australian Craton, however, are potentially prospective for hydrocarbons, as some regions are highly deformed or metamorphosed (Betts et al., 2006; Spampinato et al., 2015; Withnall and Hutton, 2013).

The craton in north-west Queensland is considered a multiply-deformed terrane (Page and Sweet, 1998) as it was proximal to the eastern margin of the North Australian Craton during the Proterozoic and it experienced a series of extensional and compressional events before further Phanerozoic evolution. The Isa Superbasin on the northern Lawn Hill Platform was less impacted by deformation events, and it contains recognised organic-rich source rocks that exist in the gas generation window (Gorton and Troup, 2018). In other regions, geological interpretation of the North Australian Craton's Proterozoic basins is constrained by low data density and regional-scale concealment beneath younger basins.

The Isa Superbasin overlies the Paleoproterozoic Leichhardt and Calvert superbasins, which may have a similarly broad distribution across the North Australian Craton. The Isa Superbasin is in turn unconformably overlain in the west of the Isa GBA region by the Mesoproterozoic South Nicholson Basin and by the Mesozoic Carpentaria and the Cenozoic Karumba basins in the east.

3.2 Regional geological setting

3.2.1 Archean to Paleoproterozoic basement

The early history of assembly and evolution of the North Australian Craton is not well known, due to the lack of exposed rocks older than ca 1930 to 1800 Ma. The extent, composition and tectonic history of Archean to early Paleoproterozoic basement terranes older than ca 1930 Ma have been interpreted by the North West Queensland SEEBASE® update study (Figure 13), using a variety of data sources, including gravity, magnetics, literature reviews and geological maps (Frogtech Geoscience, 2018a). Although the early tectonic history of the North Australian Craton remains poorly constrained, evidence from detrital geochronology studies suggest that basement is dominated by Paleoproterozoic crust (ca 2500 to 2200 Ma), with minor Archean crust (Frogtech Geoscience, 2018b and references therein).

One of the last accretion events in the amalgamation of the North Australian Craton was that of the Eastern Fold Belt basement (see Section 3.2.3), either before or during the ca 1860 Ma Barramundi Orogeny (Bierlein et al., 2011). The Barramundi Orogeny is recorded over a large area of the North Australian Craton and may represent the final stages of its continental growth (Betts et al., 2006). Widespread and isotopically homogenous magmatism across the Mount Isa Inlier indicates that amalgamation was complete by about 1720 Ma (Bierlein et al., 2011).

The Isa GBA region is closely coincident with the Murphy South Terrane (Figure 13). This basement terrane is interpreted to be Paleoproterozoic in age and represents a cratonised island arc, most likely to have formed and been accreted during the original amalgamation of the North Australian Craton (ca 2500 to 2200 Ma) (Frogtech Geoscience, 2018a). Cratonisation is interpreted to have increased the competence (the resistance of rocks to deformation) of the Murphy South arc terrane (Frogtech Geoscience, 2018a).

The North West Queensland SEEBASE® update study includes an interpretation of basement composition, which provides constraints on possible variations in basement rheology, radiogenic heat production and basement heat flow (Figure 14) (Frogtech Geoscience, 2018a). These variations in basement terrane properties exerted a major control on the subsequent patterns of deformation and structural reactivation across the region. The effects of radiogenic heat production from different basement terranes across the Mount Isa Inlier have been used to explain the development of crustal segments of varying strength, bounded by steep deformation fabrics and structures (Gessner, 2011). Elevated lithosphere temperatures increased potential for shallow crustal melting, thermal weakening of the lithosphere and predisposition to ductile deformation (Gessner, 2011; Giles et al., 2006b). In turn, the influence of basement properties on regional burial and thermal history controlled the maturation of organic matter and preservation of generated oil and gas.

The Murphy South Terrane, over which the Isa GBA region is located, is associated with relatively low radiogenic heat production (Figure 14). Basement across the Isa GBA region was apparently more resistant to post-Paleoproterozoic deformation events than adjacent terranes weakened by radiogenic heat flow. Patterns of deformation change significantly across the southern boundary of the Isa GBA region over the Tennant Terrane, where the basement composition is altered by radiogenic intrusive rocks (Frogtech Geoscience, 2018a).

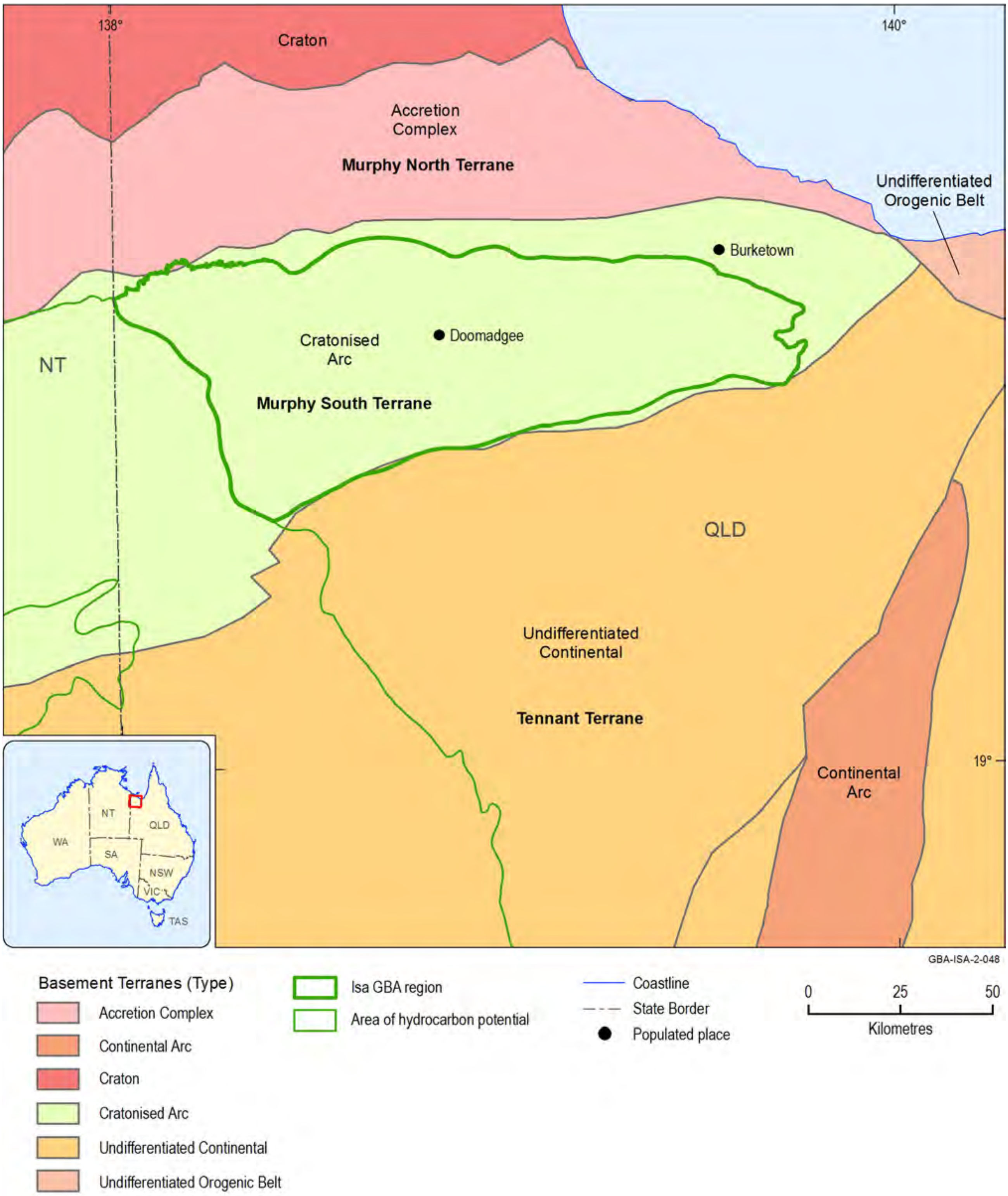


Figure 13 Interpreted basement terranes of the Isa GBA region and surrounds

Data: Frogtech Geoscience (2018a)
Element: GBA-ISA-2-048

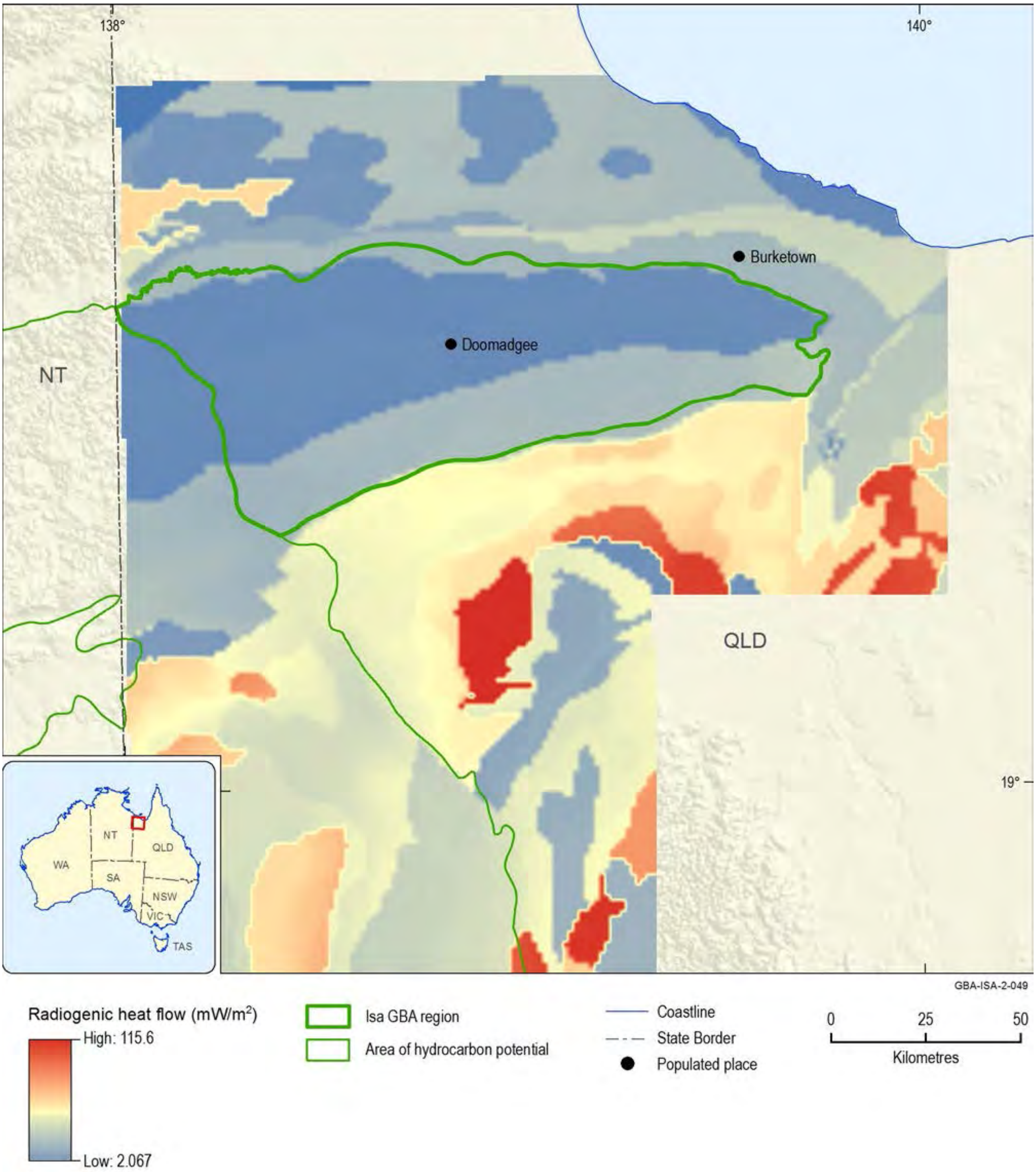


Figure 14 Modelled radiogenic heat flow of the Isa GBA region and surrounds

mW/m^2: milliwatts per metre squared

Data: Frogtech Geoscience (2018a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)

Element: GBA-ISA-2-049

3.2.2 Paleoproterozoic superbasins

3.2.2.1 Superbasins of the North Australian Craton

Superbasins developed across the North Australian Craton in the late Paleoproterozoic, including the Isa Superbasin (Withnall and Hutton, 2013). Superbasins, after Walter et al. (1995), are interpreted as originally very large single depositional systems that have been disrupted internally by later tectonism to form numerous structural basins and related features. They can be defined as 'first order sequences' in a sequence stratigraphic approach (see the methods snapshot of Section 3.4), but they do not necessarily require this approach for definition.

Four superbasins have been defined in the North Australian Craton on a sequence stratigraphic basis (Abbott and Sweet, 2000; Bierlein et al., 2008; Jackson et al., 2000; Scott et al., 2000). Three of these are Paleoproterozoic to earliest Mesoproterozoic in age and are exposed in the Leichhardt River Fault Trough and Lawn Hill Platform of the Mount Isa Inlier (Figure 15). These are the Leichhardt (ca 1800 to 1740 Ma), Calvert (ca 1710 to 1690 Ma) and Isa (ca 1670 to 1575 Ma) superbasins (Jackson et al., 2000; Neumann et al., 2006; Southgate et al., 2000a). A fourth superbasin, the Roper Superbasin, is Mesoproterozoic in age and is described in Section 3.2.3.2.

The superbasin chronostratigraphy was established on the basis of sequence stratigraphic interpretation of outcrop, drill core, wireline and seismic datasets integrated with SHRIMP zircon and paleomagnetic determinations (Southgate et al., 2000a). Much of the Isa Superbasin chronostratigraphic framework was based on interpretation of seismic and well data from the northern Lawn Hill Platform where all seven supersequences are preserved (Bradshaw and Scott, 1999; Southgate, 2000).

Although a geochronostratigraphic basin framework has been established for the region, the individual extents of the superbasins have not yet been defined. The interpreted present-day distribution of the Leichhardt, Calvert and Isa superbasin rocks (Figure 15) was mapped by Tarlowski and Scott (1999) and Scott et al. (2000) using traverse models of magnetic data constrained by surface geology. The models were extrapolated to interpretative contour maps indicating the interpreted thicknesses and extents of superbasin bodies. Figure 15a shows the areal extent that could potentially include any or all of these superbasins.

The Paleoproterozoic superbasins and associated structures are interpreted, from regional potential field analysis, to continue southwards under the Paleozoic Georgina Basin for approximately a further 250 km; with the undifferentiated Calvert and Isa superbasins being marked by low magnetic and low gravity responses (Spampinato et al., 2015). Recent preliminary interpretation of data from the L210 South Nicholson Deep Crustal Seismic Reflection Survey (17GA-SN), acquired by Geoscience Australia in 2017, indicate relatively undeformed Paleoproterozoic to Mesoproterozoic basin units 5 to 8 km thick beneath the Georgina Basin to the immediate west of the Mount Isa Inlier (Henson et al., 2018). The depths of the Calvert and Isa superbasins here are alternatively interpreted from the 17GA-SN2 line, gravity and magnetic data to be as thick as 7 to 14 km in the identified depocentre (Frogtech Geoscience, 2018a).

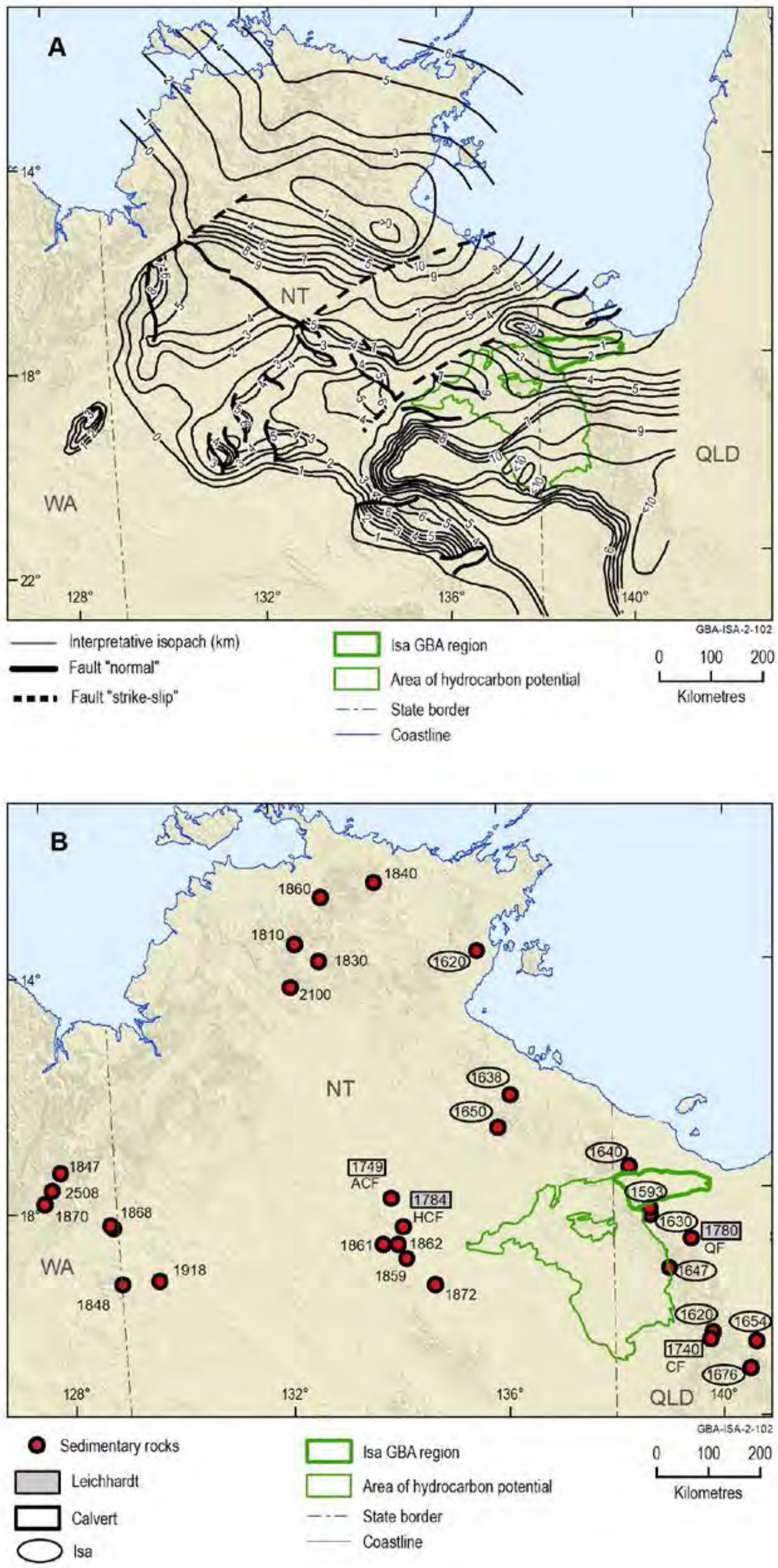


Figure 15 Interpreted widespread distribution of Paleoproterozoic superbasin sedimentary rocks in the North Australian Craton: (a) the interpreted distribution and thicknesses of Paleoproterozoic superbasin bodies, derived from magnetic data and surface geology, and (b) spatial distribution of selected SHRIMP (OZCHRON) geochronological ages, in millions of years, of sedimentary rocks and classified by superbasin

Selected ages are predominantly of tuffs in sedimentary rocks. Ages older than 1800 Ma date pre-superbasin crustal rocks
Source: Tarlowski and Scott (1999), Scott et al. (2000). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element GBA-ISA-2-102

3.2.2.2 Isa Superbasin

The Isa Superbasin was initiated at approximately 1670 Ma after a major 20 to 25 million-year depositional hiatus (Jackson et al., 2000; Southgate et al., 2000a) and ended with the onset of the Middle Isan Orogeny at about 1575 Ma (Scott and Tarlowski, 1999). The sedimentary succession comprises seven second-order supersequences, which have been subdivided into 30 third-order sequences. These are the Gun 1 to 3, Loretta 1 to 2, River 1 to 8, Term 1 to 5, Lawn 1 to 4, Wide 1 to 3 and Doom 1 to 5 sequences. They include fluvial, coastal and shallow marine sandstone facies, shallow and deep marine carbonate successions and deep water shale or fan deposits (Bradshaw et al., 2000; Krassay et al., 2000b; Krassay et al., 2000a; Southgate et al., 2000a).

Extensive organic-rich shale units in the Isa Superbasin correspond to the periods encompassing maximum marine flooding (highstand intervals) in the marine sediments, with the best developed hydrocarbon source rocks in the River and Lawn supersequences (Gorton and Troup, 2018). Shales of these supersequences on average have more than 2% total organic carbon by weight (Jarrett et al., 2018).

These organic-rich sediments were deposited before the evolution of woody, vascular plants. Organic matter in the northern Lawn Hill Platform sediments may have been derived from planktonic algae (Glikson et al., 2006; Glikson et al., 1992), bacteria (Brocks et al., 2017) or from the growth of microbial mats, such as stromatolites, in Proterozoic marine waters.

The conditions under which the organic matter was preserved in the Isa Superbasin sediments differ substantially from later Phanerozoic marine conditions. Proterozoic organic-rich sediments were deposited under conditions of widespread ocean anoxia in the 1800 to 1000 Ma period (Planavsky et al., 2011). Anoxic conditions in depositional environments are associated with organic matter preservation and can result in enrichment of total organic carbon in sediments.

Some of the traditionally important paleogeographic parameters of Phanerozoic black shale deposition (such restricted circulation and distance from organic matter sources) are less applicable to the interpretation of Proterozoic organic-rich shale development due to these differences in organic matter sources and preservation. Organic-rich shales have the potential to be widely distributed in the marine sedimentary rocks of the Proterozoic superbasins because the conditions for organic matter preservation were more pervasive in the subsurface ocean.

Despite this potential, establishing the current preserved extent of Isa Superbasin sedimentary rocks is difficult due to the geological changes that have occurred in the long period after superbasin formation. The extent of the Isa Superbasin outcrop mapped across the northern and central Lawn Hill Platform region is shown in Figure 16. However, the known occurrence of the Isa Superbasin sequences across the North Australian Craton, indicate that the superbasin's extent is much broader than its surface exposure and current mapped subsurface extent across the Lawn Hill Platform (Figure 15).

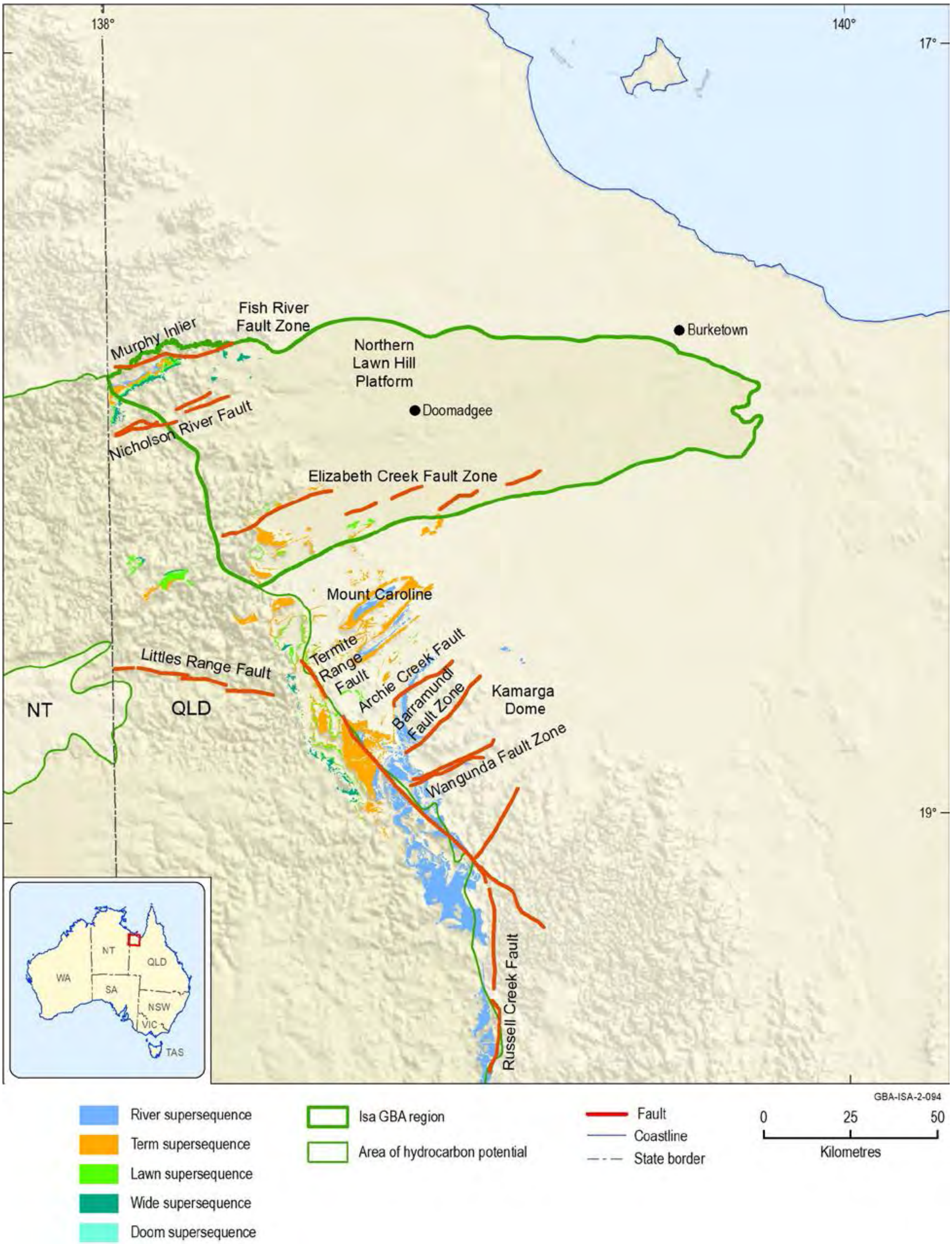


Figure 16 Northern and central Lawn Hill Platform with main structural elements and outcrop exposures of the River, Term, Lawn, Wide and Doom supersequences of the Isa Superbasin

Source: Krassay et al. (2000b); Krassay et al. (2000a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-094

The initial chronostratigraphic interpretation using U-Pb SHRIMP ages of zircon crystallisation from tuffaceous sedimentary rocks, for example, indicate that Isa Superbasin phase sediments extend into the southern McArthur Basin (Figure 15b) (Page et al., 2000; Scott et al., 2000; Southgate et al., 2000a). Even more broadly the Isa Superbasin sequences correlate to the Yangtze Block Luoxue Formation in southern China; the Yangtze Block is hypothesised to have been connected to the North Australian Craton and then separated by ca 1590 Ma (Wang et al., 2014).

The lack of attempts to map the full distribution of the Isa Superbasin to date reflects the frontier status of exploration in the broader region. Mapping the extent of the Isa Superbasin is constrained as most exposed boundaries are structurally or erosionally defined and true margins are likely to be concealed beneath younger basins (Bradshaw et al., 2000). An exception is where the Isa Superbasin sediments onlap the discrete basement high of the Murphy Tectonic Ridge (or 'Murphy Inlier'); here a basin margin succession is preserved as the Fickling Group, in which all seven supersequences of the Isa Superbasin have been identified using outcrop sections and well logs, supported by seismic data and U-Pb zircon ages.

Despite the perceived petroleum resource potential of the Isa Superbasin, most wells and seismic data acquisition in north-west Queensland has been limited to the northern Lawn Hill Platform region (Figure 3). Further data acquisition from regions under cover is required to effectively map the Isa Superbasin extent beyond the Isa GBA region and enable broader stratigraphic correlation of the Paleoproterozoic sedimentary rocks across northern Australia.

3.2.3 Mesoproterozoic to Cenozoic

Tectonism after superbasin sedimentation formed numerous structural basins and fold belts, creating heterogeneity in the preservation, depth and alteration of superbasin sediments. The Mesoproterozoic Isan Orogeny (Section 3.3) was a major event that contributed to the geological heterogeneity. Younger Proterozoic and Phanerozoic cover successions overlie the superbasin units.

The Mesoproterozoic to Cenozoic geological history of the region led to the development of a salient feature in the present landscape of north-west Queensland: the Mount Isa Inlier. The Mount Isa Inlier is a large area of exposed Paleoproterozoic to Mesoproterozoic crust (Section 3.2.3.1; Figure 17) that has been exhumed and is surrounded by younger rocks. The inlier is the exposed part of a much larger area of Paleoproterozoic to Mesoproterozoic rocks that underlies parts of the Neoproterozoic to Paleozoic Georgina Basin and the Mesozoic Carpentaria and Eromanga basins (Figure 2).

The Mount Isa Inlier was the initial focus of geological mapping and interpretation of Proterozoic geology in this region of the North Australian Craton. Tectonic elements were originally interpreted to the extents of the surface exposure (Section 3.2.3.1).

3.2.3.1 Tectonic elements

The tectonic elements of the Mount Isa Inlier include the Western Fold Belt (including the Lawn Hill Platform and Leichhardt River Fault Trough), the Kalkadoon-Leichhardt Belt, the Mary Kathleen Fold Belt, Murphy Tectonic Ridge (or Murphy Inlier) and the Eastern Fold Belt (Figure 17) (Blake, 1987). These tectonic elements represent structural domains that formed largely as a result of the Mesoproterozoic Isan Orogeny, and are not primary depositional basins.

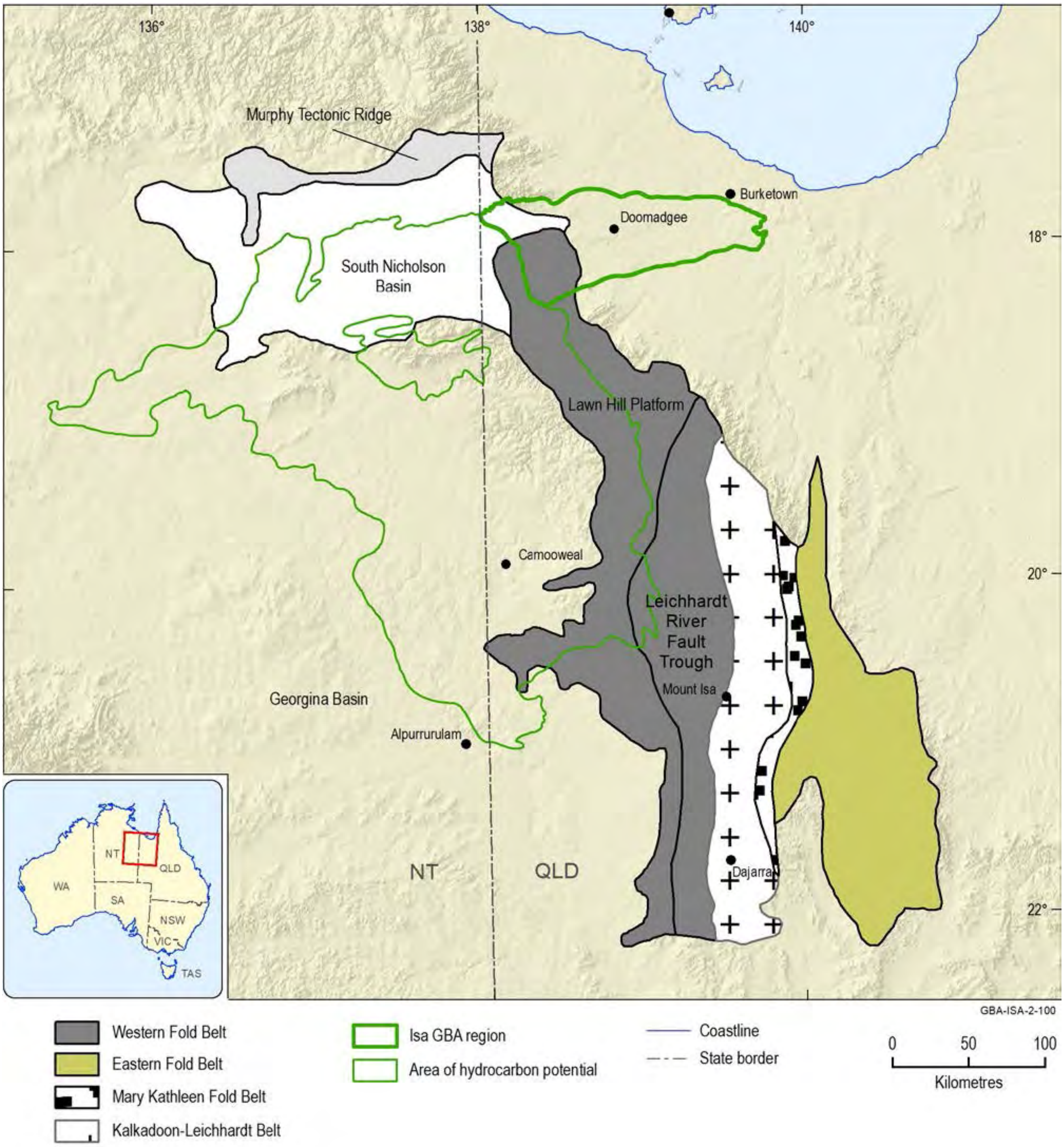


Figure 17 Simplified geological map of the Mount Isa Inlier, showing major tectonic elements and extent of Paleoproterozoic to Mesoproterozoic rock outcrop

Source: Modified from Betts et al. (2006). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-100

The Geological Survey of Queensland refined and expanded the classification of north-west Queensland tectonic elements into the Proterozoic geological domains that represent regions of similar structural grain and metamorphic grade, as determined from surface geology and geophysical interpretation (Figure 18) (Geological Survey of Queensland, 2011a). These Proterozoic geological domains form the basis of the Mount Isa Orogen geological province, as described in the Australian Geological Provinces 2018.01 edition (Raymond et al., 2018).

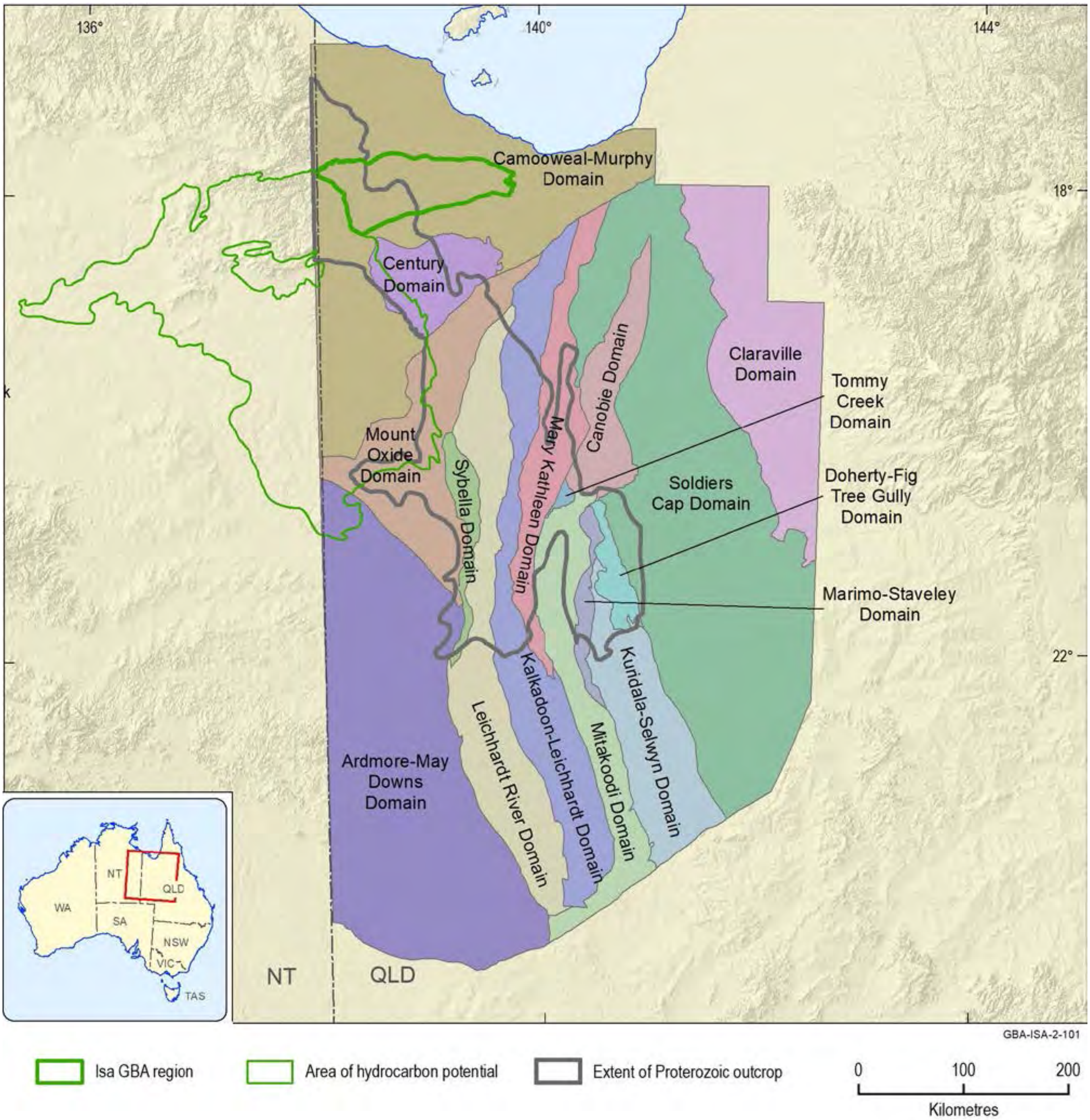


Figure 18 Geological domains in the Geological Survey of Queensland's North West Queensland Mineral and Energy Province study area

Source: Geological Survey of Queensland (2011a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-101

3.2.3.2 Overlying basins

The Isa Superbasin is overlain in the Isa GBA region from the west by the Mesoproterozoic South Nicholson Basin and from the east by the Mesozoic Carpentaria Basin and the Cenozoic Karumba Basin (Figure 19).

The South Nicholson Basin is made up of the South Nicholson Group sedimentary rocks. These rocks form part of the fourth Proterozoic superbasin of the North Australian Craton: the Mesoproterozoic Roper Superbasin (Abbott and Sweet, 2000; Jackson et al., 1999). The Roper Superbasin incorporates the South Nicholson and Roper groups (see Section 3.4.2) of north-west Queensland and the NT in a sequence stratigraphic context. The South Nicholson Group in the Isa GBA region lies over the eroded uppermost supersequence of the Isa Superbasin (Bradshaw et al., 2000).

The Mesozoic Carpentaria Basin overlies the eroded Paleoproterozoic and Mesoproterozoic basin sequences across most of the Isa GBA region (Figure 19). The Karumba Basin forms a thin veneer over the Carpentaria Basin in the Isa GBA region.

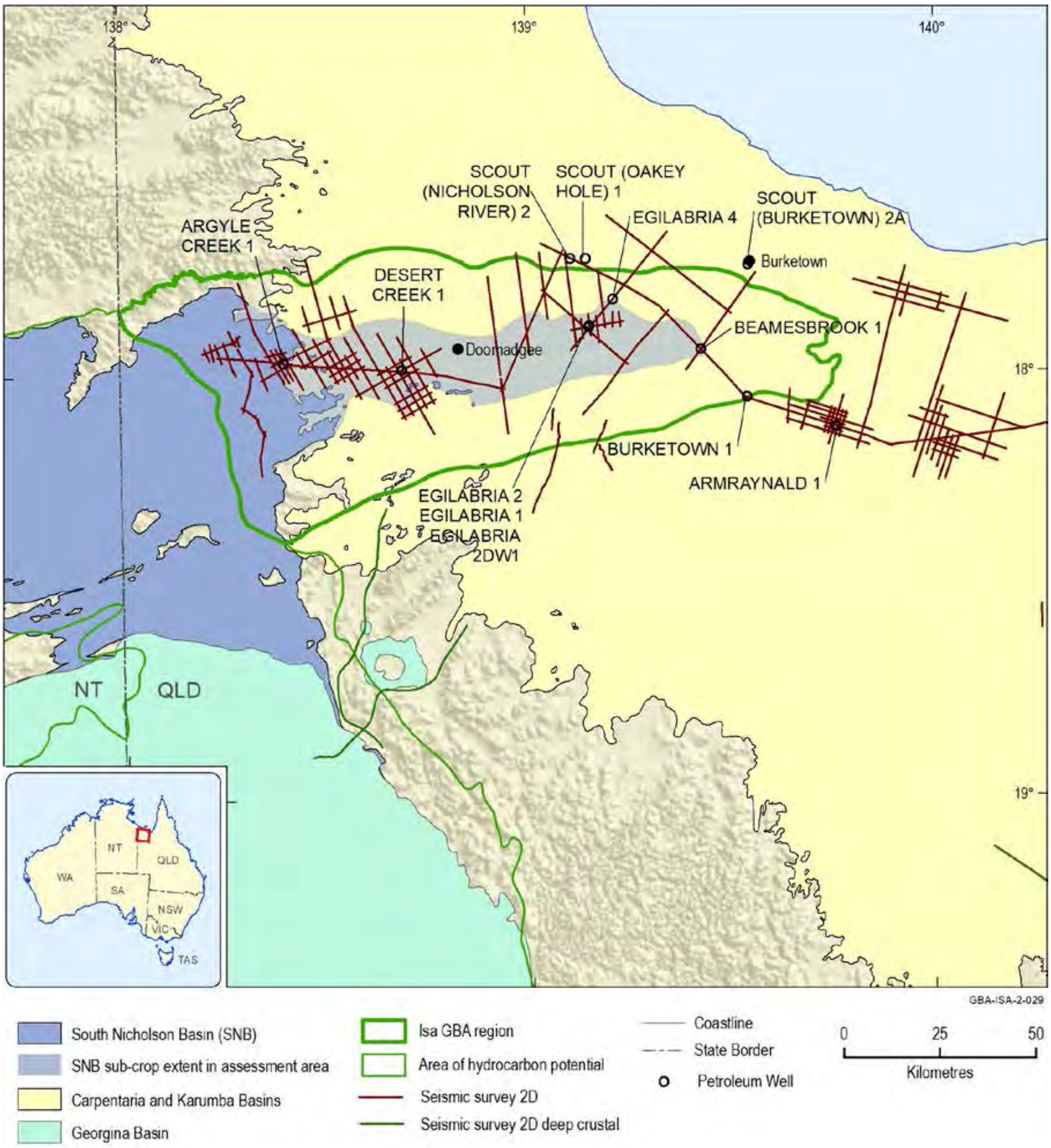


Figure 19 Distribution of post-Paleoproterozoic basins in the Isa GBA region and surrounds

Data: Carpentaria Basin distribution from Ransley et al. (2015), Georgina and South Nicholson basins distribution from Raymond et al. (2018), South Nicholson Basin subcrop extent in the Isa GBA region from Bradshaw et al. (2018c), two-dimensional seismic survey line locations from Department of Natural Resources (2017b), deep seismic line locations from Department of Natural Resources (2017c), petroleum well locations from Department of Natural Resources (2017a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-029

3.3 Tectonic evolution

More than 1.5 billion years of further geological activity has occurred since the deposition of the Isa Superbasin sediments. The near absence of rocks in the Isa GBA region aged from the mid-Mesoproterozoic to the late Mesozoic eras means that significant spans of geological time are not preserved in the rock record of the region.

The following section reviews the tectonic evolution of the Isa GBA region and surrounds, from the Proterozoic to the Cenozoic. Tectonic and erosional events during the long gap in the rock record are reviewed from studies of post-depositional basin deformation and from thermochronological analyses of rocks currently at or near the surface (see the methods snapshot box of Section 3.3.6).

The events interpreted to have influenced deposition, deformation, alteration, burial and erosion of the Isa Superbasin sequences in the Isa GBA region are shown in the chart of Figure 20. They are used as background for the interpreted timing of hydrocarbon generation and the burial history modelling component of the prospectivity technical appendix (Bailey et al., 2020). Figure 20 provides also a regional comparison with the Beetaloo GBA region, as many events impacted both areas of the North Australian Craton.

3.3.1 Paleoproterozoic Leichhardt and Calvert superbasins

Sediments of the Leichhardt, Calvert and Isa superbasins were deposited over a period of over 200 million years, from 1800 to 1575 Ma, and were affected by lithospheric extension, episodic intraplate sedimentation, intraplate magmatism, and syn-depositional uplift and basin inversion events (Betts et al., 2006; Gibson et al., 2016; Southgate et al., 2013).

The basal Leichhardt Superbasin (ca 1800 to 1740 Ma) formed during intracontinental rifting that produced asymmetric overlapping half-graben from east-north-east to west-south-west extension, accompanied by marine and fluvial sedimentation and syn-rift volcanism (Betts et al., 2006; Gibson et al., 2016; Jackson et al., 2000).

A period of post-rift thermal subsidence was followed by a major basin inversion event between ca 1740 and 1710 Ma (Blaikie et al., 2017; Gibson et al., 2016). The overlying Calvert Superbasin (1710 to 1690 Ma) formed after a 25 million-year hiatus in sedimentation, in which predominantly fluvial and shallow marine sediments and volcanic rocks were deposited in a half-graben series formed from north-west to south-east directed extension (Betts et al., 2006; Blaikie et al., 2017).

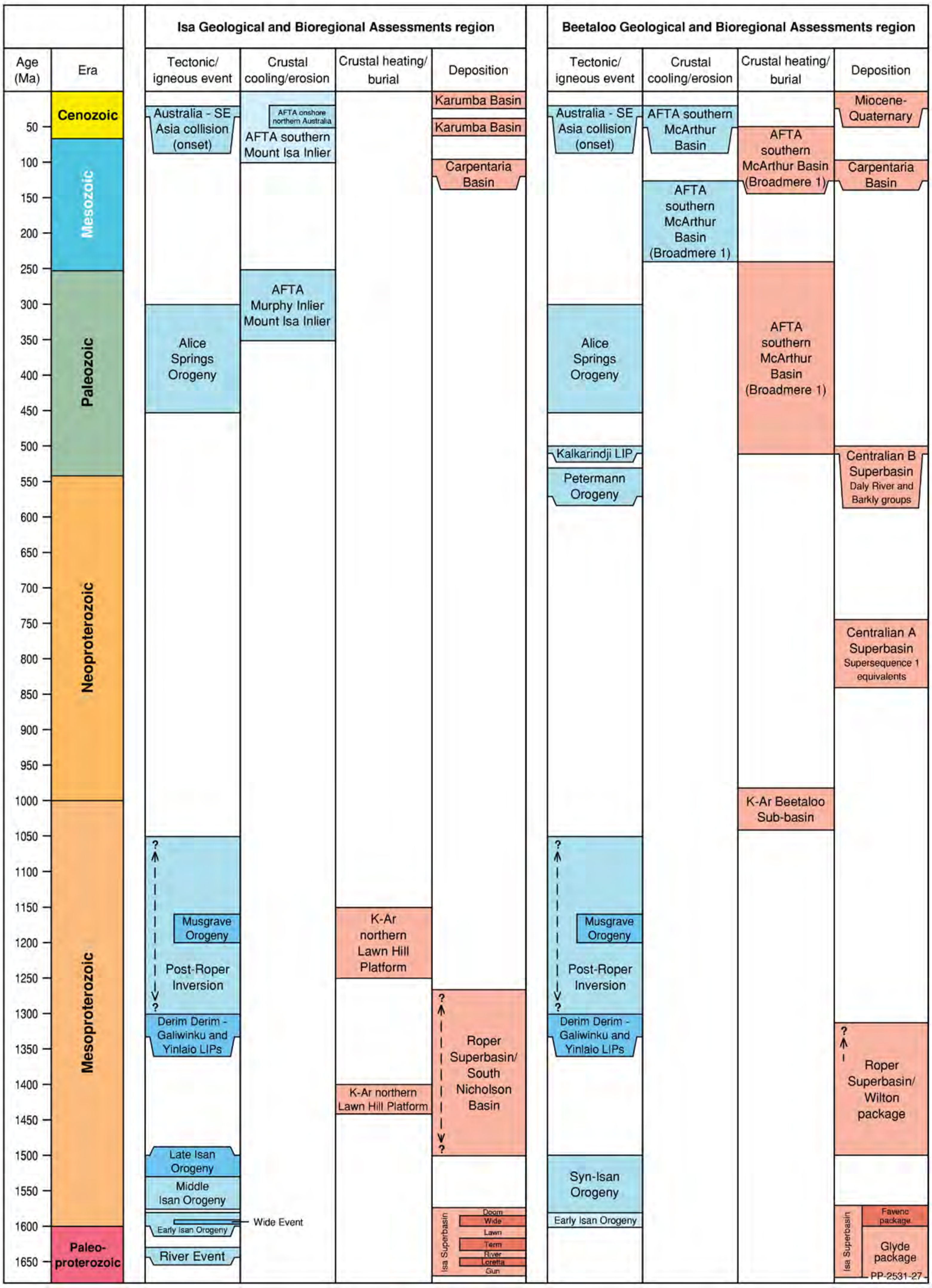


Figure 20 Regional Qld-NT comparison of tectonic, igneous, thermal and depositional events interpreted to have affected the Isa (northern Lawn Hill Platform) and Beetaloo (Beetaloo Sub-basin) GBA regions from the time of Isa Superbasin deposition to the present

LIP = Large Igneous Province, AFTA = Apatite Fission Track Analysis, K-Ar = potassium-argon dating. Colour scheme is for ease of viewing. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Source: Tectonic and igneous events from Geological Survey of Queensland (2011a), Scott and Tarlowski (1999), Jackson and Southgate (2000), Giles et al. (2006a), Jackson et al. (1999), Betts et al. (2015), Zhang et al. (2017), Ahmad and Scrimgeour (2013), Walsh et al. (2013), Glass et al. (2013), Marshall et al. (2018), Edgoose and Ahmad (2013); thermal events from Golding et al. (2006), Spikings et al. (2006), Duddy et al. (2003), Delle Piane et al. (2019), Faiz et al. (2016); deposition events from Southgate et al. (2000b), Page et al. (2000), Krassay et al. (2000b), Krassay et al. (2000a), Rawlings (1999), Munson (2016), Betts et al. (2015), Anderson et al. (2019), Munson et al. (2013b), Walter et al. (1995), McConachie et al. (1997), Cook et al. (2013), Cook and Jell (2013), Munson et al. (2013a), Edgoose and Ahmad (2013)

Element GBA-ISA-2-012

3.3.2 Paleoproterozoic to early Mesoproterozoic Isa Superbasin

The Isa Superbasin was initiated at approximately 1670 Ma after a major 20 to 25 million-year hiatus in sedimentation (Jackson et al., 2000; Southgate et al., 2000a). Sediment deposition terminated at ca 1575 Ma (Southgate et al., 2000a) at the onset of the Middle Isan Orogeny. The Isa Superbasin has been divided into seven supersequences (Gun, Loretta, River, Term, Lawn, Wide, Doom) (e.g. Bradshaw and Scott, 1999), the timing and distribution of which have been strongly influenced by tectonic activity (Betts et al., 2006).

The redeposition of tuffaceous beds, likely sourced from distal fallout from major far-field ignimbrite eruptions, throughout most of the Isa Superbasin sequences suggest that a long-lived magmatic arc was peripheral to the superbasin for much of its history (Southgate et al., 2000a). A north-dipping subduction zone has been interpreted along the southern margin of the North Australian Craton (Figure 21) that was active during the development of the Isa Superbasin (Geological Survey of Queensland, 2011a). The evolution of northern Australia's superbasins has been increasingly recognised to have been influenced by the distal effects of accretionary events along this southern margin (Betts et al., 2006).

Along the eastern margin an ocean basin opened between the Australian continent and Laurentia (proto-North America) at the time of initiation of Isa Superbasin sedimentation (Figure 21) (Geological Survey of Queensland, 2011a). The eastern margin of the Australian continent is interpreted to have undergone continental thermal subsidence, resulting in broad Isa Superbasin sedimentation, and Laurentia is interpreted to have experienced uplift and erosion, resulting in a depositional hiatus at this time (Geological Survey of Queensland, 2011a).

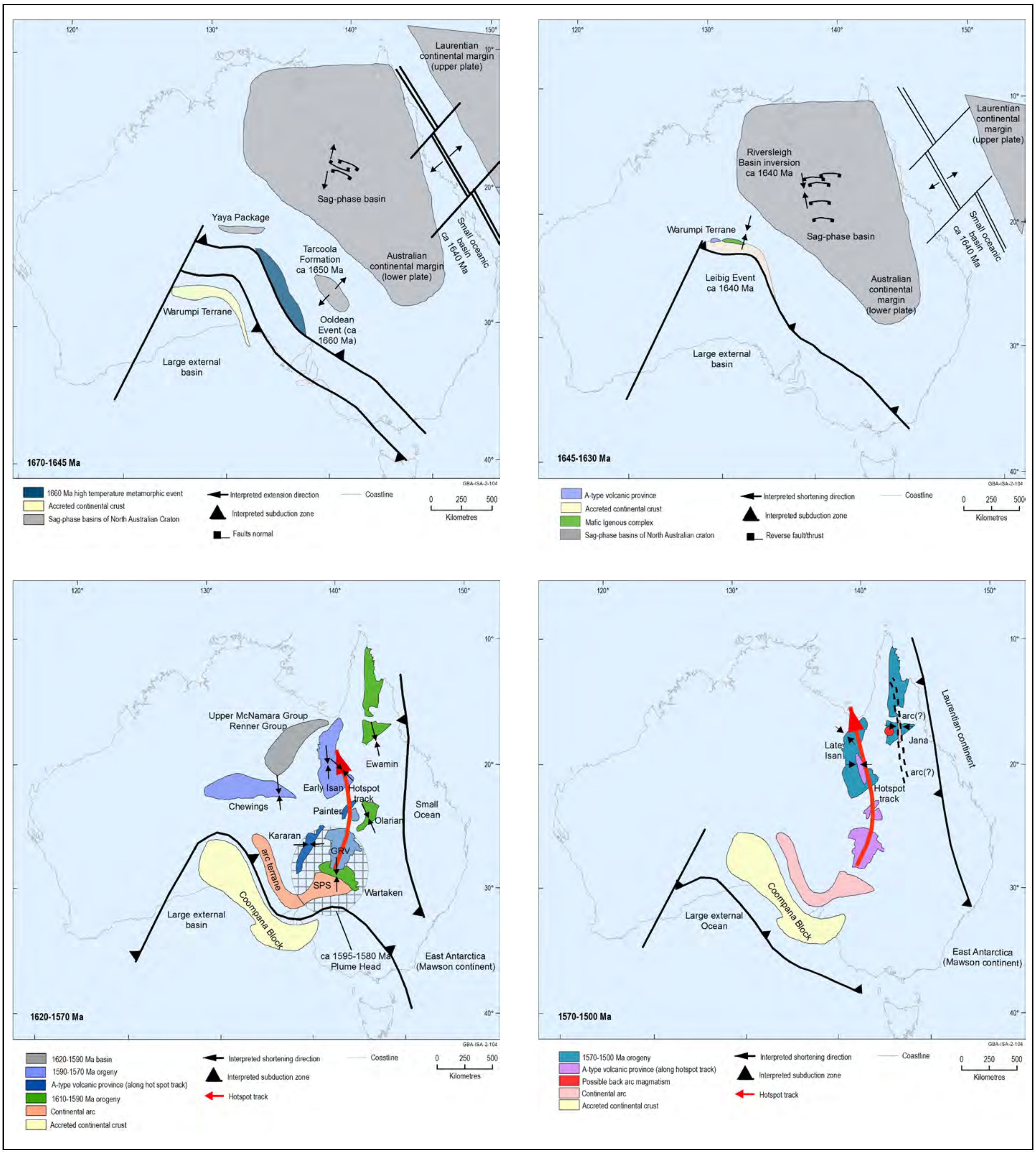


Figure 21 Australian Proterozoic geodynamic context time slices from 1670 to 1500 Ma

Australian coastline shown for reference only. This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Source: Geological Survey of Queensland (2011a)

Element: GBA-ISA-2-104

Plate motion changes during Isa Superbasin deposition, evident in palaeomagnetism recorded in Lawn Hill Platform rocks (Idnurm, 2000), are likely to have produced structural events that changed basin geometry, sediment accommodation rates and sediment supply (Southgate et al., 2000a). Each of the plate motion changes corresponds to a major supersequence boundary (Idnurm, 2000), marking the initiation of the Gun, Loretta, River and Wide supersequences (Southgate et al., 2000a).

Interplate tectonic events at the southern and eastern margins (Figure 21) may have caused the plate motion changes that promoted intraplate deformation (Southgate et al., 2000a). The combination of the opening of the ocean basin in the east at ca 1660 Ma (Geological Survey of Queensland, 2011a) (Figure 21) and compressive tectonic processes beginning at 1680 Ma at the southern convergent margin, created a south-east facing ramp in the Mount Isa region at the initiation of the Isa Superbasin (Southgate et al., 2000b). The ramp, which extended from the Murphy Inlier in the north-west to a depocentre in the south-east, became the depositional setting for the Gun Supersequence (Southgate et al., 2000b) in the Isa GBA region. Strike-slip tectonism, synchronous with 1680 to 1650 Ma orogenic activity at the southern margin, accompanied Gun Supersequence sedimentation (Southgate et al., 2000b).

Active deformation in the northern Lawn Hill Platform is most notable during deposition of the River, Wide and Doom supersequences (Scott et al., 1998; Scott and Tarlowski, 1999). Onset of River Supersequence deposition at ca 1640 Ma was linked to north–south extension (Bradshaw and Scott, 1999), coincident with a plate motion change and interpreted as a response to farfield plate reorganisation (Scott and Tarlowski, 1999). The 1640 to 1630 Ma River Event produced normal faults with downthrow to the north, producing local depocentres within tilt blocks (Scott and Tarlowski, 1999). A probable inversion event also occurred in this period (Scott and Tarlowski, 1999).

After the River Event there is no evidence of active faulting during deposition of the Term and Lawn supersequences, up to ca 1597 Ma. The wrench-style Wide Event of ca 1595 Ma developed a complex strike-slip fault network that was significantly influenced by underlying structures (Scott and Tarlowski, 1999). Sediment thickness changes across the faults indicate syn-tectonic growth of the Wide Supersequence, particularly along north-east trending splays (Scott and Tarlowski, 1999).

3.3.3 Mesoproterozoic Isan Orogeny

Concomitant with, and perhaps related to, changes in basin architecture were indications of the early development of the Isan Orogeny during 1600 to 1580 Ma (Giles et al., 2006a), or Early Isan Orogeny (Geological Survey of Queensland, 2011a). The early orogenic phases are marked by the progressive decrease in accommodation space of the Doom Supersequence, the uppermost Isa Superbasin supersequence (Scott et al., 1998; Scott and Tarlowski, 1999). Joint patterns in the Doom Supersequence in the northern Lawn Hill Platform suggest north to south compression (Scott and Tarlowski, 1999), while regionally both north to south and north-west to south-east shortening are evident (Geological Survey of Queensland, 2011a).

Deposition of the Isa Superbasin ended at about 1575 Ma (Southgate et al., 2000a) with the onset of the Middle Isan Orogeny. This represented a period of major east to west shortening that included reverse reactivation of faults (1570 to 1550 Ma), followed by a transition from ductile to brittle deformation, characterised by wrench tectonics (1550 to 1540 Ma) (Abu Sharib and Sanislav, 2013; Frogtech Geoscience, 2018a; Geological Survey of Queensland, 2011a). A peak in metamorphism occurred between 1540 and 1530 Ma in the western Mount Isa Inlier (Giles et al., 2006b). Isan Orogeny metamorphic grade varies by geological domain (Figure 18), increasing from sub-greenschist facies in the north-west to upper amphibolite facies in the south-east, where maximum temperatures and pressures of 650 to 700 °C and 400 to 600 MPa were reached (Giles et al., 2006b and references therein).

The Late Isan Orogeny (ca 1530 to 1500 Ma) was characterised by east-south-east to west-north-west shortening and brittle fault reactivation (Geological Survey of Queensland, 2011a). Collision between Laurentia and Australia on the eastern margin of the continent (Figure 21) is interpreted to have caused the extensive east-west shortening of the Middle and Late Isan orogenic phases (Geological Survey of Queensland, 2011a).

The Isan Orogeny was superimposed on crust that was already unusually hot (Giles et al., 2006a; Giles et al., 2006b). Igneous rocks of the Mount Isa Inlier emplaced both before and during the Isan Orogeny were enriched in heat-producing radiogenic isotopes, believed to have increased geothermal gradients, weakened continental crust and increased hydrothermal fluid flow (Gessner, 2011). Hydrothermal alteration was extensive but varied regionally (Duncan et al., 2014). Higher geothermal gradients in the Eastern Fold Belt domains created more vigorous fluid flow and large-scale fluid mixing, whereas in the west geographically separate areas produced distinct fluids (Duncan et al., 2014).

The Isan Orogeny contributed to the complex juxtaposition of fault blocks on the Mount Isa and Murphy inliers that vary in metamorphic grade, intensity of deformation and age (Spikings et al., 2006). The Isa GBA region, located in the Camooweal–Murphy Domain (Figure 18), did not receive the full impact of orogenic deformation and metamorphism as experienced in those domains to the south and south-east. Further detail on the impact of the Isan Orogeny on the Isa Superbasin units in the Isa GBA region is provided in Section 4.1.

3.3.4 Mesoproterozoic erosion and South Nicholson Basin

After the Isan Orogeny the North Australian Craton was tectonically reactivated and cooled several times in response to supercontinent amalgamation and break-up (Golding et al., 2006; Spikings et al., 1997; Spikings et al., 2006; Spikings et al., 2002). The Proterozoic rocks of the Mount Isa Inlier and northern Lawn Hill Platform experienced thermal events that are revealed by thermochronological analyses, as explained in the methods snapshot box ahead (Section 3.3.6). Uplifted regions experienced erosional cooling and contemporaneous basin regions experienced heating from sediment burial.

Lithospheric extension associated with the separation of the North Australian Craton from Laurentia led to Mesoproterozoic basin formation (Yang et al., 2018). Sedimentation in the Mesoproterozoic South Nicholson Basin (Figure 19) is generally interpreted to have begun after 1500 Ma following the prolonged period of deformation during the Isan Orogeny (Frogtech Geoscience, 2018a; Jackson et al., 1999; Rawlings et al., 2008; Sweet, 2017). Erosional cooling of the Isa Superbasin rocks in the southern central Lawn Hill Platform at 1500 Ma indicate a potential provenance region for South Nicholson Basin sediments at this time (Golding et al., 2006).

Provenance analysis of other Mesoproterozoic sedimentary units in the NT suggests that the sediments were initially sourced from the Mount Isa Orogen and other eastern areas due to erosion after the Isan Orogeny (Yang et al., 2019).

The South Nicholson Basin fill thickens significantly to the west from the Isa GBA region. Direct ages have not been determined for the South Nicholson Basin, as ages from the constituent South Nicholson Group units are controlled by recycled older crustal material (Carson et al., 2011). Recent geochronological data suggest that the South Nicholson Group is temporally related to the Roper Group of the NT, with deposition from 1483 Ma to before 1266 Ma, the latter being the age of post-diagenetic fluid flow in the sampled units (Anderson et al., 2019).

^{40}Ar-^{39}Ar analyses by Perkins et al. (1999) and Spikings et al. (2002) suggest that erosional cooling of the Mount Isa Inlier region occurred after 1460 Ma and reached the highest erosion rates between 1440 and 1390 Ma. Differential uplift and fault-related tectonic activity continued in the Mount Isa Inlier after the end of the Isan Orogeny (Perkins et al., 1999). High grade metamorphic rocks were uplifted along faults to their present position after 1460 Ma (Perkins et al., 1999).

Tectonic activity is also recorded by syn-depositional deformation of the South Nicholson Basin sediments. Inversion, associated with faulting and minor uplift along mainly east-north-east trending faults, affected the regional distribution of the lower South Nicholson Basin units in Queensland (Sweet, 2017). Another period of inversion led to an unconformity associated with folding and uplift within the upper units (Sweet, 2017). Thrust faulting, of up to one kilometre vertical displacement along the Elizabeth Creek Fault Zone west of the Isa GBA region (Section 4.1), occurred during and after deposition of the South Nicholson Group (Sweet, 2017).

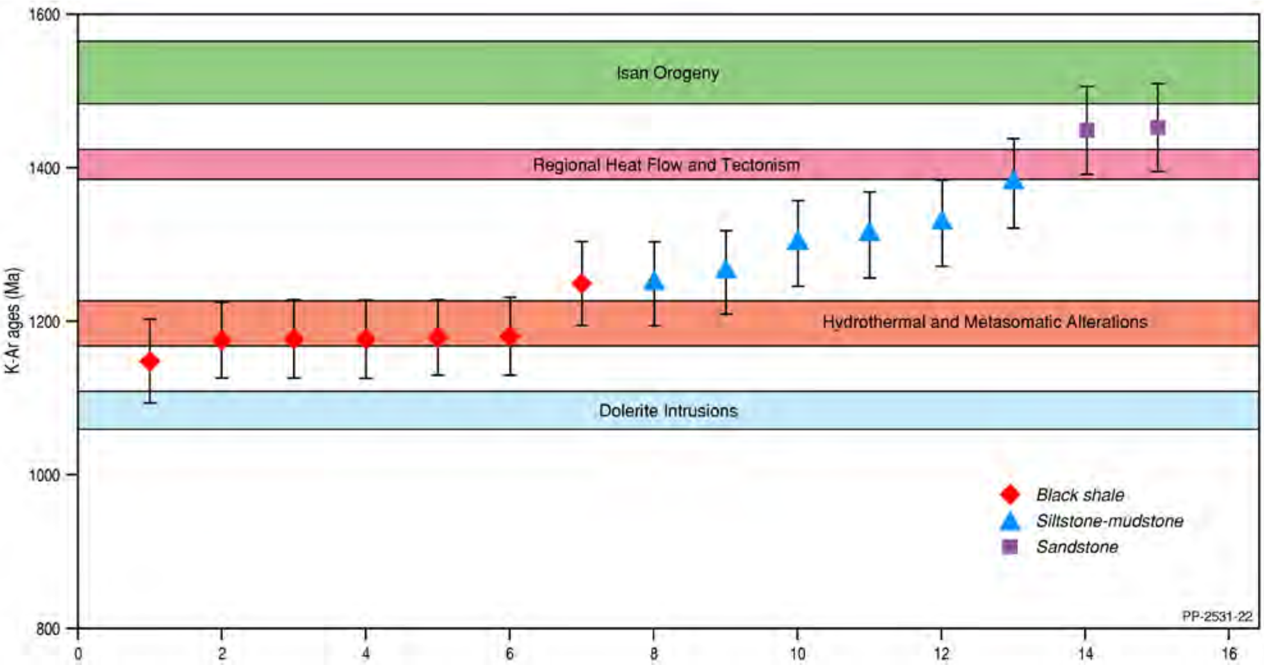


Figure 22 Illite K-Ar ages with interpreted thermal and tectonic events experienced by rocks of the northern and central Lawn Hill Platform

X axis indicates sample number.
Source: Uysal et al. (2004)
Element: GBA-ISA-2-112

Thermal pulse or hydrothermal fluid flow events occurred in the central Lawn Hill Platform between 1440 and 1400 Ma (Golding et al., 2006) (Figure 22). High heating rates and temperatures of up to 350 °C experienced in this period were focused around the Termite Range Fault (Figure 16) (Golding et al., 2006).

Crustal cooling from 1400 to 1300 Ma followed on the Lawn Hill Platform (Golding et al., 2006). In this 1400 to 1300 Ma period the North Australian Craton began to separate from the North China Craton as part of the final break-up of the Nuna (Columbia) supercontinent (Zhang et al., 2017).

3.3.5 Mesoproterozoic non-deposition and basin inversion

Tectonic deformation terminated South Nicholson Basin sedimentation (Sweet, 2017). The timing is poorly known but likely to be before 1324 Ma by correlation with the end of Mesoproterozoic Roper Group deposition in the NT (Sweet, 2017). Plume-related uplift of northern Australia during the break-up of the Nuna supercontinent may have terminated Roper Group deposition (Yang et al., 2019; Zhang et al., 2017).

Widespread moderate deformation of the South Nicholson Group occurred at a later period (Sweet, 2017). North-block-up movement on east-north-east to east trending faults indicate north-north-west to south-south-east compression (Sweet, 2017). Minor thrusting and strike-slip movement occurred on predominantly high angle reverse faults (Sweet, 2017).

The deformation likely corresponded to a regionally extensive compressional event in the NT termed the Post-Roper Inversion (Rawlings et al., 1997). The timing of the Post-Roper Inversion is unconstrained and may relate to any of the Mesoproterozoic orogenic events that affected large tracts of central Australia between 1300 and 1050 Ma (Betts et al., 2015).

The northern Lawn Hill Platform experienced a further thermal event in the later Mesoproterozoic, between 1250 and 1150 Ma (Golding et al., 2006) (Figure 22). A thermal pulse and likely hydrothermal fluid flows crystallised illite in the Isa Superbasin rocks, including those sampled from the Desert Creek and Egilabria wells in the Isa GBA region (Golding et al., 2006; Uysal et al., 2004). The timing coincides in part with the 1200 to 1160 Ma Musgrave Orogeny of central Australia (Ahmad and Scrimgeour, 2013). Hydrothermal events in the Isa GBA region are interpreted to have particularly affected rocks near faults, near supersequence and sequence boundaries, away from the northern Lawn Hill Platform onlap margin in the north and below the shallowest stratigraphic levels of the Isa Superbasin sequences (Glikson et al., 2006).

3.3.6 Neoproterozoic to Paleozoic

The near absence of rocks in the Isa GBA region aged from the mid-Mesoproterozoic to the late Mesozoic eras indicates that significant spans of geological time are not preserved in the rock record in the region. However, the tectonic history of the broader region can be still interpreted using a range of thermochronological analyses (see method box for further details). Those events interpreted to directly affect the Isa GBA region are selected from the broader regional review and summarised in Figure 20. They inform the interpreted timing of hydrocarbon generation and the burial history modelling component of the prospectivity technical appendix (Bailey et al., 2020).

Methods snapshot: measuring temperature changes through time on the Mount Isa Inlier

The tectonic history of the Mount Isa Inlier and northern Lawn Hill Platform, after the Isan Orogeny, is interpreted regionally using a range of thermochronological analyses, including $^{40}Ar/^{39}Ar$ (Perkins et al., 1999; Spikings et al., 2001, 2002), K-Ar (Golding et al., 2006) and fission track (Spikings et al., 1997; Spikings et al., 2006), which date the temperature changes experienced by the rocks through geological time. These studies, in conjunction with evidence of syn- and post-depositional basin deformation, are used to describe tectonic events that may explain spatial heterogeneity in the thermal history of the Lawn Hill Platform. These differences in thermal history can be related to hydrocarbon generation and expulsion in and around the Isa GBA region.

K-Ar ($^{40}K/^{40}Ar$), and the related $^{40}Ar/^{39}Ar$, analyses estimate the amount of time since rocks cooled through mineral crystallisation temperatures by measuring the products of radioactive decay preserved in the minerals since their formation. As the temperature windows differ by mineral types the techniques enable quantification of the rate, timing and magnitude of crustal cooling, which can be further related to crustal exhumation and fault displacements. Ages from within the Isa GBA region and proximally to the south were obtained using K-Ar dating from illite in Isa Superbasin mudstones, siltstones and carbonates of the northern and central Lawn Hill Platform (Golding et al., 2006). In conjunction with the K-Ar analyses, illite and chlorite crystallinity values are used to obtain temperature estimates for the formation of the clays and organic matter reflectance values to determine maximum paleotemperatures reached (Golding et al., 2006).

Apatite fission track analysis provides information on the cooling history of the Mount Isa Inlier after the Proterozoic (Spikings et al., 1997; Spikings et al., 2006). Fission track analyses record the accumulation over time of linear damage tracks caused by spontaneous nuclear fission of ^{238}U that are preserved in apatite crystals after rocks cool to below 110 °C. Apatite fission track analyses were undertaken by Spikings et al. (1997) for rocks exposed across the southern half of the Mount Isa Inlier and by Spikings et al. (2006) for those of both the Mount Isa and Murphy inliers.

The timing of thermal changes in the rocks of the Mount Isa Inlier and northern Lawn Hill Platform is measurable at the temperature windows of mineral crystallisation and the formation of fission tracks in crystals, but between these temperature windows there are periods of geological time over which thermal changes will not be recorded using current techniques.

Changes in temperature recorded in the region relate to cooling periods in which rocks progressively approached the surface. Increased rates of cooling and exhumation of the northern Kalkadoon-Leichhardt Belt (Figure 17; Figure 18) over the 600 to 400 Ma period is suggested by modelling of $^{40}Ar/^{39}Ar$ thermochronological data (Spikings et al., 2002). The cooling may be a response to the amalgamation of Gondwana, which included events such as the 580 to 530 Ma Petermann Orogeny (Spikings et al., 2002).

Sediments of the central-northern platform succession of the Georgina Basin, located to the south of the Isa GBA region in the area of hydrocarbon potential, were deposited in this period, from the Neoproterozoic (Ediacaran) to Paleozoic (Cambrian). Unlike the southern Georgina Basin, the thin cover of sediments on the platform are little deformed and flat-lying (Munson, 2014).

Modelling of fission track data suggests that an episode of relatively rapid cooling of the Mount Isa and Murphy inliers occurred between 350 and 250 Ma, during the Carboniferous and early Permian periods (Spikings et al., 1997; Spikings et al., 2006). More than two kilometres of erosional exhumation occurred across the Mount Isa and Murphy inliers at that time, broadly coincident with intracontinental deformation associated with the Alice Springs Orogeny and Australian eastern margin events (Spikings et al., 2006). Intracratonic stresses associated with orogenic events may have led to erosional cooling of the inlier rocks by around 30°C or more (Spikings et al., 1997). Variable cooling histories of fault-bounded blocks indicate reactivation of minor faults and segments of major faults since ca 350 Ma (Spikings et al., 2006).

This was followed by a period of relative tectonic stability between the Late Permian to Early Cretaceous (Spikings et al., 2006).

3.3.7 Mesozoic Carpentaria Basin

The Carpentaria Basin (Figure 23) deepens to the north from the Carpentaria Lowlands and underlies most of the Gulf of Carpentaria (Bradshaw et al., 2009; McConachie et al., 1997). The onshore Carpentaria Basin is the northernmost of a number of onshore basins that consist of Mesozoic sediments deposited during Cretaceous marine incursion across the Australian continent. Marine transgression commenced in the earliest Cretaceous and reached the maximum extent across more than half of the Australian continent during the Aptian (125 to 113 Ma) (Campbell and Haig, 1999).

Four sub-basins are recognised in the onshore and offshore Carpentaria Basin (Figure 23) based on the provenance and timing of Mesozoic sedimentary fill: the Western Gulf, Weipa, Staaten and Boomarra sub-basins (McConachie et al., 1990). The thickest section, of 1600 m, is offshore in the Weipa Sub-basin (McConachie et al., 1990). Sediments of Jurassic age are confined primarily to the Weipa and Staaten sub-basins (McConachie et al., 1990).

The Isa GBA region is located in the southern Staaten Sub-basin and the Western Gulf Sub-basin (Figure 23). It consists almost entirely of Cretaceous sediments (Section 3.4.3). The present boundaries of the Carpentaria Basin, in the vicinity of the Isa GBA region, are erosional (Figure 2) and the original extent of the basin was once much greater (Figure 23). Seismic interpretation suggests that at least 700 m of Cretaceous strata may have been eroded from over the western part of the Isa GBA region (Section 4.2.3).

The offshore Carpentaria Basin formed from relatively uniform flexural downwarping, with some reactivation of basement faults before Mesozoic sedimentation (McConachie et al., 1997). It experienced only minor extensional tectonism during its evolution, according to seismic interpretation of the Gulf of Carpentaria and Weipa regions (McConachie et al., 1990) and minor fault growth during the Jurassic and Cretaceous (McConachie et al., 1997). The nature of minor fault displacements in and near the Isa GBA region is discussed further in Section 4.2.3 and in the hydrogeology technical appendix (Buchanan et al., 2020).

Together with the Eromanga and Surat basins, the onshore component of the Carpentaria Basin in Queensland forms part of the Great Artesian Basin. More information on the Great Artesian Basin and its relationship to the Isa GBA region is provided in the hydrogeology technical appendix (Buchanan et al., 2020).

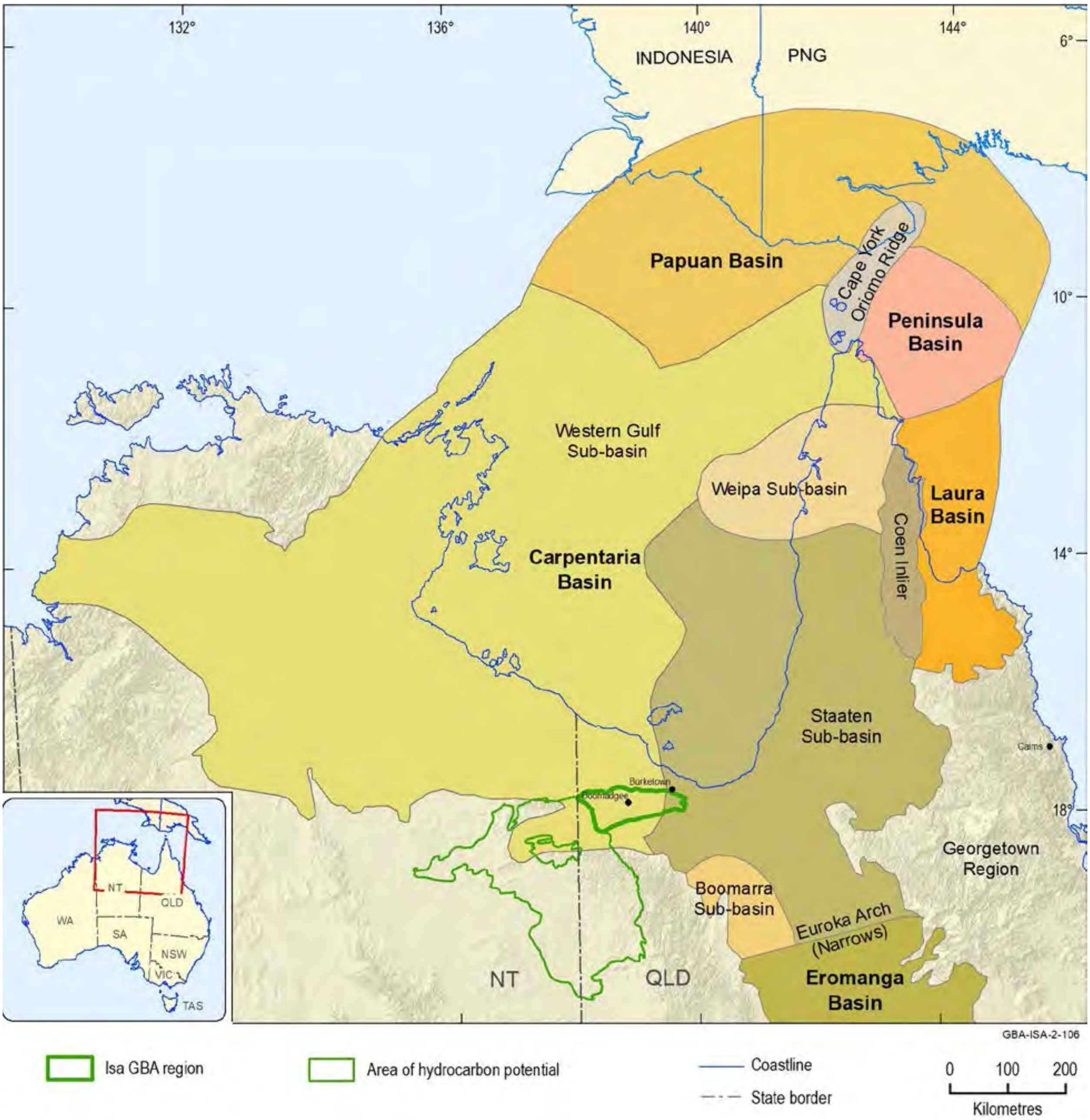


Figure 23 Interpreted original extent of the Carpentaria Basin and sub-basins, ridges and contiguous Mesozoic basins of Queensland and the Gulf of Papua

Carpentaria Basin sub-basins are the Western Gulf, Staaten, Weipa and Boomarra sub-basins. This figure shows the more extensive original distribution of the Carpentaria Basin: the present preserved remnants near the Isa GBA region are shown in Figure 2.
Source: McConachie et al. (1997), Munson et al. (2013a) and Cook et al. (2013). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-106

3.3.8 Cenozoic erosion and Karumba Basin

Much of the original distribution of Carpentaria Basin fill has been eroded to the present distribution indicated in Figure 2 (Section 3.3.7). Erosion of the Carpentaria Basin cover (Section 3.3.7) appears to coincide with erosion also of the Mount Isa Inlier rocks. Modelling of fission track data from the Mount Isa Inlier suggest that around 30 to 50 °C of cooling occurred within the last 100 Ma, corresponding to approximately 1.2 to 2.0 km of exhumation for an assumed geothermal gradient of 25 °C per km (Spikings et al., 1997).

Duddy et al. (2003) compiled apatite fission track analysis results across northern Australia and interpreted Cenozoic uplift and erosion that was widely experienced in northern and north-western basin areas during the Eocene, Oligocene and Pliocene to recent epochs. The erosion may be related to Oligocene to Miocene collision at the northern margin of the Australian plate.

The Carpentaria Basin is unconformably overlain by the Cenozoic Karumba Basin, which extends into the NT and parts of Papua New Guinea. Mid-Cretaceous extensional tectonics in eastern Australia may have initiated the Karumba Basin while Cenozoic collision at the northern Australian margin contributed regionally to its sedimentation and growth (Spikings et al., 2006 and references therein). More locally the erosion of the Mount Isa Inlier may have provided a sedimentary source for the Cenozoic Karumba Basin in the Gulf of Carpentaria (Spikings et al., 1997). The Karumba Basin experienced periodic localised deformation during its evolution (Bradshaw et al., 2009; McConachie et al., 1997).

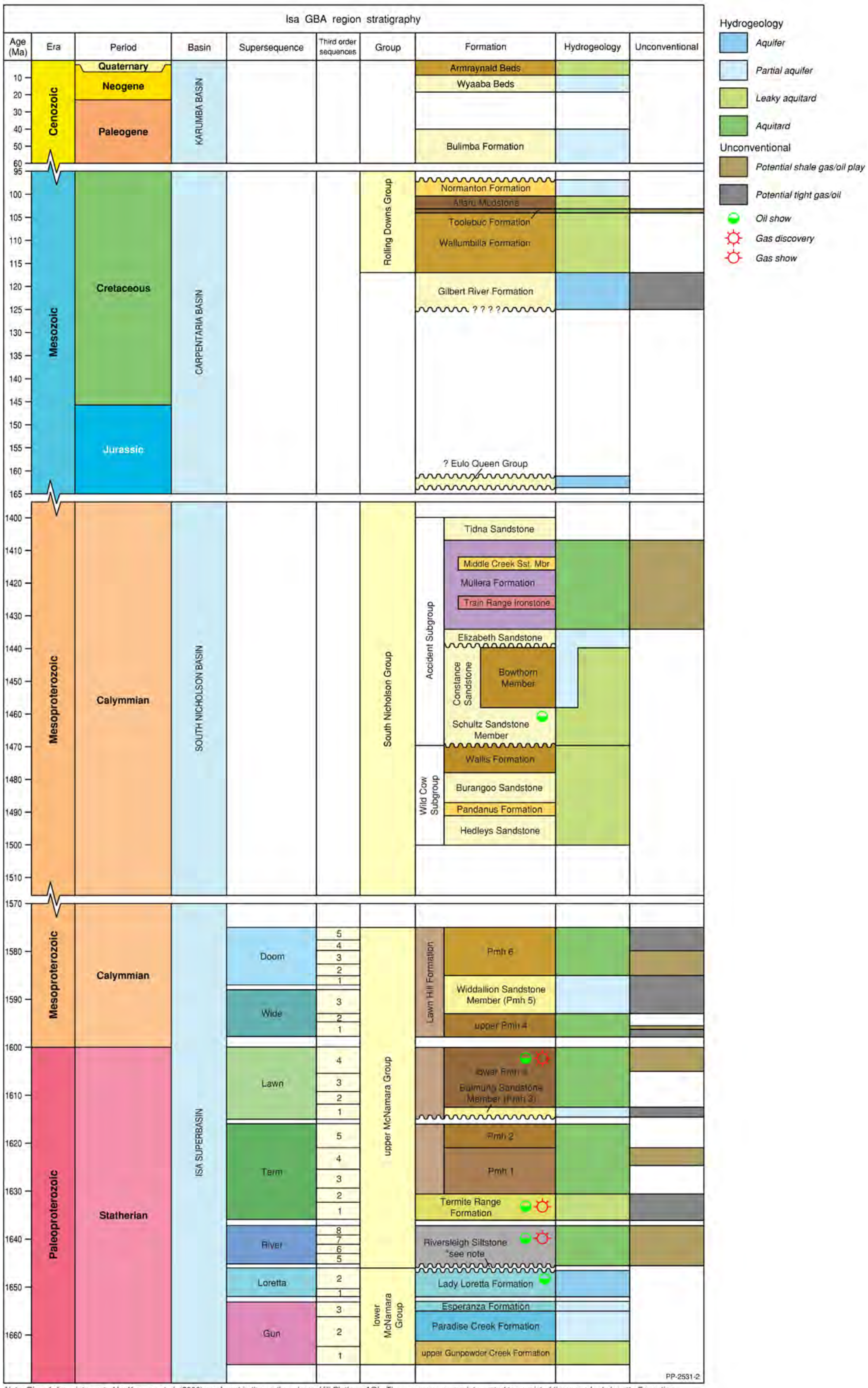
3.4 Stratigraphy and depositional environments

The following section describes the stratigraphy and depositional environments of the Isa Superbasin and the overlying South Nicholson, Carpentaria and Karumba basins (Figure 24). Published stratigraphic frameworks for basins in the Isa GBA region vary between the sub-disciplines of sequence stratigraphy and lithostratigraphy. The Isa Superbasin is described using sequence stratigraphy, whereas the Carpentaria and Karumba basins are described using lithostratigraphy. Both approaches are applied to the South Nicholson Basin.

Methods snapshot: sequence stratigraphy vs lithostratigraphy

The supersequences and sequences of sequence stratigraphy are composed of genetically linked strata related in time. Supersequences are controlled by the periodicity of tectonic evolution; third-order sequences encompass conformable lowstand tract to highstand tract sedimentation (that is, sedimentation controlled by relative sea level change from the initial marine flooding surface to the maximum marine flooding surface); and sediment lithologies vary not only temporally but laterally for the sequences to encompass these cycles. The boundaries between sequences are time-correlative. The implication of sequence stratigraphy is that the lithological characteristics of sediments assigned to a sequence in one area may be different from those of the same sequence and age in another area. Accordingly, the descriptions provided here for the Isa Superbasin describe locations and lateral variations in the lithology of sediments within each of the supersequences as well as changes over time.

By contrast, units in lithostratigraphy are defined on mappable units of comparable lithology or similar properties, in which a formation is the unit based on primary lithology. Formations may be subdivided into members or beds or aggregated with other formations into groups. The descriptions provided here for the South Nicholson Basin, Carpentaria and Karumba basins refer to the primary lithological characteristics of the formations, beds and groups in the region, and as the classification is based on these characteristics there is not the same requirement to describe lateral variations.



Note: River 1-4 are interpreted by Krassay et al. (2000) as absent in the northern Lawn Hill Platform AOI. These sequences are interpreted to consist of the upper Lady Loretta Formation (Pmll, River 1) the Shady Bore Quartzite (River 2-3), and the lower Riversleigh Siltstone (Pmr, River 3-4).

Figure 24 Sequence stratigraphy, lithostratigraphy and hydrostratigraphy of the Isa Superbasin, South Nicholson Basin, Carpentaria Basin and Karumba Basin, and hydrocarbon occurences

The chart breaks at 1570 to 1510 Ma, 1400 to 165 Ma and 95 to 60 Ma are for display purposes. This figure has been optimised for printing on A3 paper (297 mm x 420 mm)
Source: Isa Superbasin and South Nicholson Basin after Gorton and Troup (2018); Carpentaria Basin after Cook et al. (2013) and McConachie et al. (1997); Karumba Basin after Cook and Jell (2013); hydrostratigraphic units – see the hydrogeology technical appendix (Buchanan et al., 2020)
Element: GBA-ISA-2-113

3.4.1 Isa Superbasin

The sequence stratigraphy of the Isa Superbasin, and corresponding lithostratigraphy for the northern Lawn Hill Platform, is shown in Figure 24.

The Isa Superbasin sedimentary rocks are divided into seven second-order supersequences and 30 third-order sequences, as follows: Gun 1 to 3, Loretta 1 to 2, River 1 to 8, Term 1 to 5, Lawn 1 to 4, Wide 1 to 3 and Doom 1 to 5 sequences (Table 2; Figure 25). All Isa Superbasin supersequences are present in the Lawn Hill Platform region, southern flanks of the Murphy Inlier, and in the NT in the southern McArthur Basin (Figure 17; Figure 20) (Neumann and Fraser, 2007). In contrast, only the Gun and Loretta supersequences are preserved in the Leichhardt River Fault Trough (Neumann and Fraser, 2007).

Gorton and Troup (2018) summarised the supersequences of the northern Lawn Hill Platform and their relationship to source and reservoir rocks as follows. The lowstands of the supersequences are sandstone-rich; the highstand tracts are marked variably by carbonate platforms in the Gun and Loretta supersequences and by thick, organic-rich mudstones in the River, Term, Lawn, Wide and Doom supersequences. The platform carbonates and lowstand sandstones are potential hydrocarbon reservoirs and the highstand organic-rich mudstones are potential petroleum source rocks. Proven source rock reservoirs in the northern Lawn Hill Platform occur in the River and Lawn (Lawn 4) supersequences, where the organic-rich mudstones are best developed (Gorton and Troup, 2018).

For further discussion on the deposition of organic matter-rich sediments in Proterozoic environments, refer to the methods snapshot box overleaf.

Table 2 Stratigraphy of the Isa Superbasin

Supersequence	Age	Lithological description	Maximum thickness (m)	Depositional environments
Doom	Mesoproterozoic	Sandstone, siltstone, shale, carbonate	1000	Fluvial, coastal, marine shelf, deep marine
Wide	Mesoproterozoic	Sandstone, siltstone, dolomitic siltstone, shale	1100	Coastal, marine shelf, deep marine
Lawn	Paleoproterozoic	Sandstone, siltstone, tuffaceous sandstone and siltstone, shale	900	Shoreface, marine shelf, deep marine
Term	Paleoproterozoic	Sandstone, siltstone, tuffaceous sandstone and siltstone, shale	3500	Marine shelf to deep marine
River	Paleoproterozoic	Sandstone, siltstone, shale	3500	Coastal, marine shelf, deep marine
Loretta	Paleoproterozoic	Breccia, carbonate	1400	Coastal to marine shelf
Gun	Paleoproterozoic	Sandstone, siltstone, carbonate	1700	Fluvial, coastal, marine shelf, deep marine

Source: Based on data published in Krassay et al. (2000a) and Bradshaw et al. (2000)

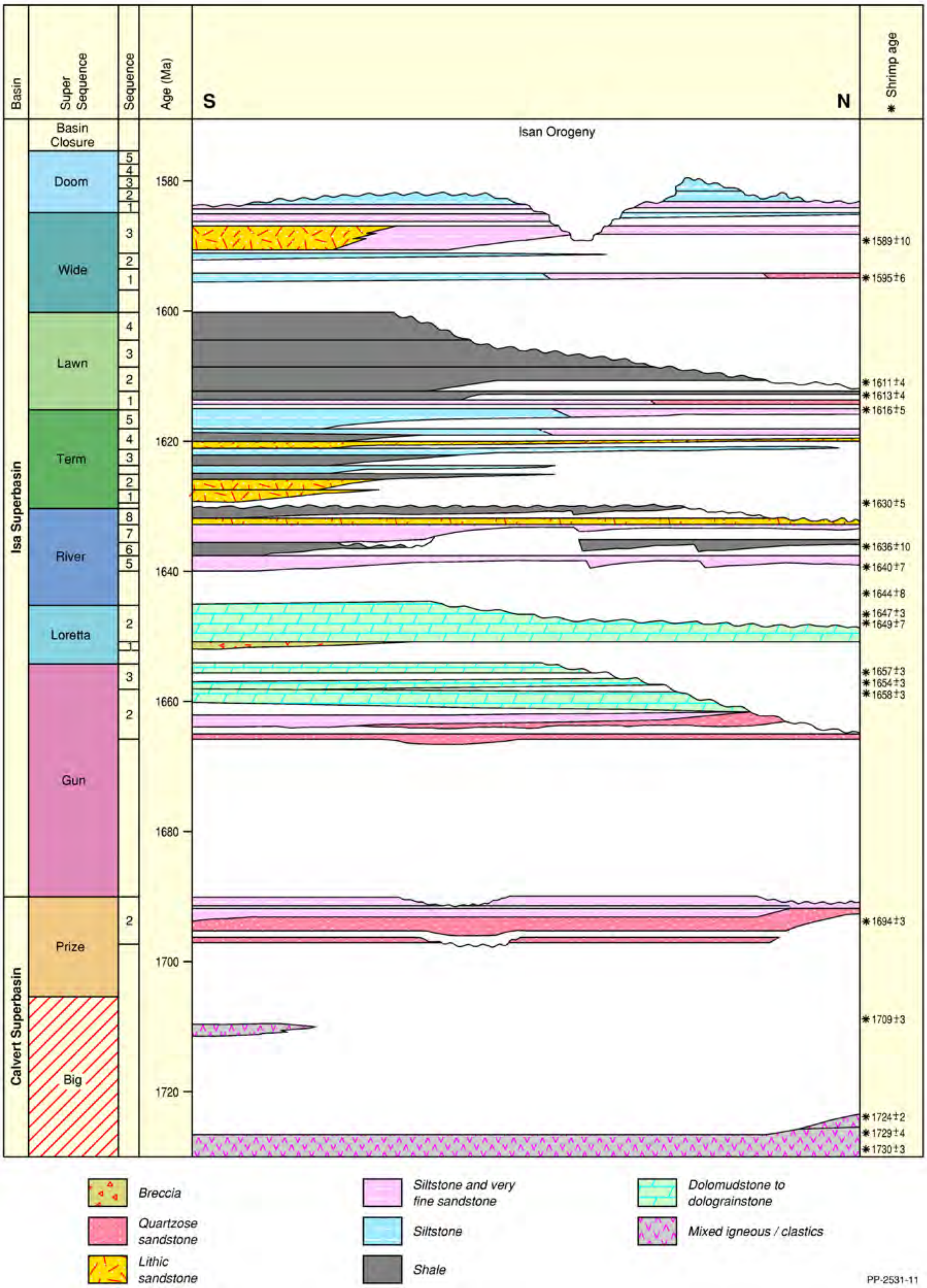


Figure 25 Chronostratigraphic chart for the Isa Superbasin and Calvert Superbasin, south to north across the northern Lawn Hill Platform

Source: Bradshaw and Scott (1999)
Element: GBA-ISA-2-115

Methods snapshot: Proterozoic depositional environments

Proterozoic depositional environments of organic matter-rich sediments differ in some key aspects from Phanerozoic environments. Organic-rich shale formation requires both low energy and low oxygen depositional environments in a sediment-starved setting to allow organic matter concentration. In the Proterozoic this was assisted by widespread ocean anoxia that corresponded to the return to low atmospheric oxygen levels by ca 1850 Ma, after the Great Oxidation Event (Daines et al., 2017; Planavsky et al., 2014). Atmospheric oxygen and ocean oxygenation remained low, barring transient excursions, until they eventually approached modern levels during about 600 to 400 Ma (Daines et al., 2017). Anoxic (Fe^{2+}- rich) conditions were widespread in the mid-Proterozoic ocean in the 1800 to 1000 Ma period (Planavsky et al., 2011).

Proterozoic sediments were deposited before the evolution of woody, vascular plants. Organic matter in the northern Lawn Hill Platform sediments may have been derived from planktonic algae, interpreted as *Botryococcus*, based on the imaging of algal cell walls in younger undermature alginite in Cambrian Georgina Basin sediments and compared on a maturation scale to the middle Proterozoic alginite of the McArthur Basin (Glikson et al., 2006; Glikson et al., 1992; Gorton and Troup, 2018). Alternatively bacteria may have been the dominant primary producers of oceanic sedimentary organic matter before the Neoproterozoic (Brocks et al., 2017). In either case, alginite dominated the resulting macerals; analysis of samples collected from Isa Superbasin source rocks consistently indicate alginite, pyrobitumen and bitumen as the primary organic matter types (Energy Resources Consulting, 2017; Glikson et al., 2006).

Organic matter deposition may also occur in shallow waters from the growth of microbial mats, such as stromatolites. Proterozoic carbonate platforms are believed to have developed from the accretion of carbonate sediments by stromatolites, as they are the principal component of Proterozoic platform and shelf carbonates (Grotzinger and Knoll, 1999).

3.4.1.1 Gun Supersequence

The Gun Supersequence (1670 to 1655 Ma) developed as a response to sinistral strike-slip tectonism associated with compressive stresses generated in central Australia (Southgate et al., 2000b). Ancestral north and north-east structures in the Leichhardt River Fault Trough and Lawn Hill Platform controlled deposition of the Gun Supersequence in these locations (Southgate et al., 2000b).

All three third-order sequences recognised in the Gun Supersequence are present on the Lawn Hill Platform south of the Isa GBA region and in the Leichhardt River Fault Trough, while only Gun 2 and Gun 3 are in the Isa GBA region on the northern Lawn Hill Platform (Southgate et al., 2000a). The supersequence was deposited on a ramp; by terminal Gun 2 time it extended from the Murphy Inlier in the north-west to a depocentre in the south-east (Southgate et al., 2000b). Siliciclastic shoreline facies developed in the north and west and deeper water basinal facies to the east and south, shown by facies maps for an area south of the Isa GBA region in Figure 26 (Southgate et al., 1999; Southgate et al., 2000b).

The Gun Supersequence can be characterised laterally by transitions from fluvial and coastal facies in the north and west to progressively peritidal, inner to outer ramp carbonate facies and deeper water, fine-grained siliciclastic and carbonate rocks in the south and east (Southgate et al., 1999). It is characterised also by changes over time between siliciclastic and carbonate facies. Siliciclastic sediments dominate the transgressive deposits on the Leichhardt River Fault Trough; high rates of sediment supply led to the accumulation of 1000 m of siltstone and shale in the trough by Gun 2.3f time, as indicated in Figure 26b (Southgate et al., 1999; Southgate et al., 2000b).

Initial transgression on the Lawn Hill Platform produced siliciclastic very fine-grained sandstone and siltstone, fining upwards into shale, dolomudstone and carbonaceous shale (Southgate et al., 2000a). Gradual onlap, the drowning of the siliciclastic provenance area and declining sedimentation rates led to the transition from siliciclastic sediments to those dominated by carbonates (Southgate et al., 1999; Southgate et al., 2000a). The upper Gun 2 and Gun 3 highstand deposits reached the basement high of the Murphy Inlier in the north-west (Southgate et al., 2000a) and across the Isa GBA region. An example section is shown in Section 4 (Figure 33).

The prevalence of algal (or microbial) mats near the end of the supersequence could have generated hydrocarbons that subsequently migrated, however the Gun Supersequence is not considered to contain potential shale gas source rocks (Gorton and Troup, 2018).

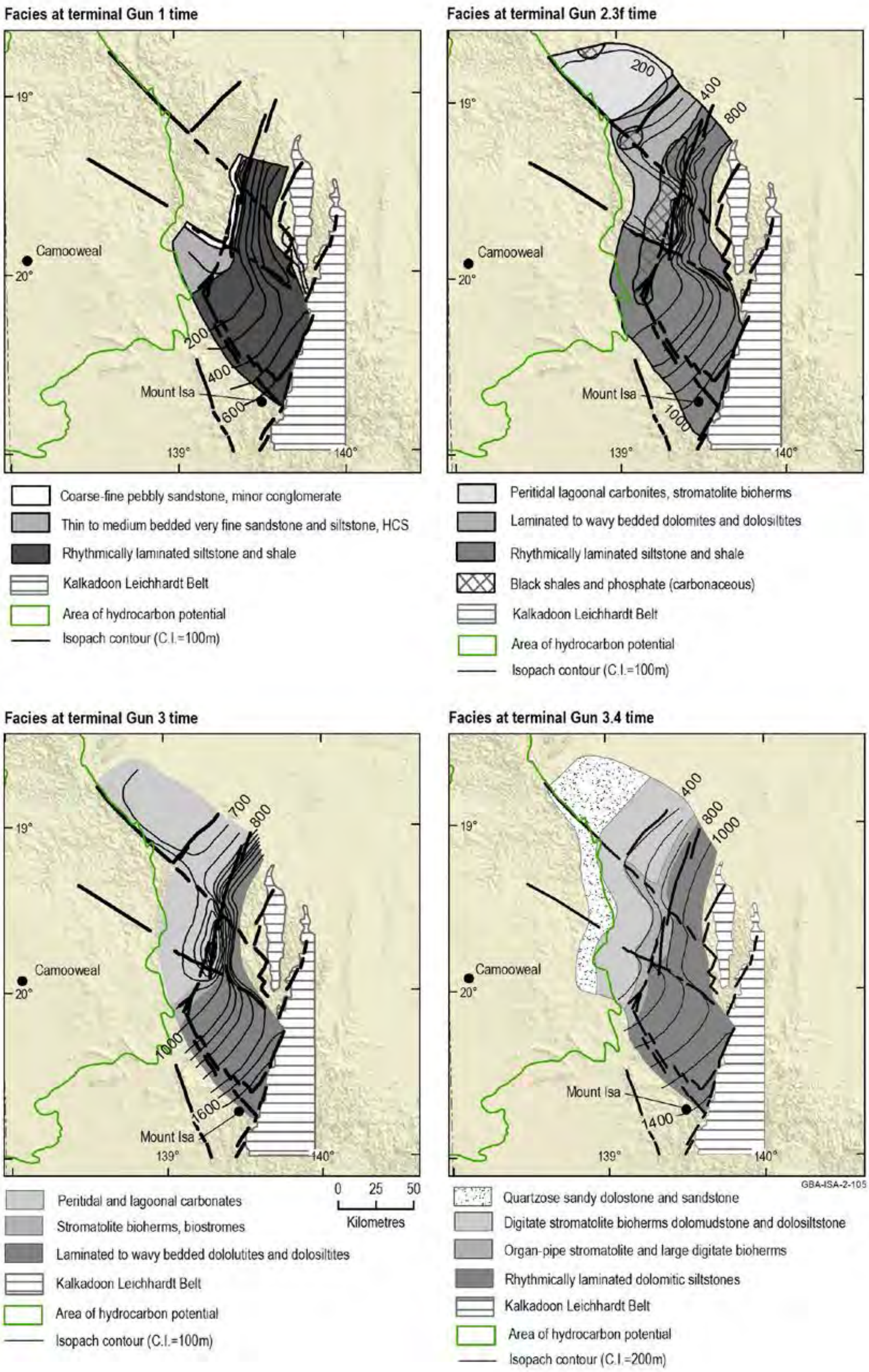


Figure 26 Isopach and facies maps for the Gun Supersequence to the south of the Isa GBA region, indicating a south-east facing ramp with shoreline facies in the north and deeper water basinal facies in the east and south

Eastern boundary of the area of hydrocarbon potential shown for reference.
Source: From the full set provided in Southgate et al. (2000b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-105

3.4.1.2 Loretta Supersequence

Uplift extending from the basement high of the Murphy Inlier produced a regional south-east-dipping monocline that resulted in the erosion of the Gun Supersequence and controlled the geometry of subsequent Loretta Supersequence sedimentation (Southgate et al., 2000a). The erosion may have supplied the basal breccia of the Loretta Supersequence (Southgate et al., 2000a) classified as the Loretta 1 sequence (Bradshaw et al., 1999). Initiation of deposition is dated at about 1655 Ma at a sequence boundary and a further depositional age is given by a SHRIMP zircon date at 1647 ± 4 Ma (Page et al., 2000).

The eroded monocline was transgressed in the south by a carbonate platform and the supersequence is characterised by deposition of a thick carbonate succession in a largely shallow marine ramp setting (Krassay et al., 2000b; Scott and Bradshaw, 1999; Southgate et al., 2000a). In the Isa GBA region it thins to the north primarily due to erosion at the overlying River Supersequence boundary with minor thinning due to onlap (Scott and Bradshaw, 1999). The platform carbonates of the Loretta Supersequence are indicated as potential reservoirs for the northern Lawn Hill Platform but potential unconventional hydrocarbon source rocks are not identified in this supersequence (Gorton and Troup, 2018).

Much of the Loretta Supersequence was eroded over the southern flanks of the Murphy Inlier and on the shoaling hinge side of half-graben depocentres before River Supersequence deposition during a basin-wide north-east to south-west crustal shortening and inversion event (Gibson et al., 2017; Gibson et al., 2016; Idnurm, 2000; Scott and Bradshaw, 1999).

3.4.1.3 River Supersequence

The River Supersequence was deposited during a period of regional north to south extension, which generated a series of east, east-north-east and south-east trending faults downthrown to the north across the northern Lawn Hill Platform (Scott and Tarlowski, 1999).

The erosion of the Loretta Supersequence along the southern margin of the Murphy Inlier basement high produced a terrigenous sediment influx in River 1, in contrast to the underlying shallow-water carbonate facies (Krassay et al., 2000b). Up to 700 m of incision occurred before the River Supersequence was deposited on the northern Lawn Hill Platform (Krassay et al., 2000b).

SHRIMP age determinations indicate that the River Supersequence was deposited probably between 1645 and 1630 Ma (Krassay et al., 2000b). Eight third-order sequences are identified for the River Supersequence on the central Lawn Hill Platform, but only River 5, 6 and 7 are present on the southern flanks of the Murphy Inlier (Krassay et al., 2000b; Lindsay et al., 1999). The River Supersequence is marked by the partitioning of sedimentation into fault-controlled sub-basins. It forms at least two southward-thickening depositional wedges, bounded in the north by regional basement highs (Krassay et al., 2000b). The area of the present Murphy Inlier formed the bounding basement high for the northern Lawn Hill Platform wedge and the central Lawn Hill Platform wedge was bounded by a basement high that extended westwards from the Kamarga Dome (Figure 16) (Krassay et al., 2000b) south of the Isa GBA region. Syn-sedimentary fault movement also produced smaller half-graben across which abrupt changes in sediment thickness occur (Krassay et al., 2000b). Extension during the River Event at about 1640 Ma created local depocentres within tilt blocks in the northern Lawn Hill Platform, evidenced by growth of River Supersequence strata across faults (Krassay et al., 2000b; Scott and Tarlowski, 1999).

River 5 is the oldest sequence of the River Supersequence preserved on the northern Lawn Hill Platform and it rests directly on the Loretta Supersequence carbonate rocks (Krassay et al., 2000b). The River 5 to 7 sequences of the northern Lawn Hill Platform are marked by lowstand tracts that consist of silty sandstones (River 5), siltstones (River 6) and variably canyon-base marine siltstones and valley-base fluvial to shallow marine conglomerates and sandstones in River 7 (Bradshaw et al., 2000; Bradshaw et al., 1999). Transgressive systems tracts include siltstones transgressing into carbonaceous shales. Highstand systems tracts in River 5 to River 7 were periods of deep water or below storm wave-base anaerobic deposition of carbonaceous shale coarsening up to dolomitic siltstone and sandstone with tuff interbeds (Bradshaw et al., 2000). River 8 was intersected by wells in the western portion of the Isa GBA region but was believed to have been removed by erosion from the area of the southern Murphy Inlier during the next supersequence phase (Bradshaw et al., 2000).

The organic-rich shales of the River Supersequence are among the main shale gas source rocks in the Isa Superbasin (Gorton and Troup, 2018).

3.4.1.4 Term Supersequence

The Term Supersequence was deposited between ≥1630 to 1615 Ma (Krassay et al., 2000a). Scott and Bradshaw (1999) interpreted that the Term Supersequence formed during a post-extensional thermal subsidence phase. More recently, Gibson et al. (2017) have used regional seismic data over the central Lawn Hill Platform to interpret ongoing extension during the initial depositional stages of the Term Supersequence, with thermal subsidence occurring during later stages of deposition.

A change in sedimentation from the River Supersequence is marked by the influx of thick bedded turbidite and hemipelagic deposits resulting from broad regional transgression on a surface newly downwarped to the south-west, with emergence and truncation in the north (Krassay et al., 2000a; Southgate et al., 2000a). The Term Supersequence forms a series of onlapping wedges which gradually thin to the north; in the western part of the Isa GBA region the sequences thicken significantly to the south-west (Southgate et al., 2000a). Only the upper part of the Term Supersequence is present on the southern flanks of the Murphy Inlier (Southgate et al., 2000a) and the emergent basement high here is considered as the source of the coarse-grained sandy sediments that were deposited as turbidites (Frogtech Geoscience, 2018a).

Lowstand systems tract deposits in Term 1 and Term 2 are characterised by thick, sandy, deep water fan sediments (Krassay et al., 2000a). The Term 1 sequence occurs only in the southern part of the Isa GBA region, being absent in the north due to stratal onlap (Bradshaw et al., 1999). The Term 2 transgressive deposits in the western part of the Isa GBA region culminated in the most shale-rich part of the section, with highstand deposits from low-energy deep water sedimentation of silt-sized clastic material (Krassay et al., 2000a).

The lower Term Supersequence occurs on the western side of the central Lawn Hill Platform as mid- to outer-shelf turbidites and outer fan sequences (Polito et al., 2006). The Term 3 sedimentation on the central Lawn Hill Platform was constrained by the north-eastern side of the Termite Range Fault (Figure 16) and deposition to the south-west of the fault is missing due to onlap and non-deposition (Krassay et al., 2000a). Syn-sedimentary fault activity along the Termite Range Fault and major north-east trending faults, such as those within the Elizabeth Creek Fault Zone (Figure 16), contributed to overthickened sections and switching of provenance areas and depocentres (Krassay et al., 2000a).

Term 3 to Term 4 sequences include transgressive deposits of siltstones and carbonaceous shales (Krassay et al., 2000a) that thin to the north in the Isa GBA region, and transgressional deposits that gradually coarsen in Term 4 and indicate progradation in the north (Bradshaw et al., 1999; Krassay et al., 2000a). The Term 5 sequence is more widely eroded and includes a significant tuffaceous component, interpreted to result from tectonically controlled regression that probably began during the Term 4 highstand (Bradshaw et al., 1999). The upper age of the Term Supersequence is about 1615 Ma based on SHRIMP zircon ages of tuffaceous sediments (Krassay et al., 2000a).

A potential shale gas source rock interval is recognised at the top of the Term Supersequence (Gorton and Troup, 2018).

3.4.1.5 Lawn Supersequence

The Lawn Supersequence appears to have formed during a period of broad regional subsidence over the northern Lawn Hill Platform (Scott and Bradshaw, 1999; Scott and Tarlowski, 1999). Alternatively, Gibson et al. (2017) proposed that the Lawn Supersequence was deposited at the beginning of a syn-inversion basin phase associated with onset of the Isan Orogeny, based on their seismic interpretations over the central Lawn Hill Platform. However, there is no evidence for inversion at the base of the Lawn Supersequence over the northern Lawn Hill Platform, with the seismic interpretations of Scott and Bradshaw (1999) showing a relatively conformable surface in most areas.

The Lawn Supersequence was deposited over a likely age range of 1615 to 1600 Ma (Krassay et al., 2000a). The Term and Lawn supersequences together form a megawedge which thins rapidly from 4000 m in the south to only 250 m thick on the southern edge of the Murphy Inlier (Scott et al., 1998). The Lawn Supersequence thins by erosional truncation in addition to onlap (Krassay et al., 2000a; Scott et al., 1999).

An erosional boundary and a decrease in the accommodation space in the Lawn Supersequence marks its initial stages (Krassay et al., 2000a). Coarser grained sand body deposits representing much shallower, higher energy depositional environments indicate a basin-ward shift in facies (Krassay et al., 2000a). Two main tectonostratigraphic phases are identified: initial low accommodation conditions in the lowstand systems tract of Lawn 1, followed by rapid subsidence and transgression into deep marine carbonaceous shales in upper Lawn 1, continuing into further deepening during the Lawn 2 to 4 sequences (Krassay et al., 1999). The Lawn 1 transgressive systems tract marks the change from the sand bodies to progressively finer grained and more carbonaceous sediments (Krassay et al., 2000a). The Lawn 2, 3 and 4 sequences share the characteristics of thick, fine-grained transgressive systems tract deposits (Krassay et al., 2000a). Maximum flooding occurred during Lawn 4; high total organic carbon values and elevated ditchgas concentrations, evident in Egilabria 1 and Beamesbrook 1 in the Isa GBA region, indicate a very condensed section in the deep part of the basin during Lawn 4 deposition (Krassay et al., 2000a).

The Lawn 2, 3 and 4 sequences have all been truncated in the north and north-west in the Fickling Group of the southern flanks of the Murphy Inlier; only the coarser grained Lawn 1 lowstand systems tract and an overlying transgressive systems tract have been preserved below the Wide Supersequence here (Bradshaw et al., 2000). The extensive distribution of the Lawn 1 sandstones suggests deposition in a shallow sea with little variation in sea level, which allowed significant progradation (Krassay et al., 2000a). The rapid transgression evident in Lawn 1 is interpreted to be due to broad regional subsidence as there is a lack of evidence of syn-depositional fault activity in seismic profiles (Bradshaw et al., 2000). Evidence of volcaniclastic material being incorporated into Term 5 and Lawn 1 sediments has led to a further interpretation of volcano-tectonic thermal doming and subsequent collapse to explain the changes in accommodation and the rapid drowning of the Lawn 1 lowstand shorelines (Krassay et al., 2000a).

The highly organic-rich shale units of Lawn 4 are, along with the River Supersequence, considered to be the principal shale gas source rocks for the Isa Superbasin (Gorton and Troup, 2018). Refer to the prospectivity technical appendix for further information (Bailey et al., 2020).

3.4.1.6 Wide Supersequence

The Wide Supersequence formed during a period of wrench tectonics in the early stages of the Isan Orogeny (Bradshaw et al., 2018c; Scott and Bradshaw, 1999), most likely in the period 1600 to 1585 Ma (Krassay et al., 2000a; Page et al., 2000).

The Wide Supersequence began with east-south-east strike-slip deformation on steep west-north-west trending faults and sub-basin development, folding and truncation of part of the underlying Lawn Supersequence (Krassay et al., 2000a; Scott et al., 1998). The Early Isan Orogeny began around 1600 Ma (see Section 3.3) and it overlapped with deposition of the Wide Supersequence and the subsequent Doom Supersequence (Frogtech Geoscience, 2018a). The base of the Wide Supersequence varies from relatively conformable contacts to major truncation surfaces with removal of the Lawn 2 to 4 sequences, but generally occurs as a clear unconformity with channels and erosion (Bradshaw et al., 2000; Scott et al., 1998). The oldest measured age for the Wide Supersequence is 1595 ± 6 Ma (Krassay et al., 2000a; Page and Sweet, 1998).

Three third-order sequences are defined, in which dolomitic limestone and siltstone characterise the lower Wide Supersequence and arkosic sandstone and siltstone comprise the upper part (Southgate et al., 2000a). The upward coarsening to sandier facies is unusual compared to the underlying supersequences (Krassay et al., 2000a). Syn-depositional growth fault activity is evident; thickening occurred within the hanging walls of faults defining small sub-basins (Bradshaw et al., 2000; Krassay et al., 2000a; Southgate et al., 2000a). Basin margin instability is indicated by commonly observed debris flows in the upper Wide 3 sequence (Scott and Bradshaw, 1999). The stratigraphy of the Wide Supersequence indicates broad regional transgression and locally high subsidence rates (Scott and Bradshaw, 1999) with Wide 3 sediments varying from deep marine lowstand sandstones in the south to interbedded sandstones and siltstones at Egilabria 1 and interbedded siltstones and shales at Beamesbrook 1 in the Isa GBA region (Bradshaw et al., 1999).

3.4.1.7 Doom Supersequence

The Doom Supersequence was deposited during a period of post-deformational subsidence following the Wide Event and prior to basin closure at the culmination of the Isan Orogeny.

The Doom Supersequence does not have the evidence of syn-depositional growth that characterises the Wide Supersequence (Southgate et al., 2000a). The complex geometry of the Wide Supersequence changes to a tabular planar geometry in the Doom Supersequence; the boundary is mostly conformable between the two (Bradshaw et al., 1999). The five Doom sequences were intersected in the Egilabria 1 well in the Isa GBA region but in most areas the sequences are poorly preserved due to truncation at the base of the South Nicholson Group (Bradshaw et al., 1999). The supersequence is interpreted to have formed a sediment cover of relatively uniform thickness before being variably eroded (Southgate et al., 2000a).

Doom 1 has a marked increase in sand content from the Wide Supersequence in a regionally extensive, lithologically immature sandstone (Bradshaw et al., 1999; Krassay et al., 2000a). Sediment characteristics of the Doom 1 lowstand systems tract regionally indicate rapid deposition in deep water beyond the influence of currents, with a possible but rare overlying thin siltstone-dominated transgressive systems tract (Krassay et al., 2000a). Subsequent retrogradation led to sediment starvation and the Doom 2 and 3 deep marine siltstones and carbonates, coarsening up to shelfal and fluvial sandstones in the Doom 4 and 5 sequences (Bradshaw et al., 2000). Fluvial incision and deposition in the Doom 5 sequence may indicate a rapid decline in accommodation space in response to the Isan Orogeny, marking the end of Isa Superbasin deposition (Bradshaw et al., 1999).

3.4.2 South Nicholson Basin

The South Nicholson Basin in the Isa GBA region comprises the fluvial to shallow marine South Nicholson Group sediments (Figure 24). Like the Isa Superbasin sequences, the base of the South Nicholson Group onlaps the basement high of the Murphy Inlier, but the group thickens instead to the south-west to south (Jackson et al., 1999). The South Nicholson Group is divided into the Wild Cow Subgroup and Accident Subgroup, which are separated by a regional unconformity (Gorton and Troup, 2018; Sweet, 2017) (Figure 24 and Table 3). Descriptions of the South Nicholson Basin sequences are summarised below from Sweet (2017).

Table 3 Stratigraphy of the South Nicholson Basin

Stratigraphic unit	Formation	Age	Lithological description	Maximum thickness (m)	Depositional environments
Accident Subgroup	Tidna Sandstone	Mesoproterozoic	Sandstone	350	Shallow marine
	Mullera Formation	Mesoproterozoic	Mainly shale and siltstone punctuated by sandstone, ferruginous sandstone, ironstone and minor conglomerate	2110	Shallow marine, storm-dominated marine shelf, deep marine
	Elizabeth Sandstone	Mesoproterozoic	Sandstone	200	Shallow marine
	Constance Sandstone	Mesoproterozoic	Conglomerate, sandstone (Schultz Sandstone Member); Shale, siltstone and sandstone (Bowthorn Member)	1170	Fluvial (Schultz Sandstone Member); Storm-dominated marine shelf (Bowthorn Member)
Wild Cow Subgroup	Wallis Formation	Mesoproterozoic	Shale, siltstone and minor sandstone	150	Storm-dominated marine shelf
	Burangoo Sandstone	Mesoproterozoic	Sandstone	320	Shallow marine to fluvial
	Pandanus Formation	Mesoproterozoic	Shale, siltstone and interbedded sandstone	130	Storm-dominated marine shelf
	Hedleys Sandstone	Mesoproterozoic	Conglomerate, sandstone	90	High-energy fluvial

Source: Based on data published in Sweet (2017)

The Wild Cow Subgroup in Queensland includes the Hedleys Sandstone, Pandanus Formation, Burangoo Sandstone and Wallis Formation (Sweet, 2017). The Hedleys Sandstone consists primarily of fluvial channel sediments laid down on an erosion surface cut into the underlying Isa Superbasin rocks (Sweet, 2017). The Pandanus Formation consists of storm-dominated shelf sediments, indicating marine incursion. The beds include laminated shales, deposited under low-energy deeper water conditions, and higher energy deposits, indicating variably strong, scouring currents and detritus deposition in shallower water (Sweet, 2017).

Basal fine-grained sandstones of the Burangoo Sandstone may have been deposited in a shallow marine environment, otherwise most of the unit consists of coarser grained and poorly sorted sublithic to quartzose sands and pebbles deposited in a fluvial setting (Sweet, 2017; Withnall and Hutton, 2013). The Wallis Formation consists of storm-dominated shelf deposits of shale, siltstone and thinly interbedded sandstone similar to the Pandanus Formation (Sweet, 2017; Withnall and Hutton, 2013).

The Accident Subgroup in Queensland includes the Constance Sandstone, Elizabeth Sandstone, Mullera Formation and Tidna Sandstone (Sweet, 2017). High-energy braided fluvial deposits, consisting of coarse-grained sandstones and fine-grained conglomerates, form the lower

Constance Sandstone (Sweet, 2017). These are overlain by alternating marine mudstone and fine-grained sandstone, indicating progradation across a relatively shallow shelf (Sweet, 2017).

A second unconformity marks the boundary in this region between the Constance Sandstone and the overlying Elizabeth Sandstone (Sweet, 2017). The Elizabeth Sandstone represents shallow marine upper shoreface deposits of variably medium- to coarse-grained and fine- to medium-grained sandstones (Sweet, 2017). Deeper marine siltstones and shales of the Mullera Formation include some sandstone, ironstone and minor conglomerate units (Sweet, 2017; Withnall and Hutton, 2013). The Tidna Sandstone consists of shallow marine medium- to fine-grained massive quartzose sandstone (Carr et al., 2016; Withnall and Hutton, 2013).

The South Nicholson Group does not occur across the full extent of the Isa GBA region. Seismic sections indicate that up to 300 m of strata are preserved in incised valleys around Argyle Creek 1, but in most parts of the Isa GBA region the South Nicholson Group thins, through onlap and truncation, to less than 100 m (Jackson et al., 1999). Only a thin remnant was intersected in the Comalco well Beamesbrook 1 (Figure 19) in the east (Krassay and Bradshaw, 1999) and it was not intersected in the Armour Energy well Egilabria 4 in the north-east of the Isa GBA region (Bradshaw et al., 2018c). At Argyle Creek 1 the South Nicholson Group consists predominantly of fine-grained coastal or fluvial sandstones at the base, and a thick glauconitic shelf siltstone interval at the top (Krassay and Bradshaw, 1999).

3.4.3 Carpentaria Basin

The stratigraphy of the Carpentaria Basin is summarised in Figure 24 and formations intersected in the Burketown region (including the Isa GBA region) are described in Table 4. The Jurassic Eulo Queen Group has not been identified in the Isa GBA region, but it is included in this review as it could be potentially present as thin isolated paleovalley fill. Additional detail is provided in the hydrogeology technical appendix (Buchanan et al., 2020).

The onshore Jurassic Eulo Queen Group is thin to absent in the onshore Western Gulf and southern Staaten sub-basins (Section 3.3.7). In the Western Gulf Sub-basin it is interpreted as isolated valley fill in highlands (McConachie et al., 1990). In the southern Staaten Sub-basin it occurs as thin but variable fluvial sandstones (McConachie et al., 1990).

The Gilbert River Formation is associated with the development of Cretaceous marine transgression. It commenced deposition in fluvial environments, with increasing marine influence until deeper marine conditions developed during the Aptian age of the early Cretaceous (Cook et al., 2013; McConachie et al., 1997). The Gilbert River Formation is dominated by clayey quartzose sandstones, fining upwards into siltstone and glauconitic sandstone (Cook et al., 2013). The formation is typically 30 m and up to 260 m thick (McConachie et al., 1997).

The Gilbert River Formation is significant in the Isa GBA region as it is a stratigraphic equivalent of the Cadna-owie–Hooray aquifer of the adjacent Eromanga Basin (Radke et al., 2012), the most widely utilised aquifer within the Great Artesian Basin. The southern Carpentaria Basin is contiguous with the Eromanga Basin across the Euroka Arch (Figure 23). The formation was intersected in the eastern part of the Isa GBA region in the Armour Energy well Egilabria 4 and Comalco well Beamesbrook 1 (Figure 9).

Table 4 Stratigraphy of the onshore Carpentaria Basin (in the Burketown area)

Stratigraphic unit	Age	Lithological description	Maximum thickness (m)	Depositional environments
Normanton Formation	Upper Cretaceous (Cenomanian)	Glauconitic sandstone and siltstone	300	Marginal marine to shallow marine
Allaru Mudstone	Lower Cretaceous (Albian)	Claystone, siltstone, calcareous siltstone, glauconitic sandstone	700	Shallow marine
Toolebuc Formation	Lower Cretaceous (Albian)	Carbonaceous shale and carbonate	65	Restricted marine
Wallumbilla Formation	Lower Cretaceous (Aptian to Albian)	Glauconitic sandstone fining-up to siltstone, claystone and silty limestone	600	Marginal marine to deep marine
Gilbert River Formation	Lower Cretaceous (Barremian to Aptian)	Sandstone and siltstone	260	Fluvial to shallow marine
Eulo Queen Group	Upper Jurassic (Oxfordian to Kimmeridgian)	Sandstone interbedded with siltstone and claystone	150	Fluvial

Source: Based on data published in Bradshaw et al. (2009)

The Wallumbilla Formation contains thick successions of entirely marine siltstone, glauconitic sandstone and silty limestone, marking a major late Aptian marine transgression (Cook et al., 2013). The upper part consists of siltstone and claystone sequences, deposited in more open-water marine conditions than the lower part, which has varying proportions of sandstone from terrestrial input (McConachie et al., 1997). The Wallumbilla Formation was intersected widely by exploration wells in the Isa GBA region.

The Toolebuc Formation is a thin unit of limestone and carbonaceous shale, with minor siltstone and sandstone, representing maximum marine conditions (Cook et al., 2013). The Toolebuc Formation was also intersected widely in the exploration wells of the Isa GBA region.

The Allaru Mudstone contains siltstone, claystone and minor fine-grained sandstone, deposited in shallow marine to paralic conditions with minimum terrestrial influx (McConachie et al., 1997). It was intersected in the Comalco wells Egilabria 1, Desert Creek 1 and Beamesbrook 1 and the Armour Energy wells Egilabria 2 and Egilabria 4.

The Normanton Formation consists of glauconitic sandstone and siltstone, interpreted as the final phase of Cretaceous sedimentation (McConachie et al., 1997). Carbonaceous phases are locally common (McConachie et al., 1997). In the Isa GBA region it was intersected in the Mid-Eastern Oil well Burketown 1 only, as a soft carbonaceous grey clay shale (Perryman, 1964).

3.4.4 Karumba Basin

The Cenozoic Karumba Basin unconformably overlies much of the onshore and offshore Carpentaria Basin (McConachie et al., 1997). It is less than 250 m thick onshore, and consists of fluvial, lacustrine and minor shallow marine sediments (Table 5) (Bradshaw et al., 2009). This review draws on the updated stratigraphy and interpreted ages presented in Cook and Jell (2013), in which the Floraville Formation is synonymised into the Paleogene Bulimba Formation. Additional detail on the Karumba Basin is provided in the hydrogeology technical appendix (Buchanan et al., 2020).

The Karumba Basin was superimposed on the Carpentaria Basin after Cretaceous extensional tectonics in eastern Australia, while Cenozoic collision at the northern Australian margin contributed to its sedimentation and growth (Section 3.3.8). The Paleogene Bulimba Formation was deposited as clayey quartzose sand, sandstone, conglomerate, siltstone and claystone, in fluvial to nearshore environments (Bradshaw et al., 2009). It is generally recognisable as intensely weathered clayey sandstone (Radke et al., 2012). Erosion and deep weathering after deposition of the Bulimba Formation produced the widespread late Eocene to earliest Oligocene Aurukun Surface, consisting of deep laterites and sporadic silcretes (Cook and Jell, 2013).

The overlying Miocene to Pliocene Wyaaba beds (Cook and Jell, 2013) were deposited after the onset of collision at the northern Australian margin. The onshore units consist of fluvial to nearshore clayey sandstone, conglomerate, sandy claystone and calcareous siltstone (Cook and Jell, 2013). Localised lacustrine limestone formed to the south-west of the Isa GBA region in the Riversleigh area.

The Pleistocene to Recent Armraynald beds consist of silt, clay, sandy clay and minor sand and gravel, deposited in episodes related to tectonic, eustatic and climate variations (Cook and Jell, 2013). The presently onshore units were deposited in fluvial to nearshore environments.

Table 5 Stratigraphy of the Karumba Basin

Stratigraphic unit	Age	Lithological descriptions	Maximum thickness (m)	Depositional environments
Armraynald beds	Pleistocene to Recent	Gravel, clayey sand, silt, clay	60	Fluvial to marginal marine
Wyaaba beds	Miocene to Pliocene	Conglomerate, sandstone, calcareous siltstone	120	Fluvial to marginal marine
Bulimba Formation	Paleocene to Eocene	Conglomerate, sandstone, siltstone and claystone	65	Fluvial to marginal marine

Source: Based on data published in Bradshaw et al. (2009) and Cook and Jell (2013)

The Karumba Basin geological history was simplified by Smart et al. (1980) to three cycles of deposition, weathering and erosion, termed the Bulimba, Wyaaba and Claraville cycles (Cook and Jell, 2013). These cycles are discussed further in the hydrogeology technical appendix (Buchanan et al., 2020).

Karumba Basin sediments were not recorded in the exploration wells in the Isa GBA region, except for a tentative ascription to the (now obsolete) Lynd Formation of the surface sediments to a depth of 27 m in the Mid-Eastern Oil well Burketown 1 (Perryman, 1964). Cenozoic alluvium, not ascribed to a formation, was also intersected in the drilling of the Comalco well Beamesbrook 1 from the surface to 26 m measured depth (Dunster et al., 1989). Both wells are located near the far eastern edge of the Isa GBA region (Figure 9).

The Cenozoic sediments intersected in the Mid-Eastern Oil well Burketown 1 are composed predominantly of reddish-brown clay with loosely clustered subrounded quartz grains and a 2 m thick layer of very fine friable sandstone at the base (Perryman, 1964). The Cenozoic sediments of the Comalco well Beamesbrook 1 were recorded as fine- to very fine-grained quartz sandstone with locally abundant clayey matrix, that is partly calcareous (Dunster et al., 1989).

4 Isa GBA region structural and stratigraphic framework

This section presents a more detailed account of the structural and stratigraphic framework of the Isa GBA region, and the relationships between deposition of supersequences and potential connectivity with overlying geological basins.

4.1 *Structural architecture*

The structural elements map for the Isa GBA region produced as part of this assessment is shown in Figure 27 and Figure 28. This is based on seismic interpretation by Bradshaw et al. (2018c), and has been extrapolated outside the limits of seismic data control using the Geological Survey of Queensland's depth to basement grid (Frogtech Geoscience, 2018a) and surface geology maps (Geological Survey of Queensland, 2011b).

Structural elements associated with the River Supersequence were used as this sequence was deposited during the tectonic event (River Event) that generated the major structural systems in the northern Lawn Hill Platform. Many of these structures were reactivated and made more complex by later tectonic events, including wrench tectonics during the Wide Event and compressional inversion during the Isan Orogeny (Frogtech Geoscience, 2018a; Scott and Tarlowski, 1999).

Example seismic sections used to highlight aspects of the regions structural and stratigraphic architecture are shown in Figure 29, Figure 30, Figure 31 and Figure 32, interpreted after Bradshaw and Scott (1999). These data show that the northern Lawn Hill Platform forms a northward-thinning wedge of gently to moderately deformed sedimentary rocks of the Isa Superbasin. Strata from the Isa Superbasin range in thickness from less than 1 km over the southern flanks of the Murphy Inlier, where the Fickling Group outcrops, to a maximum of about 9 km to the south, where the McNamara Group outcrops (Figure 33) (Scott and Bradshaw, 1999).

The northward thinning of strata over the northern Lawn Hill Platform is mainly due to a combination of onlap and truncation. Truncation is associated with a series of unconformities within the Isa Superbasin, together with younger unconformities at the base of the South Nicholson and Carpentaria basins (Bradshaw et al., 2000).

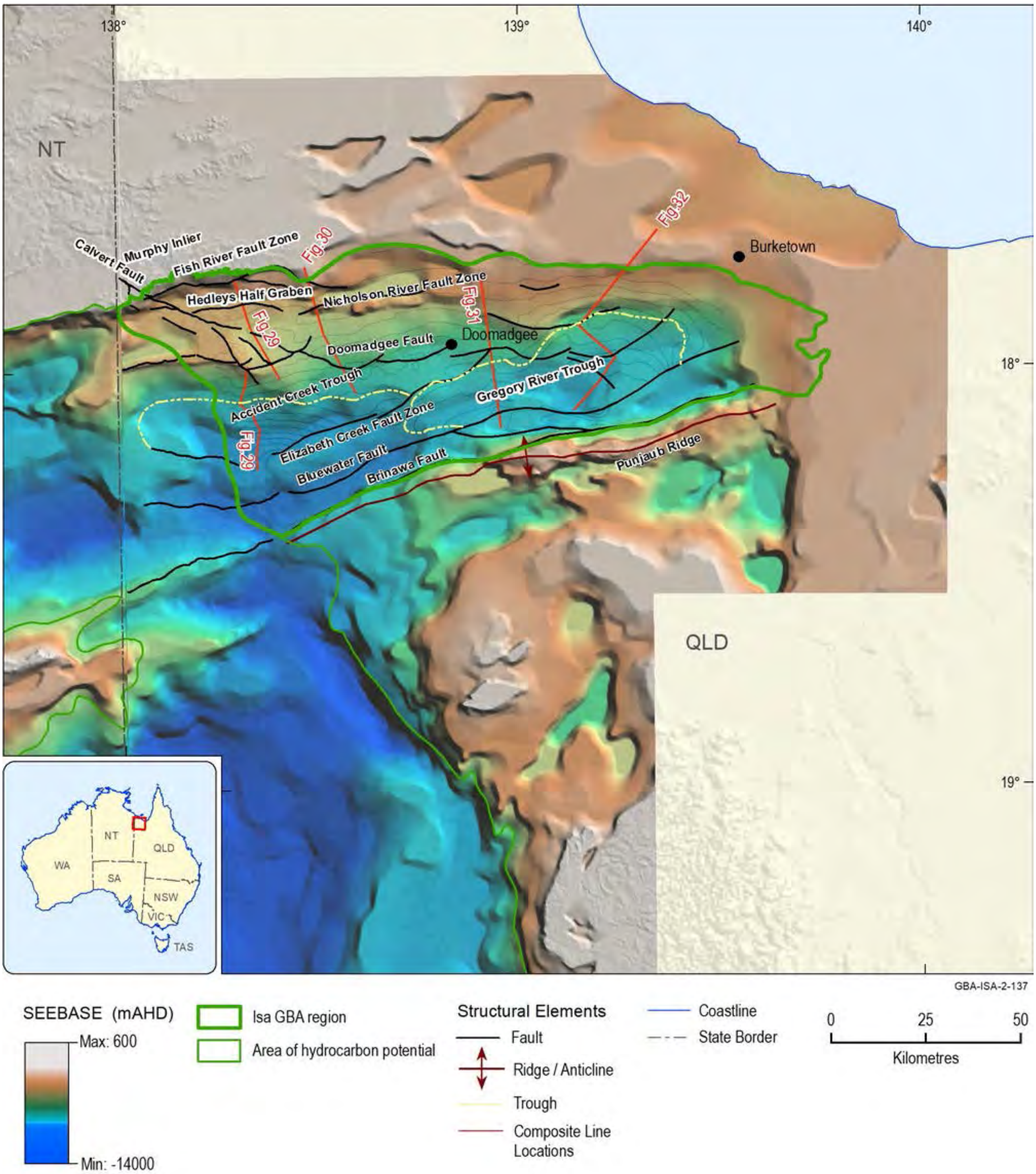


Figure 27 Structural elements map of the northern Lawn Hill Platform superimposed over the Geological Survey of Queensland's depth to basement grid

Source: Structural elements are derived from the base River Supersequence and Base Term Supersequence depth-structure maps of Bradshaw et al. (2018c). Queensland SEEBASE® image sourced from Frogtech Geoscience (2018a). NT SEEBASE® image sourced from Frogtech Geoscience (2018a)
Data: Bradshaw et al. (2018a); Frogtech Geoscience (2018a); Frogtech Geoscience (2018b)
Element: GBA-ISA-2-137

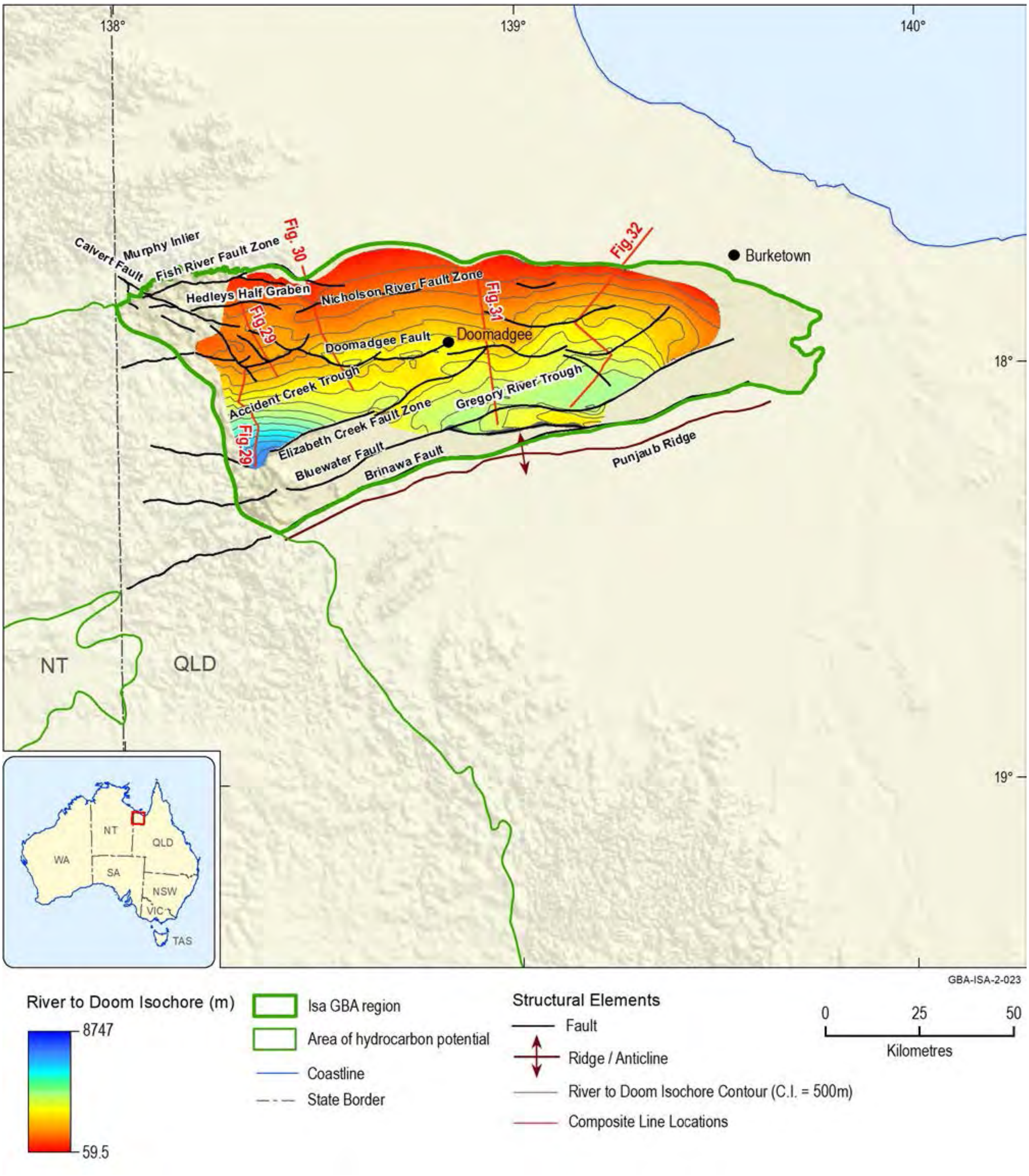


Figure 28 Structural elements map of the northern Lawn Hill Platform superimposed over an isochore (vertical thickness) map for the River to Doom supersequences

Contour interval (C.I.) = 500 m

Source: Generated using the published depth to base River Supersequence, depth to base South Nicholson Basin and depth to base Carpentaria Basin grids of Bradshaw et al. (2018c)

Data: Isochore grid, contours and structural elements from Bradshaw et al. (2018a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)

Element: GBA-ISA-2-023

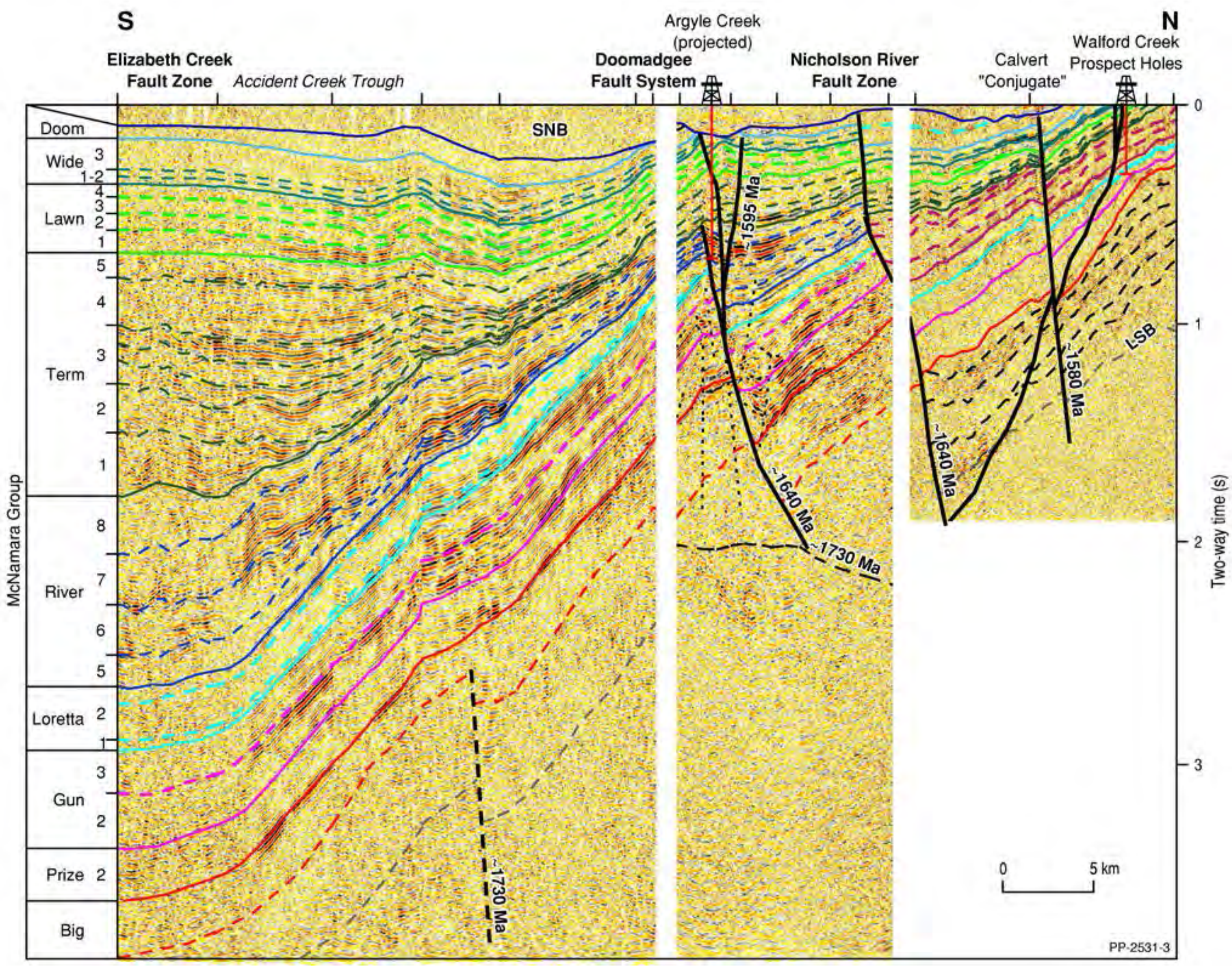


Figure 29 Argyle Creek composite seismic section showing unconformities at the base of each supersequence (solid lines) and sequence (dashed lines) from the Isa, Calvert and Leichhardt superbasins

The section shows major faults only from multiple deformation events (polyphase faulting) as per the original interpretation of Scott and Bradshaw (1999). Minor faults, expected to occur at greater density, are not interpreted at this seismic resolution. Refer to Figure 26 for interpreted lithofacies. Location of section shown on Figure 27 and Figure 28.
SNB = South Nicholson Basin; LSB = Leichhardt Superbasin
Source: Bradshaw and Scott (1999)
Element: GBA-ISA-2-116

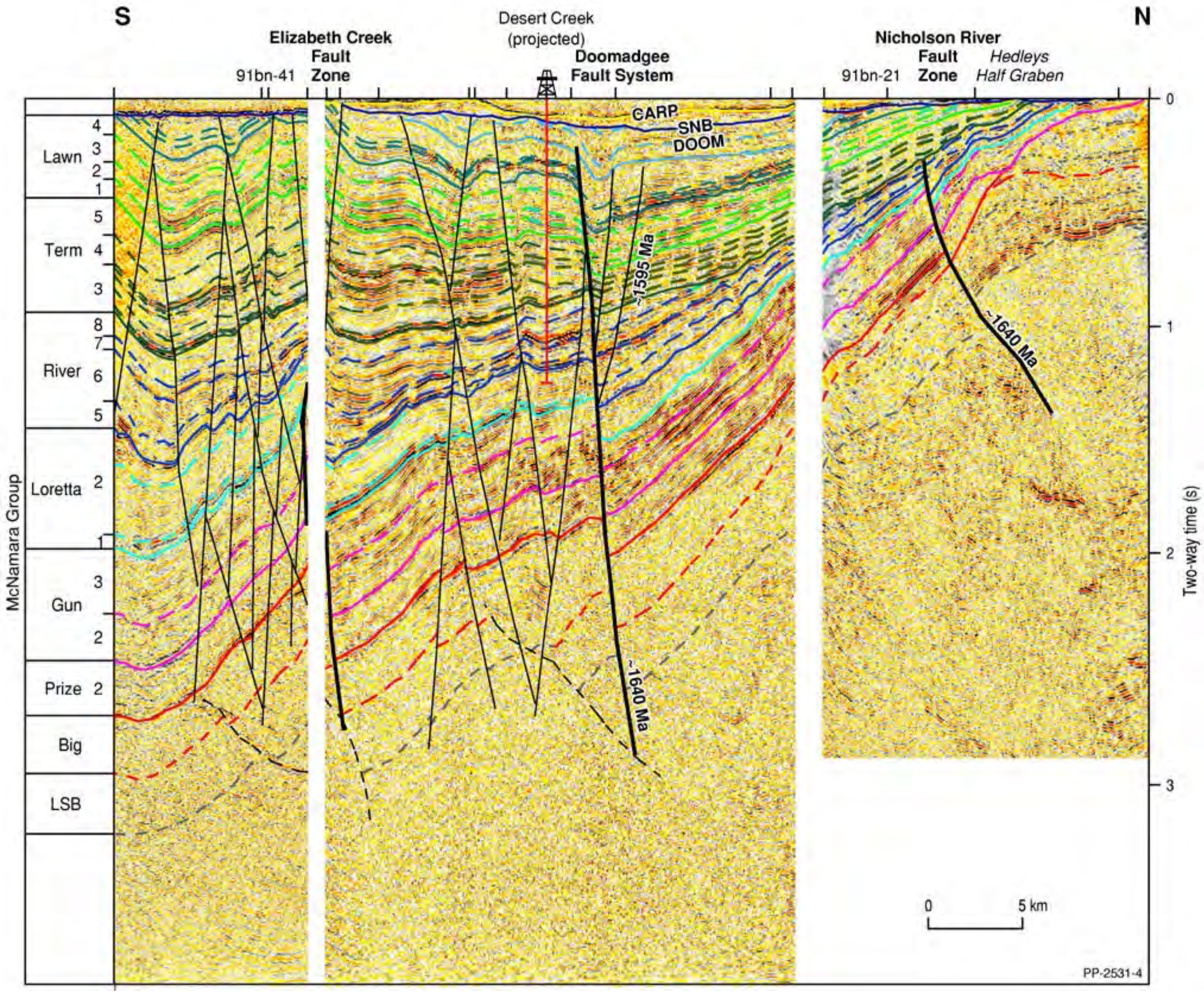


Figure 30 Desert Creek composite seismic section showing unconformities at the base of each supersequence (solid lines) and sequence (dashed lines) from the Isa, Calvert and Leichhardt superbasins

The section shows major faults only from multiple deformation events (polyphase faulting) as per the original interpretation of Scott and Bradshaw (1999). Minor faults, expected to occur at greater density, are not interpreted at this seismic resolution. Location of section shown on Figure 27 and Figure 28.

CARP = base Carpentaria Basin; SNB = South Nicholson Basin; DOOM = Doom Supersequence

Source: Bradshaw and Scott (1999)

Element: GBA-ISA-2-117

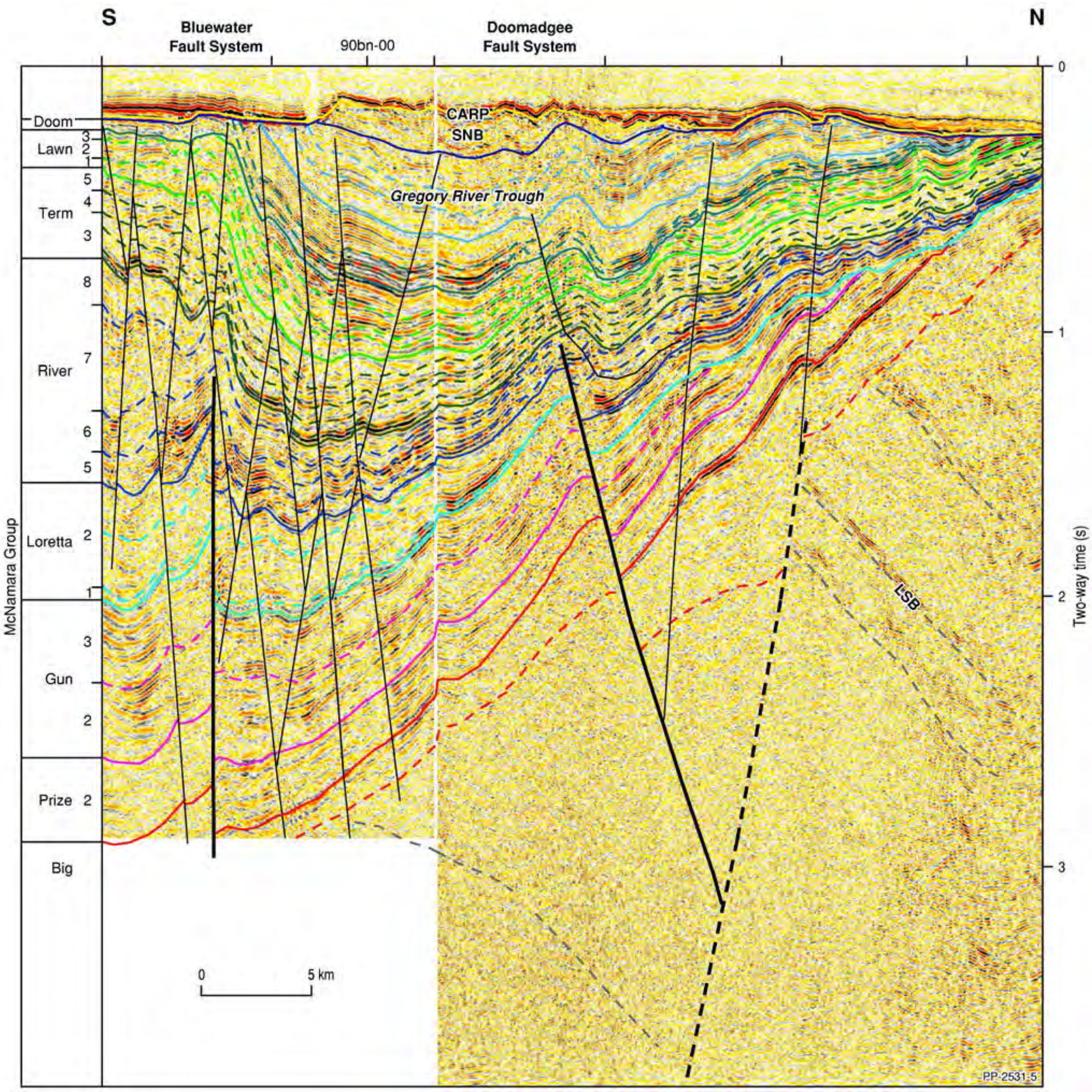


Figure 31 Central seismic composite section showing unconformities at the base of each supersequence (solid lines) and sequence (dashed lines) from the Isa, Calvert and Leichhardt superbasins

The section shows major faults only from multiple deformation events (polyphase faulting) as per the original interpretation of Scott and Bradshaw (1999). Minor faults, expected to occur at greater density, are not interpreted at this seismic resolution. Location of section shown on Figure 27 and Figure 28.

CARP = base Carpentaria Basin; SNB = South Nicholson Basin; LSB = Leichhardt Superbasin

Source: Bradshaw and Scott (1999)

GBA-ISA-2-118

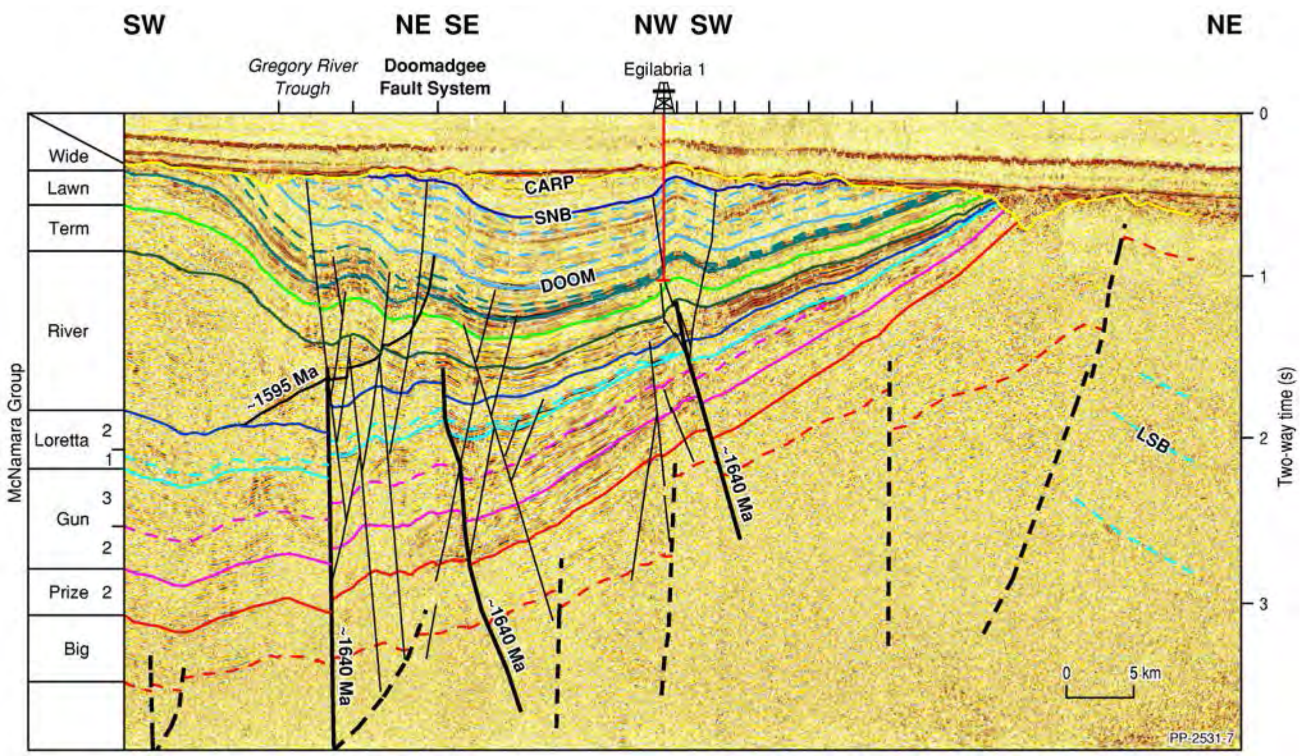


Figure 32 Egilabria composite seismic section showing unconformities at the base of each supersequence (solid lines) and sequence (dashed lines) from the Isa, Calvert and Leichhardt superbasins

The section shows major faults only from multiple deformation events (polyphase faulting) as per the original interpretation of Scott and Bradshaw (1999). Minor faults, expected to occur at greater density, are not interpreted at this seismic resolution. Location of section shown on Figure 27 and Figure 28.

CARP = base Carpentaria Basin; SNB = South Nicholson Basin; DOOM = Doom Supersequence; LSB = Leichhardt Superbasin

Source: Bradshaw et al. (2000)

Element: GBA-ISA-2-119

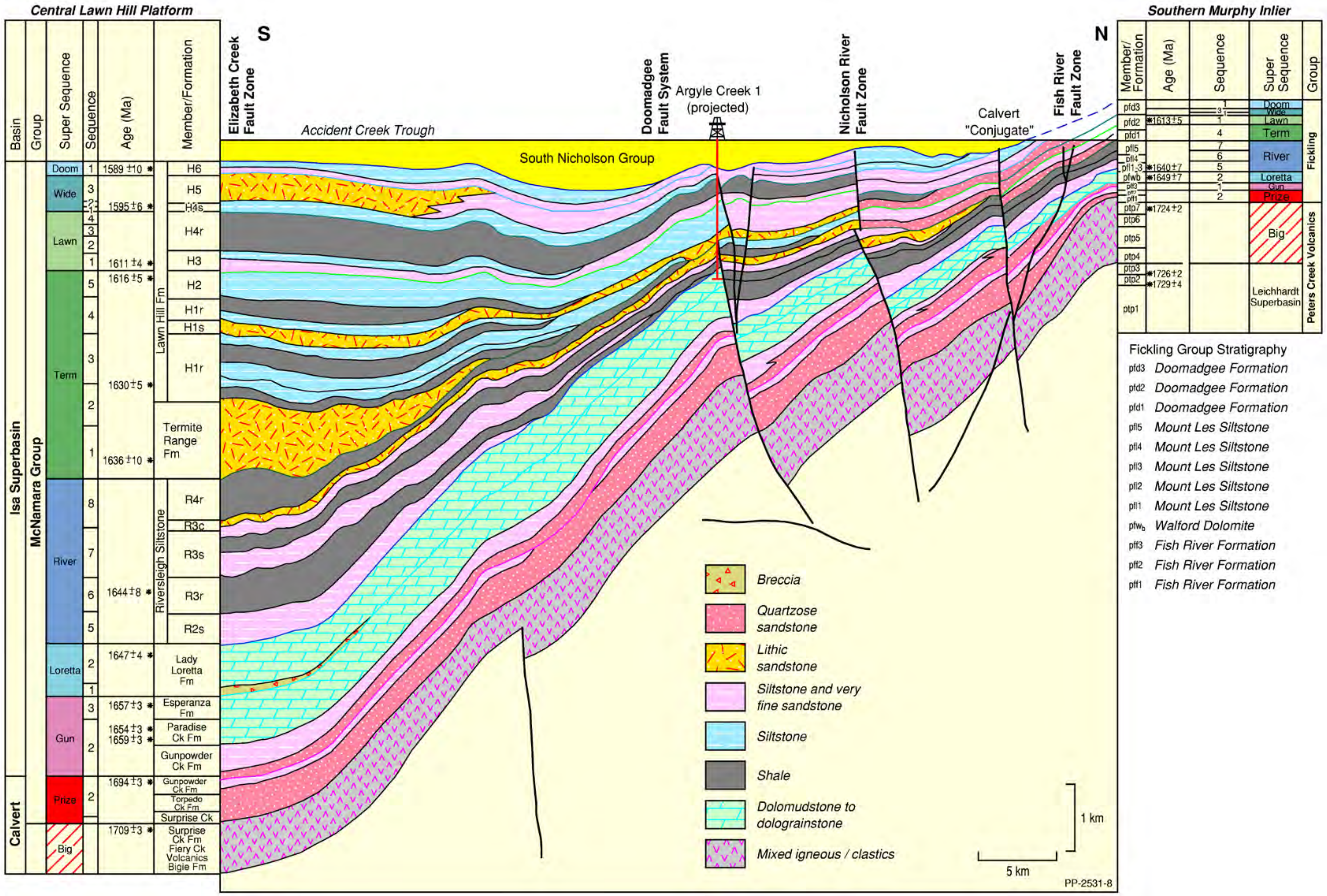


Figure 33 Correlation of lithofacies members from the McNamara Group to the Fickling Group using the NABRE Project sequence stratigraphy framework, based on the S-N composite seismic line presented in Bradshaw et al. (2000)

Source: Bradshaw and Scott (1999)

Element: GBA-ISA-2-114

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

4.1.1 Murphy Inlier

The northern Lawn Hill Platform is adjacent to an enduring east-north-east trending basement high, part of which manifests in the present landscape as the Murphy Inlier or the Murphy Tectonic Ridge (Grimes and Sweet, 1979) (Figure 27 and Figure 28). The Murphy Inlier basement complex has as its centre the isoclinally folded Murphy Metamorphics (older than 1900 Ma), which are overlain by the approximately 4000 m thick Cliffdale Volcanics (1850 to 1770 Ma) (Scott et al., 1999). Both basement units are intruded by the Nicholson Granite Complex, and are in turn overlain by the Peters Creek Volcanics of the Leichhardt Superbasin (Scott et al., 1999). Calvert and Isa superbasin sediments thin substantially over the basement high due to both truncation and onlap, resulting in an attenuated basin margin succession, the Fickling Group (Bradshaw et al., 2000).

4.1.2 Fish River Fault Zone

The Fish River Fault Zone was defined by Sweet and Slater (1975) as a north-east trending fault system, which has offset the Murphy Inlier with a 500 to 1000 m downthrow to the south. Subsequent mapping by Grimes and Sweet (1979), Rohrlach et al. (1998) and the Geological Survey of Queensland (2011b) show the Fish River Fault Zone as a series of interlinked east-north-east to south-east trending faults. Seismic interpretations by Scott and Bradshaw (1999) show that the Fish River Fault Zone is antithetic to the principal north-dipping Nicholson River growth fault located to the south, and it is associated with only minor syn-depositional growth of the River Supersequence (Figure 27 and Figure 28).

4.1.3 Calvert Fault

The Calvert Fault is a south-east trending fault system that extends for over 200 km in Queensland and the NT. It has up to 7 km of strike-slip displacement (probably dextral) and 750 m of normal displacement in basement rocks (Roberts et al., 1963; Sweet et al., 1981). The Calvert Fault appears to have been episodically active during accumulation of the Peters Creek Volcanics and the overlying Fickling Group (Calvert and Isa superbasins) (Rohrlach et al., 1998). Scott and Tarlowski (1999) documented large normal displacements on the Calvert Fault in seismic data following deposition of the Doom Supersequence, which suggest that it remained active following deposition of the Isa Superbasin. Sweet (2017) also documented 700 to 800 m of sinistral strike-slip movement along the Calvert Fault following deposition of the Hedleys Sandstone and the Pandanus Siltstone in the South Nicholson Basin.

Recently published structure maps by Bradshaw et al. (2018c) indicate that the Calvert Fault terminates to the south-east as a series of south-east to south-south-east striking and north-east dipping fault splays, which interconnect with the Doomadgee Fault System (Figure 27 and Figure 28).

4.1.4 Nicholson River Fault Zone and ‘Hedleys Half Graben’

The Nicholson River Fault Zone was first named by Rohrlach et al. (1998), but was originally mapped by Sweet et al. (1981) as a disconnected series of east-north-east trending faults that dip down to the north and are offset across the Calvert Fault. Rohrlach et al. (1998) and Scott and

Tarlowski (1999) interpreted the Nicholson River Fault Zone as the bounding fault for a half-graben that formed over the southern flanks of the Murphy Inlier during deposition of the Mount Les Siltstone (River Supersequence); this half-graben is informally termed the 'Hedleys Half Graben' by Rohrlach et al. (1998).

Recent mapping by Bradshaw et al. (2018c) indicates that the Nicholson River Fault Zone as mapped by Rohrlach et al. (1998) represents two distinct fault systems (Figure 27 and Figure 28). Bradshaw et al. (2018c) suggested restricting the name Nicholson River Fault Zone to the fault system that bounds the northernmost half-graben depocentre ('Hedleys Half Graben'), which formed over the southern Murphy Inlier during the River extensional event. The 'Hedleys Half Graben' is a relatively small extensional depocentre containing up to 550 m of syn-extensional sediments from the River Supersequence (Bradshaw et al., 2018c). The second of these distinct fault systems, the Doomadgee Fault System, is discussed below in Section 4.1.5.

4.1.5 Doomadgee Fault System

The Doomadgee Fault System (Figure 27 and Figure 28), as recently defined by Bradshaw et al. (2018c), forms an *en-echelon* series of east to west-north-west-trending north-dipping faults which originated through oblique north–south extension during the River Event, and were subsequently reactivated during the Wide Event and Isan Orogeny (Scott and Tarlowski, 1999). This fault system was originally mapped by Scott and Tarlowski (1999), and was informally termed the 'Egilabria Shear Zone' by Southgate et al. (1999). However, this old nomenclature has never been adopted in subsequent publications and is somewhat confusing given that the fault system is located south of the Egilabria wells.

The Doomadgee Fault System originated as an intrabasinal extensional system during the River Event, and bounds a series of half-graben depocentres containing up to 1500 m of syn-extensional sediments from the River Supersequence (Bradshaw et al., 2018c). Subsequent strike-slip reactivation during the Wide Event produced a series of localised depocentres for up to 500 m of strata from the Wide Supersequence over the western part of the Doomadgee Fault System (Bradshaw et al., 2018c).

4.1.6 Elizabeth Creek Fault Zone and Accident Creek Trough

The Elizabeth Creek Fault Zone (Figure 27 and Figure 28) is a major east-north-east trending fault system which extends from outcrop sections of the South Nicholson Basin in the western Isa GBA region to its north-eastern subsurface termination against the Doomadgee Fault System (Bradshaw et al., 2018c). McConachie (1993) originally named the structure as the Elizabeth Creek Thrust Zone, and defined it as an east to west striking frontal thrust fault system extending from outcrop sections in the Bowthorn region to just south of Burketown 1. Scott et al. (1998) subsequently redefined the structure as the Elizabeth Creek Fault Zone, which they interpreted as a more discontinuous *en-echelon* series of east-north-east trending and north-dipping faults with a complex polyphase history of multiple extension and inversion events.

The Elizabeth Creek Fault Zone has a complex tectonic history including extension during the 1640 to 1630 Ma River Event, and major compressional inversion during the Isan Orogeny and subsequent deformation events (Bradshaw et al., 2018c). Extension during the River Event produced a large east to east-north-east trending depocentre referred to as the Accident Creek Trough by Bradshaw et al. (2018c), which contains up to 2500 m of syn-extensional strata from the River Supersequence. Major inversion is evident along the extents of the Elizabeth Creek Fault Zone with footwall strata increasingly deformed, uplifted and eroded from north-east to south-west. These compressional inversion structures extend through the South Nicholson Basin to the surface where they produce a complex zone of faults over a distance of 3 to 4 km north of the main fault (Sweet, 2017).

4.1.7 Bluewater Fault System and Gregory River Trough

The Bluewater Fault System (Figure 27 and Figure 28) forms a major east-north-east trending, north-dipping fault system south of the Elizabeth Creek Fault Zone. Bradshaw et al. (2018c) defined and mapped this structure using updated seismic data interpretations together with the Geological Survey of Queensland's depth to basement map (Frogtech Geoscience, 2018a). The Bluewater Fault System appears to have a similar tectonic history as the Elizabeth Creek Fault Zone, with extension during the River Event and major inversion during the Isan Orogeny and subsequent orogenies. Extension during the River Supersequence was focused over the eastern extent of the Bluewater Fault System, where up to 3500 m of syn-extensional sediments were deposited in the hanging wall block (Bradshaw et al., 2018c).

The main hanging wall block depocentre is defined as the Gregory River Trough by Bradshaw et al. (2018c). Significant extension also appears to have occurred over the Bluewater Fault System during the 1600 Ma Wide Event, as indicated by a south-thickening wedge of up to 1100 m of Wide Supersequence strata in the Gregory River Trough (Bradshaw et al., 2018c). North-north-west to south-south-east shortening during one or more compressional events produced a large east-north-east striking synformal structure over the Gregory River Trough (Figure 27 and Figure 28), and extensive inversion along the Bluewater Fault Zone. Compressional inversion may have commenced during the Isan Orogeny, but most likely peaked during the Albany-Fraser, West and Musgrave orogenies (1350 to 1040 Ma) (Frogtech Geoscience, 2018a), as indicated by the propagation of deformation through the Isa Superbasin and South Nicholson Basin in the Gregory River Trough (Bradshaw et al., 2018c), together with the timing for deformation of the South Nicholson Basin interpreted by Rawlings et al. (2008) and Sweet (2017) as around 1325 Ma.

4.1.8 Brinawa Fault System and Punjaub Ridge

The Brinawa Fault System is a major east-north-east trending, north-dipping fault system located at the southern-most limit of the preserved Isa Superbasin basin fill over the northern Lawn Hill Platform (Figure 27 and Figure 28) (Bradshaw et al., 2018c). The Geological Survey of Queensland's recently published depth to basement grid (Frogtech Geoscience, 2018a) clearly images the extent of the Brinawa Fault System from outcrop sections of the Isa Superbasin and South Nicholson Basin in the west, to the subsurface area beneath Burketown 1 in the east. The Punjaub Ridge is a major east-north-east trending structural high located in the footwall block of the Brinawa Fault System (Bradshaw et al., 2018c). Seismic data used by Bradshaw et al. (2018c) show that strata from the Isa Superbasin are extensively deformed and exhumed over the Punjaub Ridge, with the River Supersequence subcropping the Carpentaria Basin over the Bluebush Prospect (Pursuit Minerals, 2017). The tectonic origins of the Brinawa Fault System are uncertain due to the limited seismic data coverage over this structure. Strata from the River Supersequence appear to thicken into the Brinawa Fault System, which suggests similar extension during the River Event as seen over the Elizabeth Creek Fault Zone and Bluewater Fault System (Bradshaw et al., 2018c).

4.2 Geological surfaces and isochore maps

Depth-structure and isochore maps are an essential component of the Geological and Bioregional Assessment of the Isa Superbasin. Of particular importance to this assessment are the proven shale gas intervals contained within the River Supersequence and the Lawn Supersequence.

Economic basement over the northern Lawn Hill Platform from the perspective of shale gas resources begins at the base of the River Supersequence (Bradshaw et al., 2018c). Older stratigraphic intervals are present, but these show no evidence of organic-rich source rocks in either well data or outcrop sections within the Isa GBA region (Bradshaw et al., 2000; Gorton and Troup, 2018). The assessment therefore excludes any stratigraphic intervals older then the River Supersequence.

The depth-structure and isochore maps for each of the Isa Superbasin supersequences and overlying basins are summarised below (see methods snapshot box for detailed workflow).

Methods snapshot: mapping geological surfaces at depth

The depth-structure and isochore maps used in this assessment are sourced from the recently published Geoscience Australia update (Bradshaw et al., 2018c) to the original NABRE seismic interpretations over the northern Lawn Hill Platform (Bradshaw and Scott, 1999).

Maps produced by Bradshaw et al. (2018b) include depth-structure and isochore maps for the base River Supersequence, Term Supersequence, Lawn Supersequence, Lawn 4 Sequence, Wide Supersequence, Doom Supersequence, South Nicholson Basin and Carpentaria Basin. These maps, and a base Karumba Basin map, are provided in this section in metres below mean sea level.

Additional maps for Mesozoic aquifer and aquitard intervals, not mapped by Bradshaw et al. (2018b), include the base Gilbert River Formation, Rolling Downs Group, Normanton Formation and Karumba Basin. These intervals have previously been mapped at a regional scale over the full extent of the Great Artesian Basin by Smerdon et al. (2012).

A set of maps, incorporating seismic data over the groundwater assessment area and at greater resolution than the regional maps, was prepared for the groundwater assessment presented in the hydrogeology technical appendix (Buchanan et al., 2020) in metres relative to the Australian Height Datum. The regional maps of Smerdon et al. (2012) were updated using the following workflow:

1. Interpret the base Carpentaria Basin (top Proterozoic), top Gilbert River Formation and base Normanton Formation on seismic sections that extend over the groundwater assessment area using well log interpretations and time-depth data in Argyle Creek 1, Desert Creek 1, Egilabria 1, Egilabria 2, Egilabria 4, Beamesbrook 1, Burketown 1, and Armraynald 1.

It was not possible to interpret the base Karumba Basin on seismic sections due to very shallow depths of this stratigraphic interval.

2. Convert the seismic two-way time interpretations into depth relative to seismic datum (metres below mean sea level) using the same workflow documented by Bradshaw et al. (2018c) and their Mesozoic velocity model.

3. Convert the maps from seismic datum (metres below mean sea level) to groundwater datum (metres relative to the Australian Height Datum).

4. Merge the depth-converted seismic grid with the regional grids of Smerdon et al. (2012) over the groundwater assessment area.

5. Verify and refine the merged grids using all available stratigraphic tops in well data over the groundwater assessment area.

6. Refine the outcrop expression of these surfaces by merging with digital elevation model data (Hutchinson et al., 2008) where they are subaerially exposed.

4.2.1 Isa Superbasin

4.2.1.1 River Supersequence

The base of the River Supersequence is a major south-dipping onlap and truncation surface that extends from surface outcrops of the Mount Les Siltstone over the southern flanks of the Murphy Inlier, to maximum depths of 7500 m in the Accident Creek Trough and 4800 m in the Gregory River Trough (Figure 34) (Bradshaw et al., 2018c).

The River Supersequence thins overall to the north, and is characterised by progressively smaller half-graben depocentres, with maximum thicknesses of 1500 m in the hanging wall block of Doomadgee Fault System, and 550 m in the ‘Hedleys Half Graben’ (Bradshaw et al., 2018c). Northward thinning of the River Supersequence occurs due to a combination of onlap over the basal unconformity and within component third-order sequences, together with some erosion by the Base Term Supersequence unconformity and the base Carpentaria Basin unconformity (Scott and Bradshaw, 1999).

Syn-depositional growth is evident across most faults that intersect the River Supersequence (Scott and Bradshaw, 1999; Scott and Tarlowski, 1999). Extension and subsidence appear to have been particularly focused within the Gregory River and Accident Creek troughs where the River Supersequence reaches thicknesses of 2500 to 3500 m (Bradshaw et al., 2018c) (Figure 35).

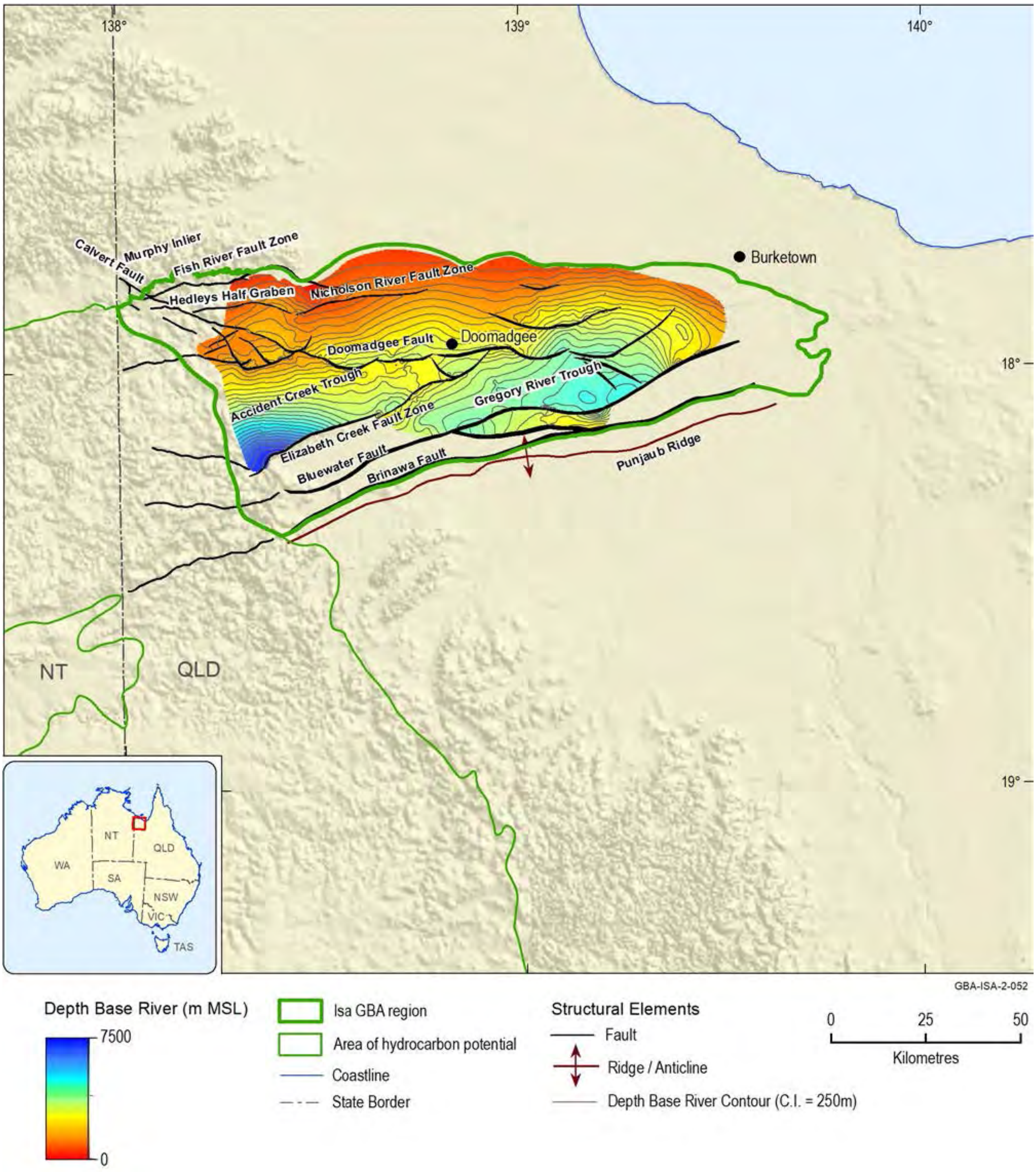


Figure 34 Base River Supersequence depth-structure map

Datum = mean sea level (MSL); contour interval (C.I.) = 250 m
Source: Bradshaw et al. (2018c)
Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-052

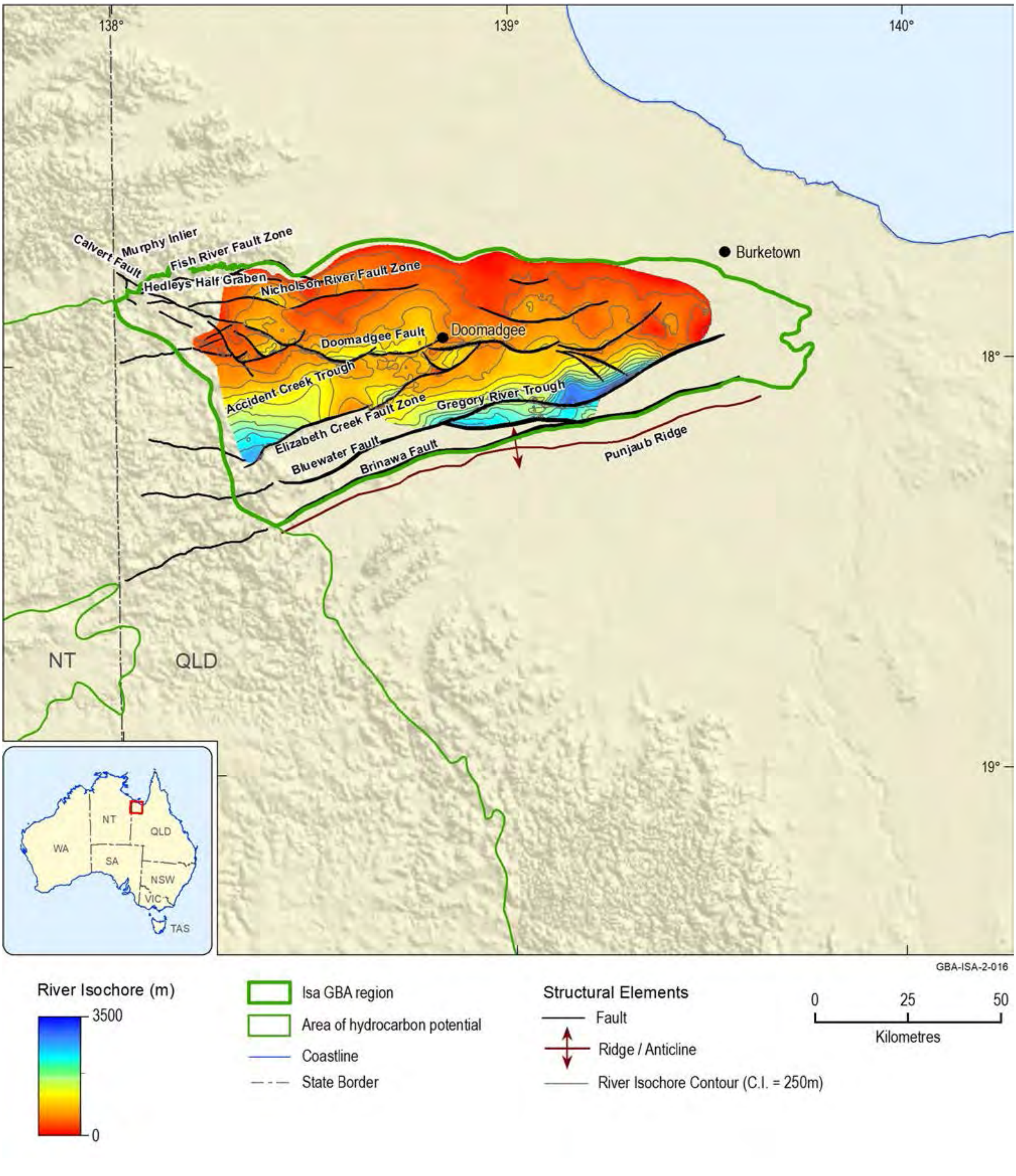


Figure 35 River Supersequence isochore (vertical thickness) map

Contour interval (C.I.) = 250 m
Source: Bradshaw et al. (2018c)
Data: Isochore grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-016

4.2.1.2 Term Supersequence

The Term Supersequence forms a northward-thinning clastic wedge across the northern Lawn Hill Platform.

The base of the Term Supersequence extends from surface outcrops of the Doomadgee Formation over the southern flanks of the Murphy Inlier, to maximum depths of 4800 m in the Accident Creek Trough and 3500 m in the Gregory River Trough (Figure 36) (Bradshaw et al., 2018c). The original wedge geometry of the Term Supersequence is partly preserved in the Accident Creek Trough, but elsewhere has been overprinted by deformation during the Isan Orogeny and subsequent deformation events (Bradshaw et al., 2018c). Compressional inversion was particularly focused between the Brinawa Fault System and Elizabeth Creek Fault Zone where the base of the Term Supersequence is deformed into a series of shallow domes and depressions, and within the Gregory River Trough where strata are deformed into a broad east-north-east trending synformal structure (Figure 36).

The Accident Creek Trough forms the main depocentre for Term Supersequence deposits over the northern Lawn Hill Platform (Figure 37). It contains up to 3500 m of massive turbidite sandstones from the Termite Range Formation (Term 1 and Term 2 sequences) in outcrop sections to the south, which fine upwards into marine siltstones, turbidite sandstones and carbonaceous shales from the Pmh1-2 members of the Lawn Hill Formation (Term 3, 4 and 5 sequences) (Bradshaw et al., 2018c; Krassay et al., 2000a). The two basal sequences pinch out and are absent to the north and east of the Accident Creek Trough (Bradshaw et al., 2018c; Krassay et al., 2000a).

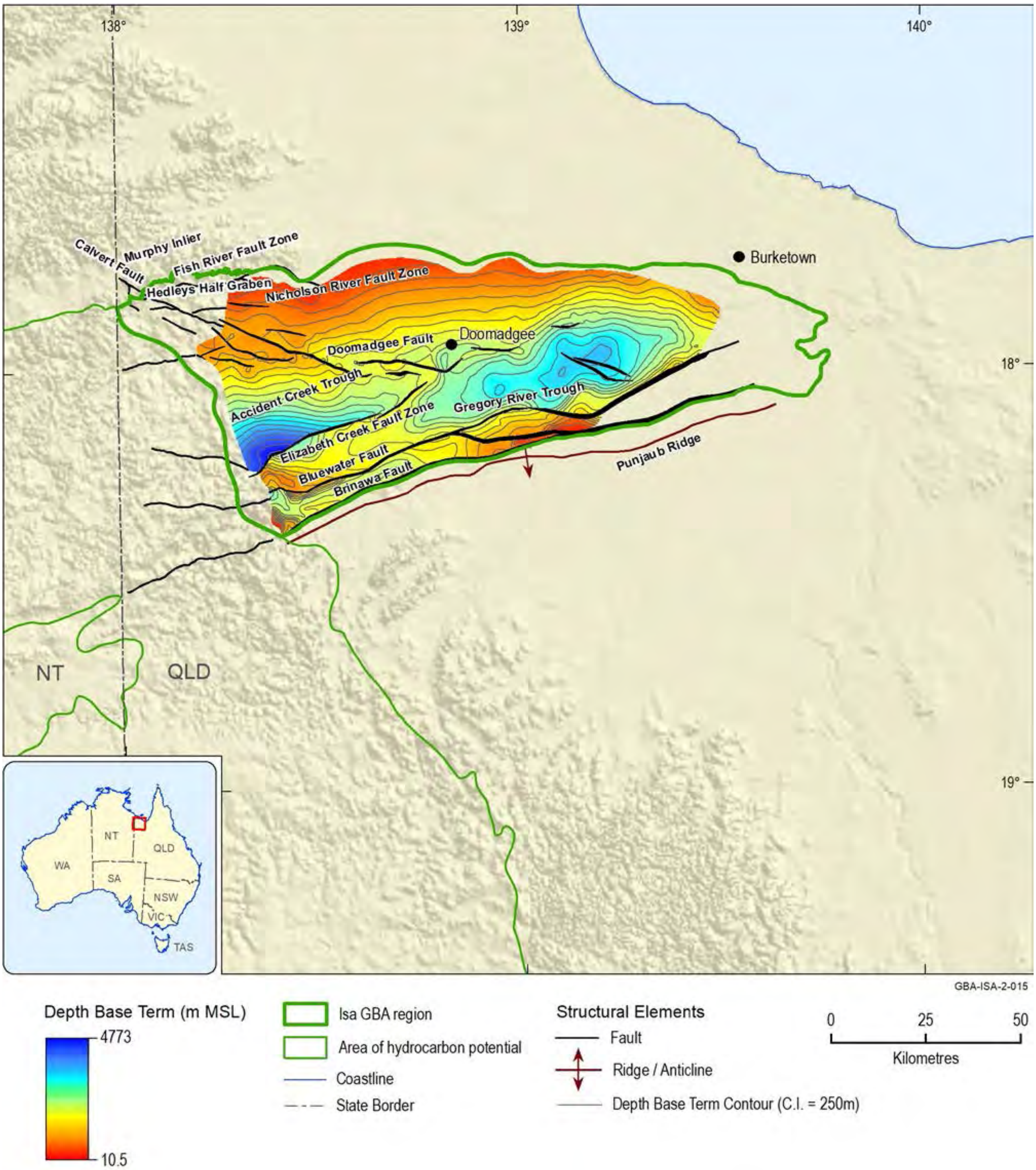


Figure 36 Base Term Supersequence depth-structure map

Datum = mean sea level (MSL); contour interval (C.I.) = 250 m
Source: Bradshaw et al. (2018c)
Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-015

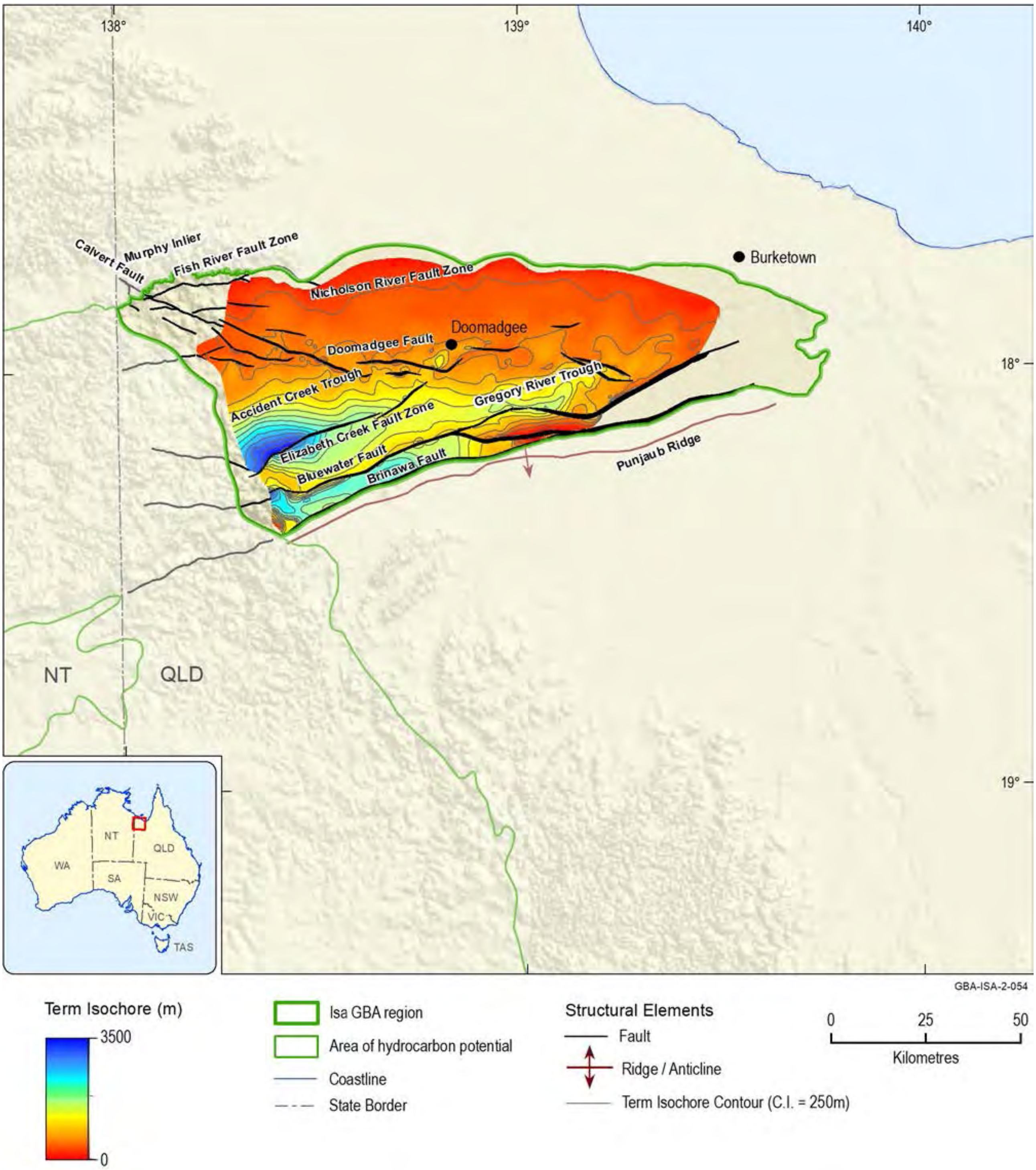


Figure 37 Term Supersequence isochore (vertical thickness) map

Contour interval (C.I.) = 250 m
Source: Bradshaw et al. (2018c)
Data: Isochore grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-054

4.2.1.3 Lawn Supersequence

In contrast to the underlying Term Supersequence, the base Lawn Supersequence is deepest (about 3100 m below mean sea level) in the axis of the Gregory River Trough, and is significantly shallower (about 1500 m below mean sea level) in the Accident Creek Trough (Figure 38).

The Lawn Supersequence reaches maximum thicknesses of 800 to 900 m in the Accident Creek Trough and the Gregory River Trough, and thins to the north and east (Figure 39) (Bradshaw et al., 2018c). Northward thinning is recognised by truncation at the base of the Wide Supersequence, where the Lawn 4, Lawn 3 and Lawn 2 sequences have been eroded over the southern flanks of the Murphy Inlier (Bradshaw et al., 2000). The eastward thinning is recognised by onlap against the base Lawn Supersequence unconformity, together with internal pinchouts within the Lawn 1, Lawn 2 and Lawn 3 sequences (Scott and Bradshaw, 1999).

Deformation during the Isan Orogeny and subsequent compressional events has uplifted and eroded most of the Lawn Supersequence between the Brinawa Fault System and the Elizabeth Creek Fault Zone (Bradshaw et al., 2018c).

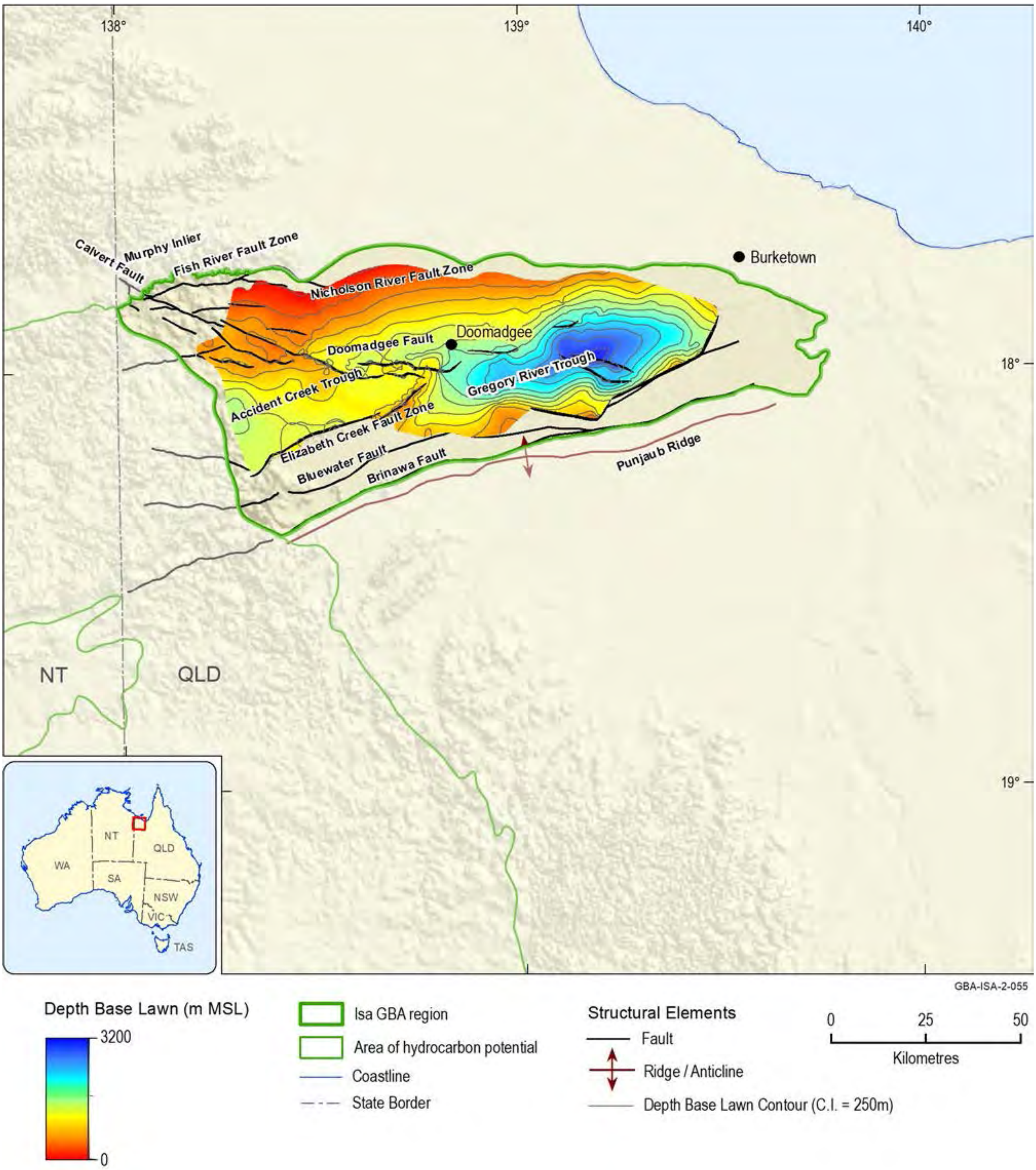


Figure 38 Base Lawn Supersequence depth-structure map

Datum = mean sea level; contour interval (C.I.) = 250 m
Source: Bradshaw et al. (2018c)
Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-055

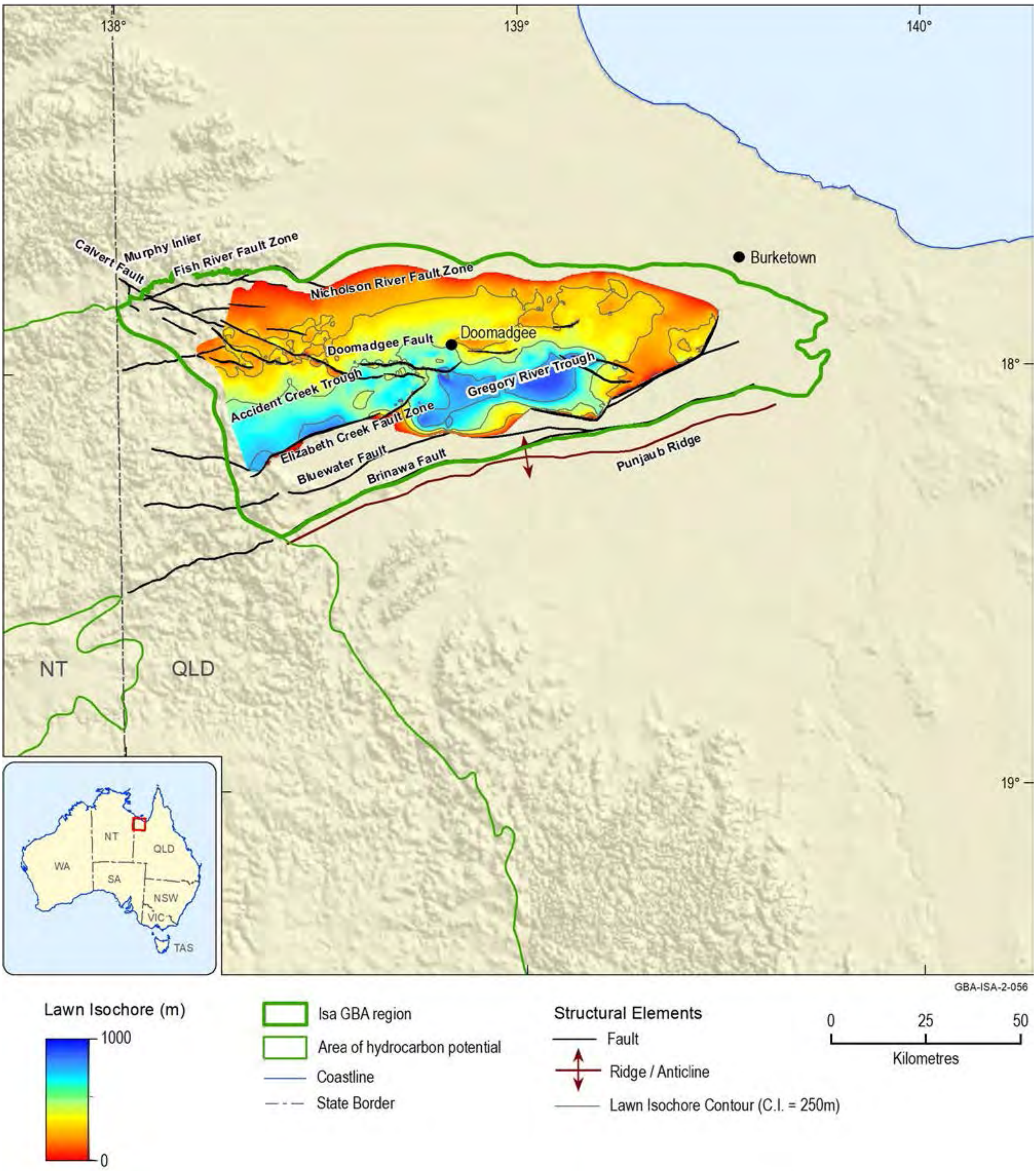


Figure 39 Lawn Supersequence isochore map

Contour interval (C.I.) = 250 m

Source: Generated using the published Lawn Supersequence isochore map of Bradshaw et al. (2018c)

Data: Isochore grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)

Element: GBA-ISA-2-056

4.2.1.4 Wide Supersequence

The base Wide Supersequence unconformity is relatively shallow over the western part of the northern Lawn Hill Platform, where it extends to depths of 1000 m below mean sea level in the Accident Creek Trough. However, post-depositional deformation has produced a much deeper surface over the Gregory River Trough, where the Wide Supersequence extends to depths of 2700 m below mean sea level (Figure 40).

Syn-depositional growth across faults is evident in the Wide Supersequence, particularly across the Bluewater Fault System where up to 1100 m of strata are preserved in the Gregory River Trough, and across the Doomadgee Fault System where the supersequence thickens southward into the fault up to 500 m thick (Figure 41). The Wide Supersequence thins to the north and north-east, recognised by onlap over the basal unconformity and within component third-order sequences (Bradshaw et al., 2018c).

Uplift and erosion during the Isan Orogeny and subsequent deformation events have removed most of the Wide Supersequence between the Brinawa Fault System and the Elizabeth Creek Fault Zone (Bradshaw et al., 2018c). The Wide Supersequence is preserved over parts of the south-eastern Murphy Inlier as the Pfd_3 member of the Doomadgee Formation (Bradshaw et al., 2000).

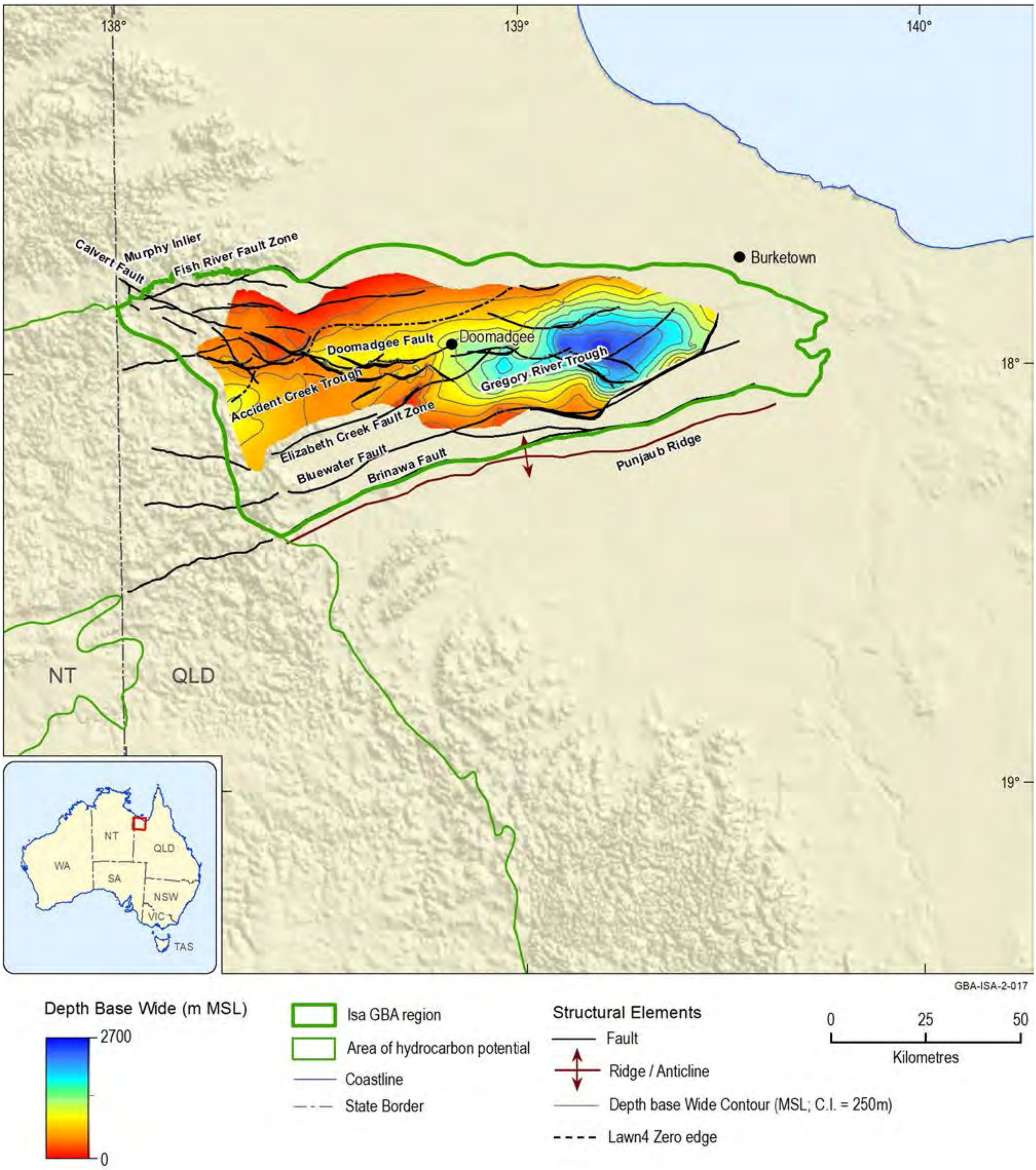


Figure 40 Base Wide Supersequence depth-structure map

Datum = mean sea level (MSL); contour interval (C.I.) = 250 m
Source: Bradshaw et al. (2018c)
Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-017

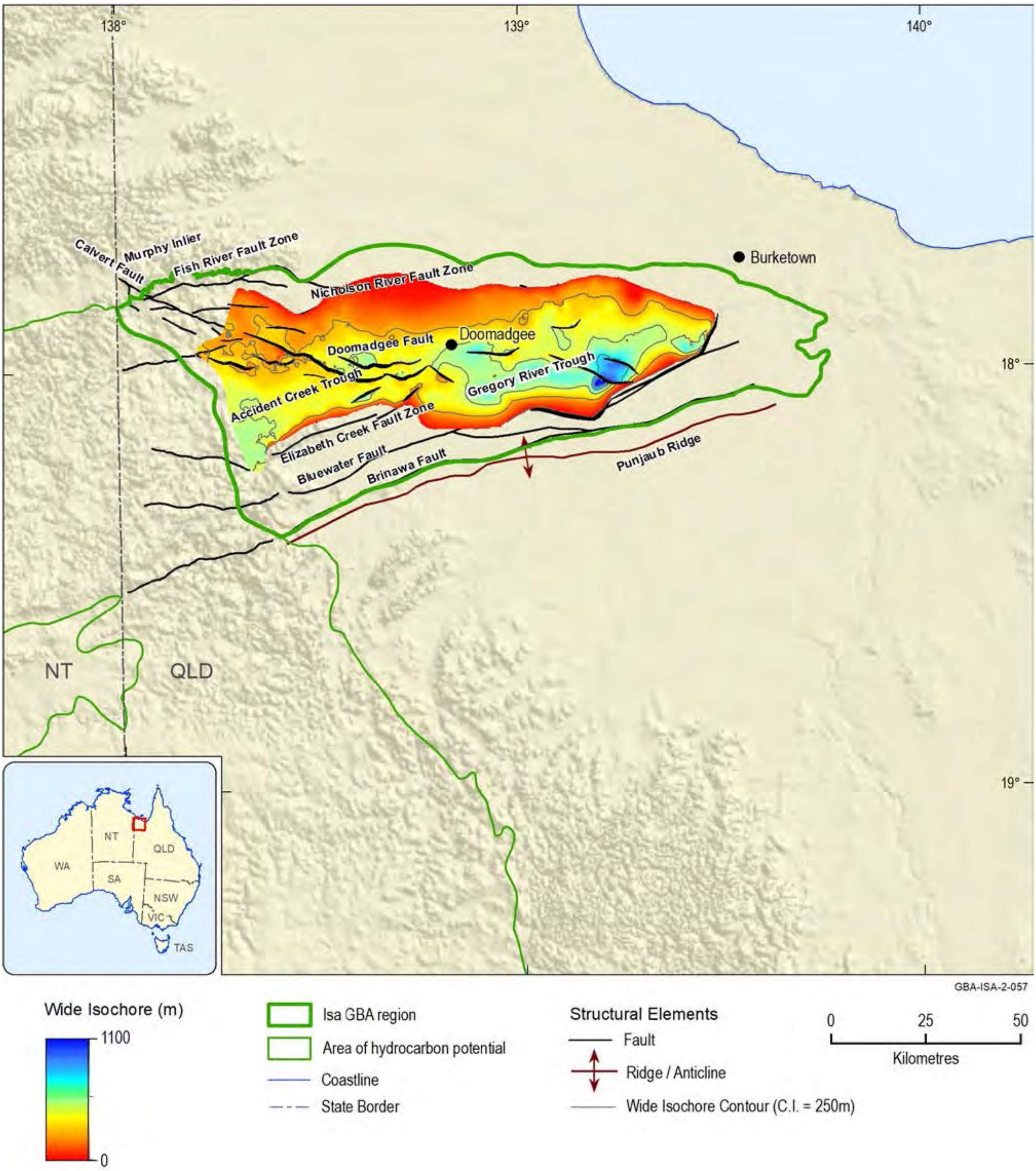


Figure 41 Wide Supersequence isochore (vertical thickness) map

Contour interval (C.I.) = 250 m
Source: Generated using the published Wide Supersequence isochore map of Bradshaw et al. (2018c)
Data: Isochore grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-057

4.2.1.5 Doom Supersequence

The base Doom Supersequence surface is relatively conformable in most areas, with little evidence for erosion or onlap (Scott and Bradshaw, 1999). The base surface is relatively shallow (600 m below mean sea level) over the Accident Creek Trough, however it deepens to 2100 m below mean sea level over the Gregory River Trough (Figure 42).

Up to 1000 m of strata from the Doom Supersequence are preserved in the Gregory River Trough (Figure 43). The Doom Supersequence is only rarely preserved in outcrop sections over the southern Murphy Inlier, and was uplifted and eroded over the Elizabeth Creek Fault Zone and Bluewater Fault System during the Isan Orogeny and subsequent deformation events.

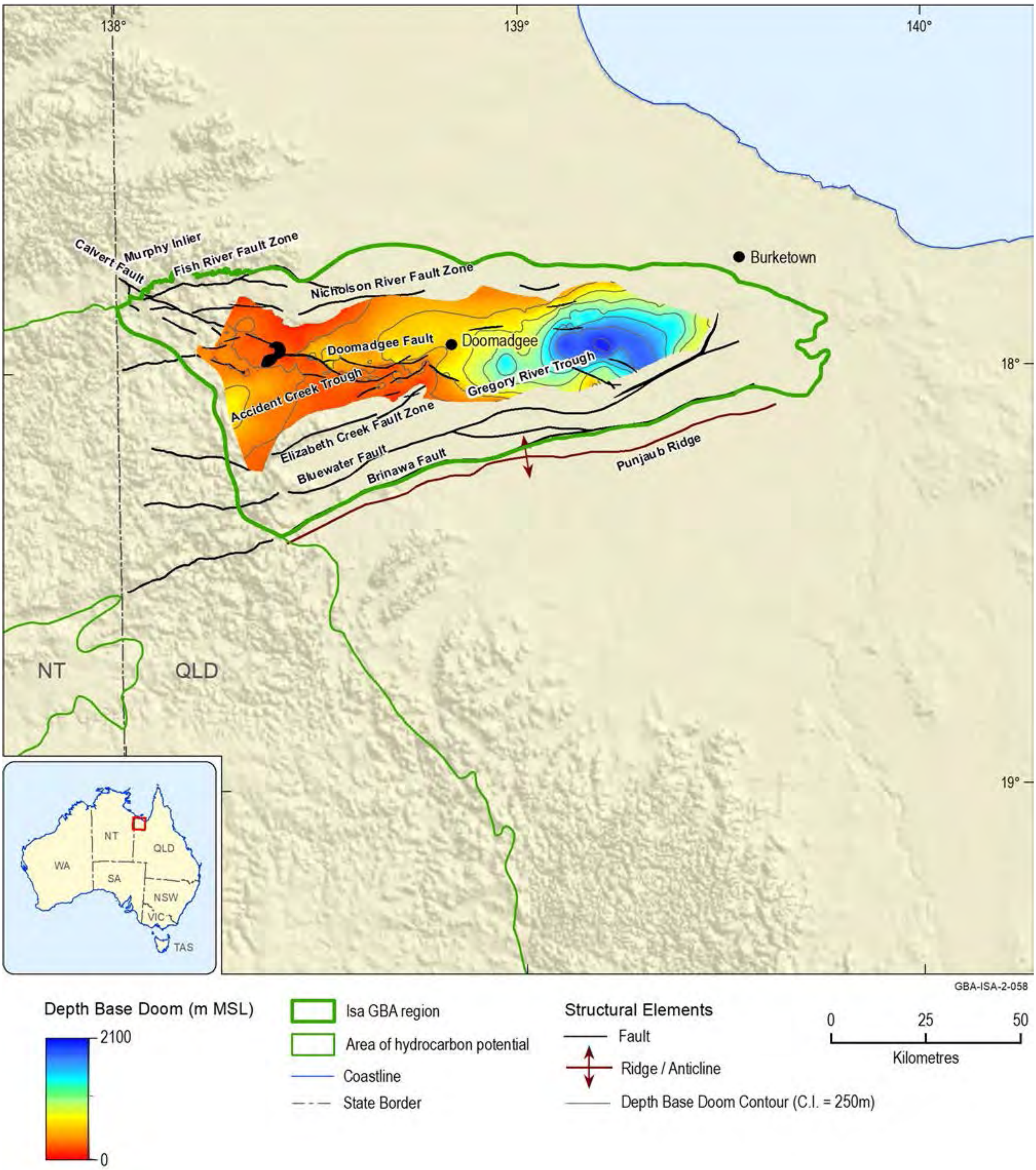


Figure 42 Base Doom Supersequence depth-structure map

Datum = mean sea level (MSL); contour interval (C.I.) = 250 m

Source: Bradshaw et al. (2018c)

Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)

Element: GBA-ISA-2-058

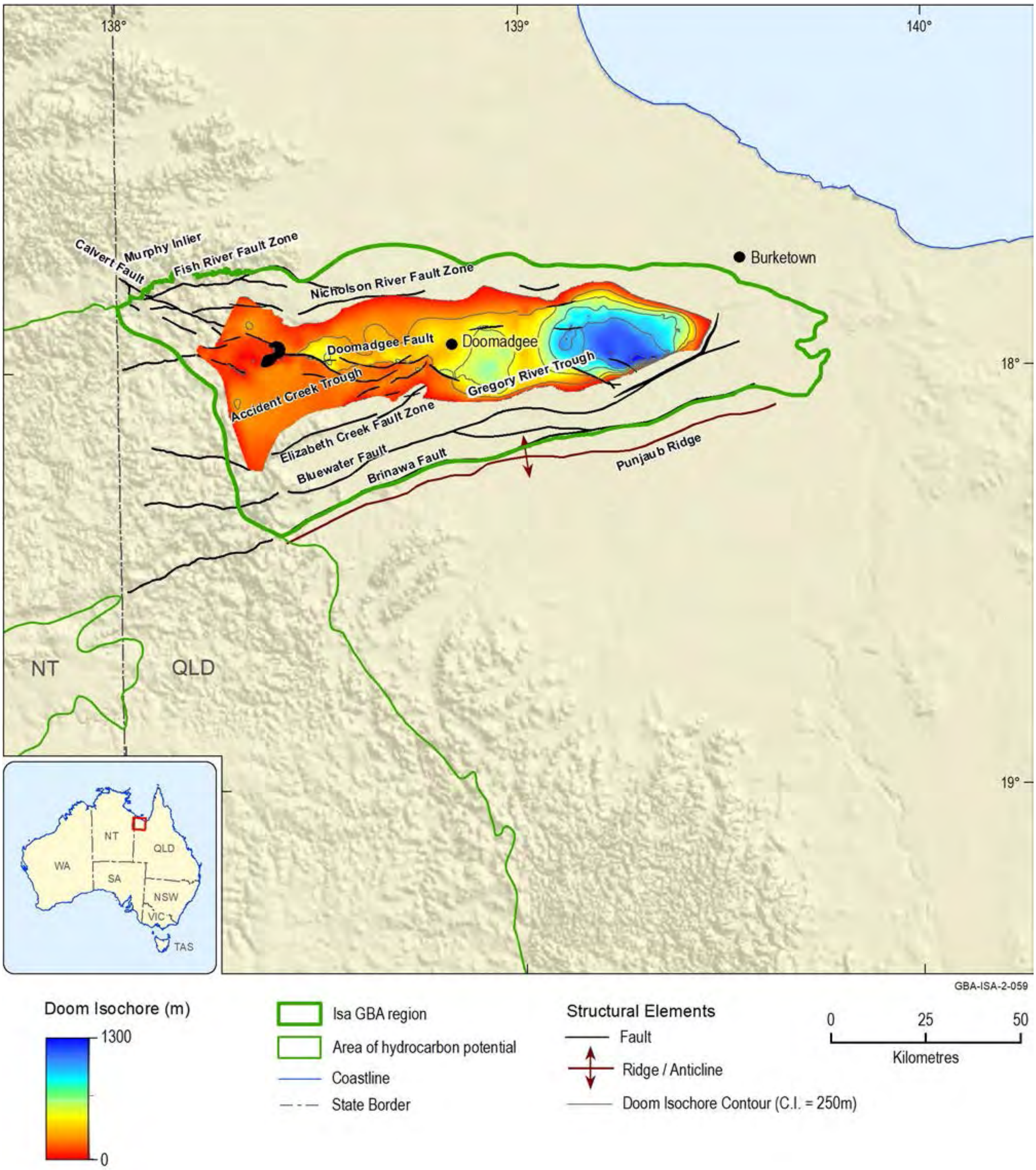


Figure 43 Doom Supersequence isochore (vertical thickness) map

Contour interval (C.I.) = 250 m

Source: Generated using the published Doom Supersequence isochore map of Bradshaw et al. (2018c)

Data: Isochore grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)

Element: GBA-ISA-2-059

4.2.2 South Nicholson Basin

The South Nicholson Basin sequences outcrop over much of the western part of the northern Lawn Hill Platform where they unconformably overlie the Isa Superbasin (Jackson et al., 1999; Scott and Bradshaw, 1999). However, the relationship between the two basins appears relatively conformable over the Gregory River Trough where deformation propagated through the Isa Superbasin into the South Nicholson Basin over the main synformal structure (Figure 44). This apparent concordance in structure between the two basin successions suggests that much of the deformation in the eastern area post-dated the Isan Orogeny during one or more tectonic events following closure of the South Nicholson Basin. Frogtech Geoscience (2018a) proposed that most uplift and erosion of the South Nicholson Basin was associated with amalgamation of the North and West Australian cratons with the South Australian Craton (1350 to 1040 Ma). Sweet (2017) also documented evidence in outcrop data for the major post South Nicholson Basin deformation event occurring at about 1324 Ma, at about the same time as deformation in the Roper Group (Abbott et al., 2001).

Up to 3600 m of fluvial and marine sediments were deposited in the main South Nicholson Basin depocentre located west of the Isa GBA region (Sweet, 2017). Uplift and erosion following basin closure has left a relatively thin (<250 m) South Nicholson Basin cover over the western part of the northern Lawn Hill Platform. However, up to 700 m of South Nicholson Basin strata are preserved over the Gregory River Trough (Figure 45). It is uncertain if a significant hiatus in sedimentation occurred between the Isa Superbasin and South Nicholson Basin in the Gregory River Trough, given the lack of evidence for a major angular unconformity in seismic data, or if there was continued subsidence and sedimentation.

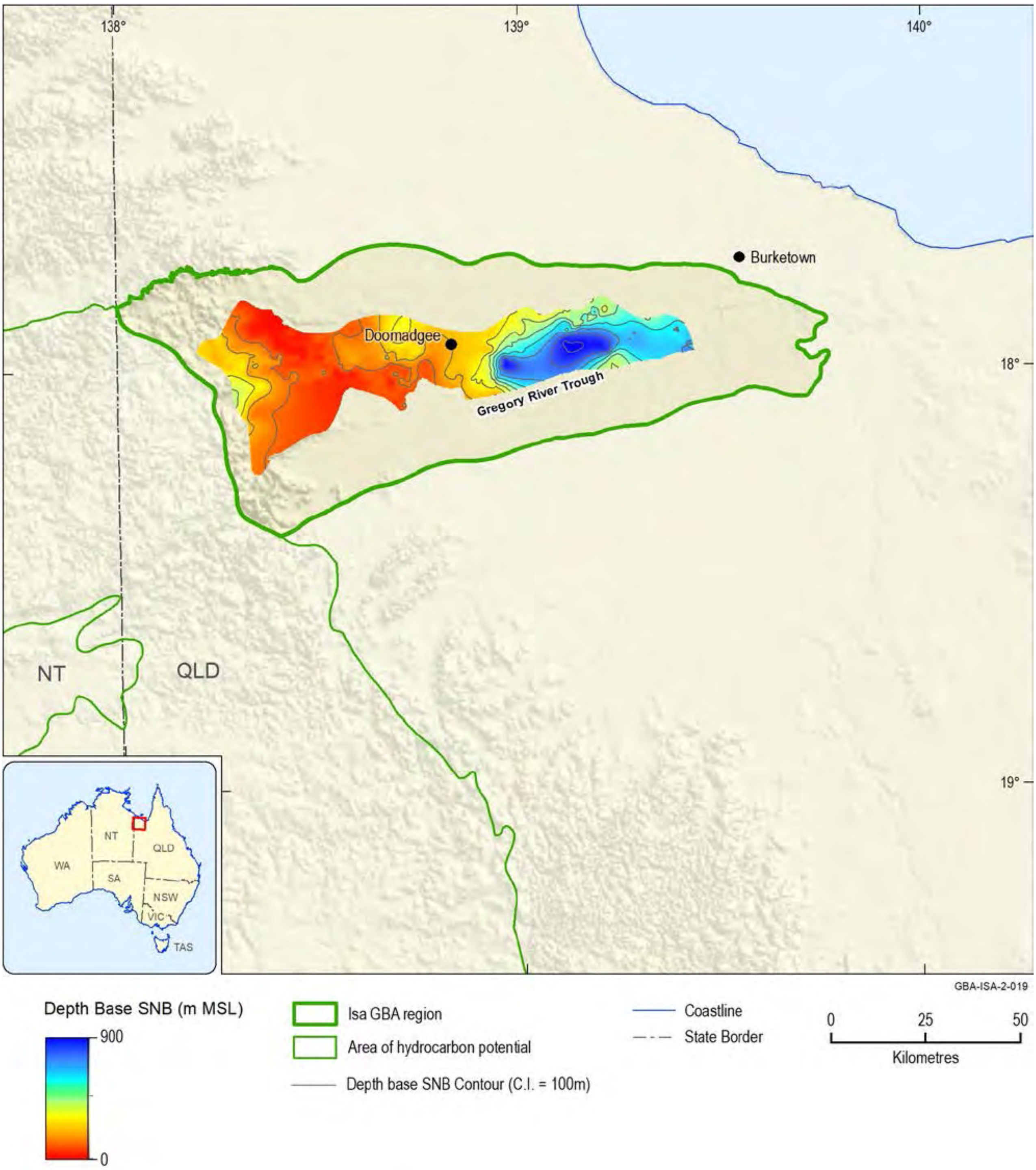


Figure 44 Base South Nicholson Basin depth-structure map

Datum = mean sea level (MSL); contour interval (C.I.) = 250 m; SNB = South Nicholson Basin
Source: Bradshaw et al. (2018c)
Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-019

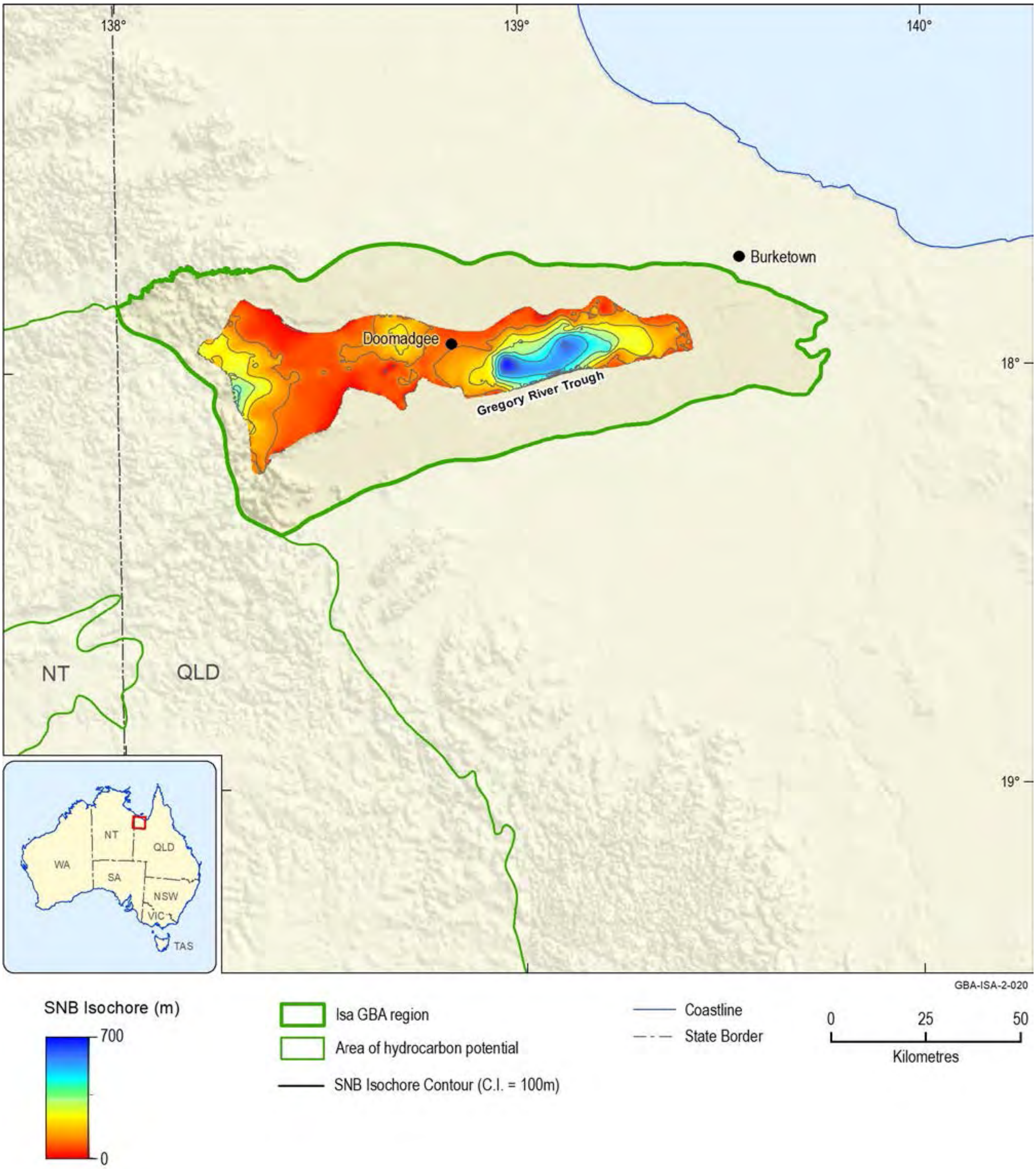


Figure 45 South Nicholson Basin isochore (vertical thickness) map

Contour interval (C.I.) = 100 m; SNB = South Nicholson Basin
Source: Bradshaw et al. (2018c)
Data: Isochore grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-020

4.2.3 Carpentaria Basin

The Isa GBA region is located at the south-western margin of the Carpentaria Basin. The area coincides with both the onshore part of the Western Gulf Sub-basin and the onshore part of the Staaten Sub-basin. The basin continues to the north, south and east of the northern Lawn Hill Platform, with most of the basin located in the offshore Gulf of Carpentaria (McConachie et al., 1997). Outlying isolated outcrops of Late Jurassic to Early Cretaceous strata (outliers) occur west of the zero edge boundary, which are preserved remnants of an originally more extensive basin (Figure 23).

Structural elements at the base of the Carpentaria Basin include a series of east-north-east to north-east trending faults with relatively small throws over the western basin margin, and a series of north-north-east to north-trending major faults and associated horst and graben structures within the main basin axis to the east. Pervasive small faults are evident in the overlying basin fill, particularly within the Toolebuc Formation (these are known as polygonal fault systems and are discussed in greater detail in the hydrogeology technical appendix (Buchanan et al., 2020)). The Carpentaria Basin thickens to the east-north-east, reaching maximum thicknesses in excess of 900 m in the eastern part of the northern Lawn Hill Platform (Figure 46 and Figure 47). Thinning of the basin to the west is mainly due to a combination of stratigraphic pinchout of Early Cretaceous strata and erosion of Early to Late Cretaceous strata. At least 700 m of Cretaceous strata are likely to have been eroded over the western Isa GBA region area based on regional thickness trends in the seismic data (Bradshaw et al., 2018c).

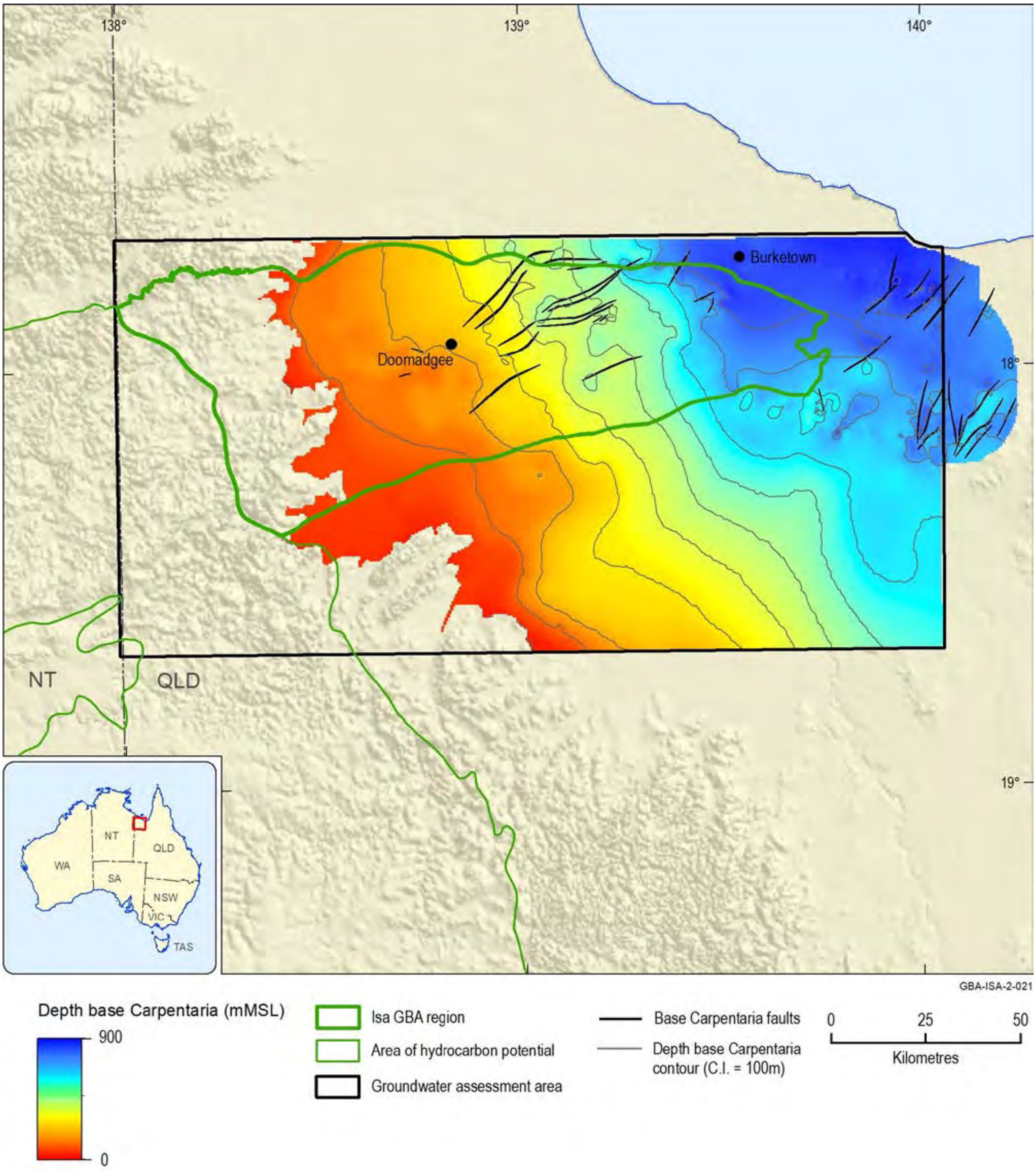


Figure 46 Base Carpentaria Basin depth-structure map

Datum = mean sea level (MSL); contour interval (C.I.) = 100 m
Source: Bradshaw et al. (2018c)
Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-021

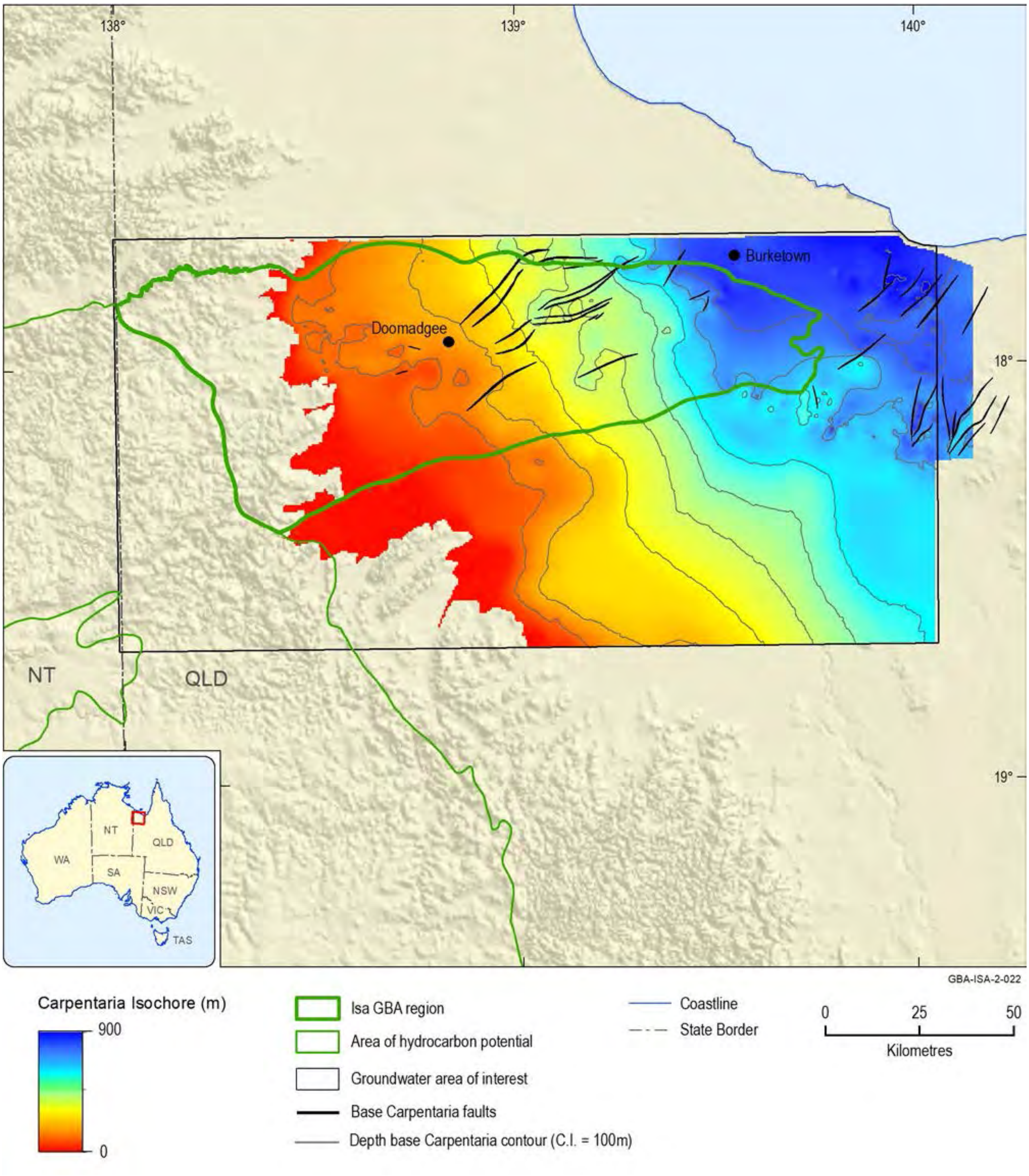


Figure 47 Carpentaria Basin isochore map

Contour interval (C.I.) = 100 m
Source: Bradshaw et al. (2018c)
Data: Isochore grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-022

4.2.4 Karumba Basin

The Cenozoic Karumba Basin is the youngest sedimentary basin succession in the Isa GBA region and forms a very thin (<50 m) veneer of Cenozoic strata across the northern Lawn Hill Platform (Figure 49).

The Karumba Basin is generally too shallow to be interpreted and mapped from seismic data. Smerdon et al. (2012) have published an isopach map for the Paleogene to Neogene sedimentary component of the Great Artesian Basin, which has been modified using the digital elevation model of Hutchinson et al. (2008) and formation tops in wells across the Isa GBA region to produce depth-structure and isochore maps for the Karumba Basin.

The derived depth-structure map shows a similar extent for the Karumba Basin as the underlying Carpentaria Basin, with strata tilted down to the east and north-east to maximum depths of 30 m below mean sea level before the basin extends offshore into the Gulf of Carpentaria (Figure 48).

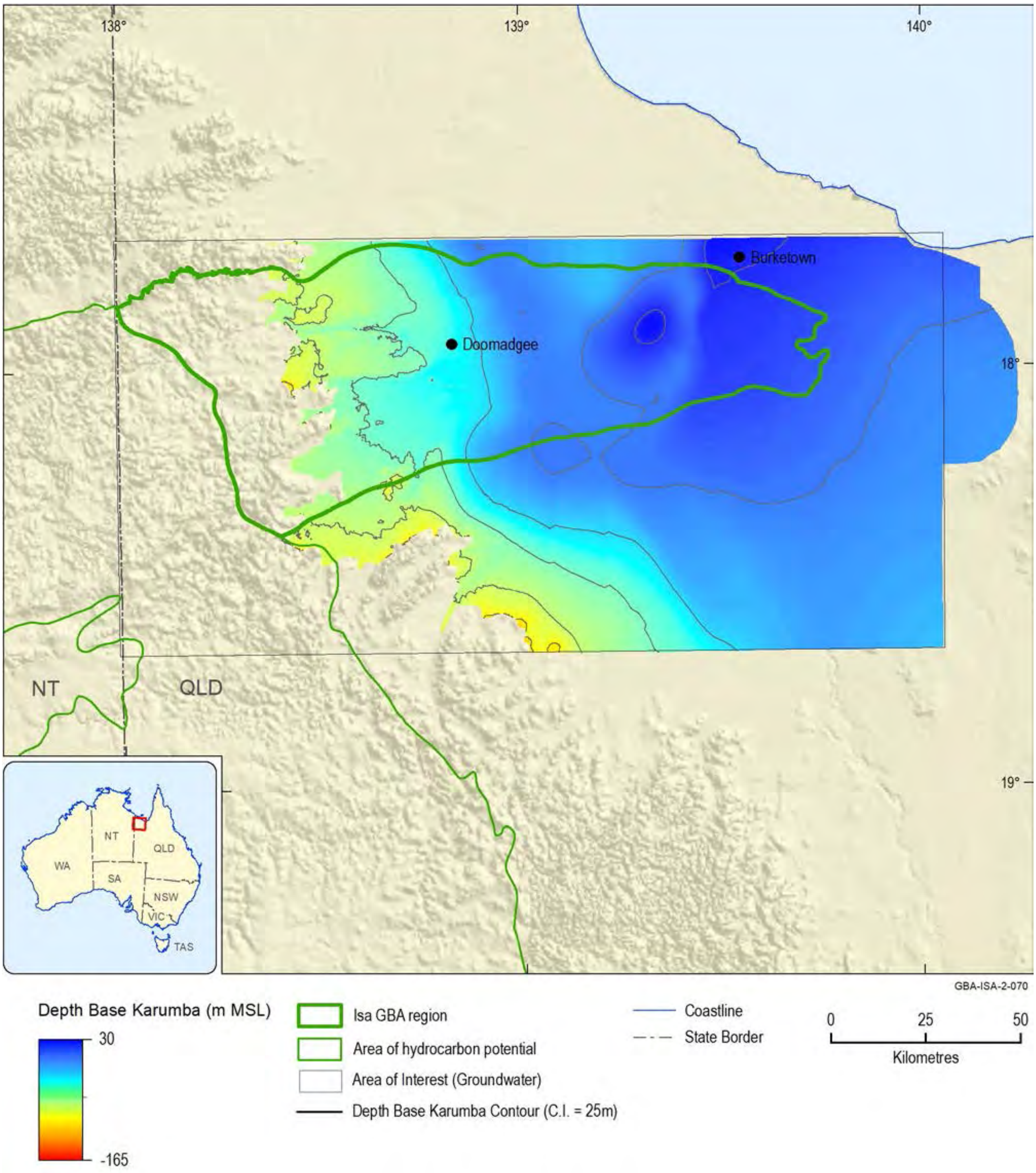


Figure 48 Base Karumba Basin depth-structure map

Datum = mean sea level; contour interval (C.I.) = 25 m
Source: Smerdon et al. (2012)
Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-070

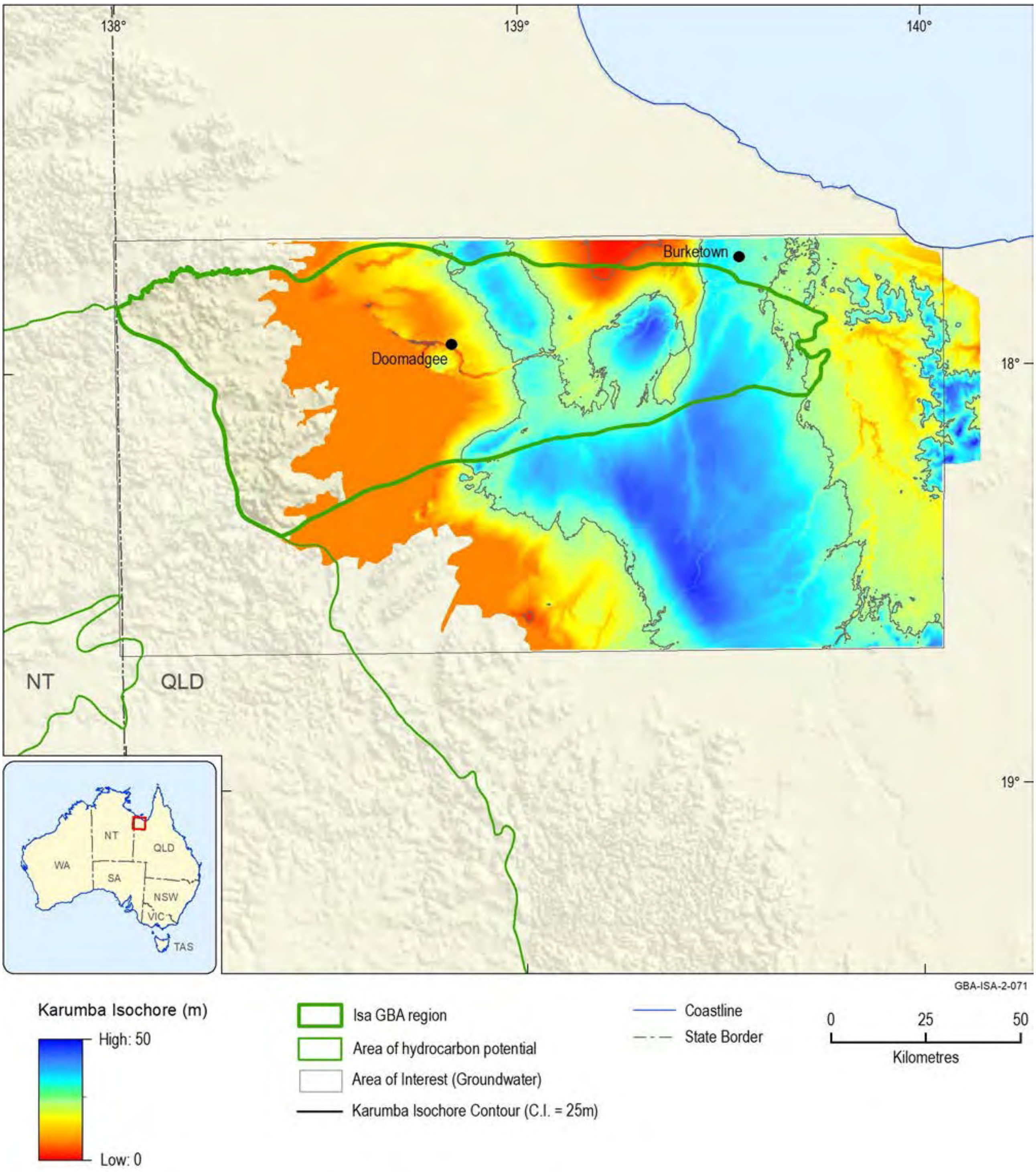


Figure 49 Karumba Basin isochore map

Contour interval (C.I.) = 25 m
Source: Derived using the published Karumba Basin isopach map in Smerdon et al. (2012)
Data: Depth-structure grid, contours and faults from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-071

4.3 Solid geology map

A geology map has been generated over the Isa GBA region to show the maximum extent of the South Nicholson Basin and each of the Isa Superbasin supersequences where they either crop out at the surface or subcrop beneath the Carpentaria Basin (Figure 50). This type of map showing the distribution of rock units without the overlying cover sequences (i.e. the younger geological units of the Carpentaria and Karumba basins) is commonly referred to as a solid geology map.

The outcrop component of the solid geology map was generated by integrating the Geological Survey of Queensland (2011b) surface geology map with logged well and outcrop section data by Krassay et al. (1999), and then assigning each map unit to an associated supersequence.

The subcrop component was generated using seismic interpretations by Bradshaw and Scott (1999) together with recent interpretations of seismic data by Bradshaw et al. (2018c). Well data from BMR Westmoreland 2, Burketown 1 and Egilabria 4 have also been used to refine the subcrop map. The solid geology supersequences assigned to each well in the Isa GBA region are summarised in Table 6.

The solid geology map generated over the Isa GBA region (Figure 50) is customised for the purposes of this study and matches the zero edges interpreted by Bradshaw and Scott (1999) as well as new seismic and well interpretations by Bradshaw et al. (2018c).

Table 6 Solid geology rock units and corresponding supersequence (Isa Superbasin) or basin (South Nicholson Basin)

Well name	Solid geology rock unit	Solid geology supersequence
Lawn Hill DDH 83-4	Constance Sandstone	South Nicholson Basin
Egilabria 2	Constance Sandstone	South Nicholson Basin
Egilabria 4	Not picked	Doom
BMR Westmoreland 1	Proterozoic basement (laminated shale and siltstone)	River
Argyle Creek 1	Constance Sandstone	South Nicholson Basin
Beamesbrook 1	Constance Sandstone	South Nicholson Basin
Desert Creek 1	Constance Sandstone	South Nicholson Basin
Egilabria 1	Constance Sandstone	South Nicholson Basin
Elf Aquitaine QLG 5001	Doomadgee Formation (Pfd_3)	Term
Elf Aquitaine QLG 5002	Doomadgee Formation (Pfd_3)	Term
Burketown 1	Proterozoic dolomites (massive and cavernous) and quartzites	Loretta
WMC HCKDO1	Doomadgee Formation (Pfd_3)	Wide
WMC WFDD17	Doomadgee Formation (Pfd_3)	Doom
WMC WFDD47	Doomadgee Formation (Pfd_3)	Term
WMC WFDD59	Doomadgee Formation (Pfd_3)	Wide
WMC WFDD74	Mount Les Siltstone (Pfl_5)	River

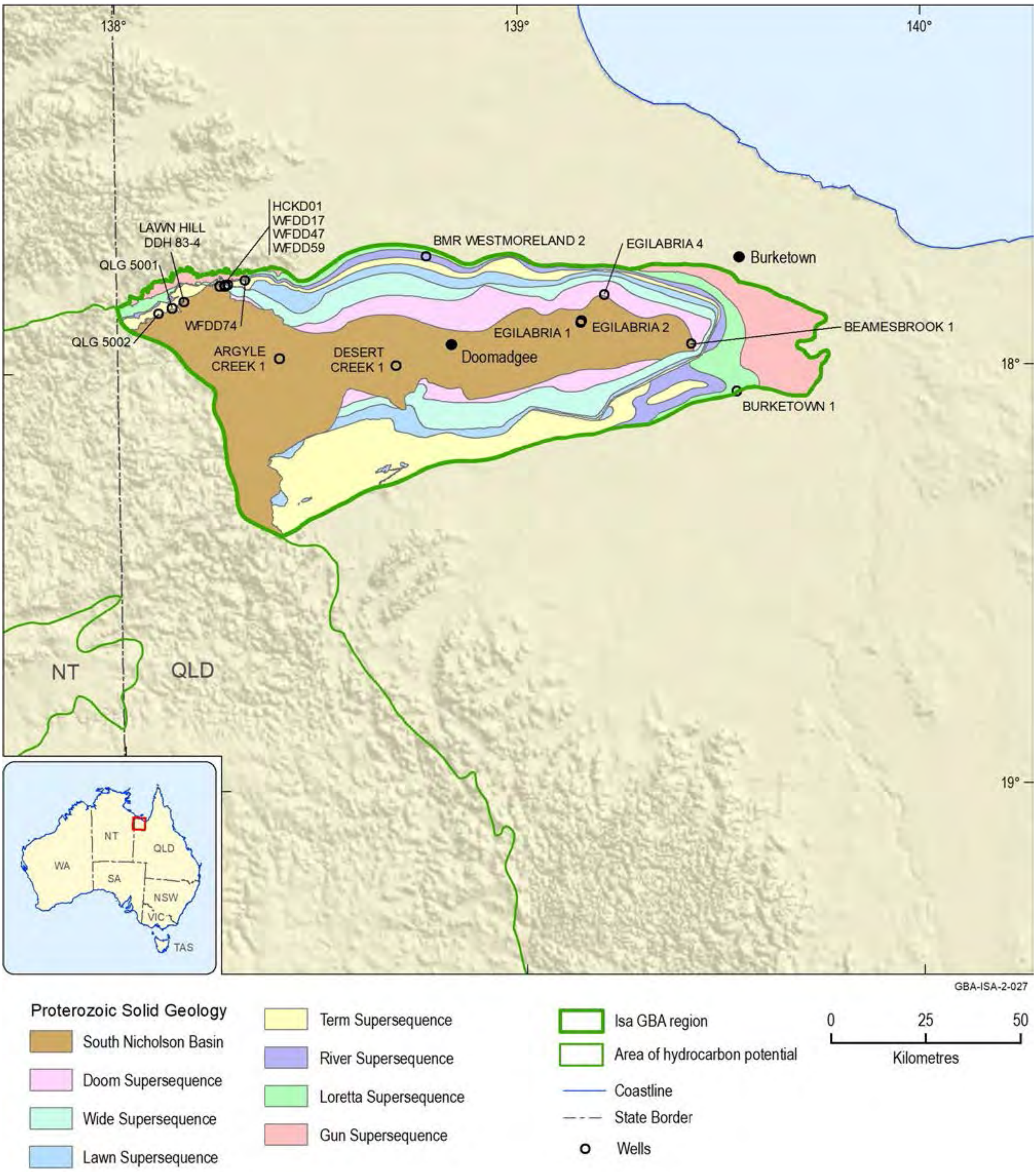


Figure 50 Solid geology map for Proterozoic supersequences from the Isa Superbasin and the South Nicholson Basin over the Isa GBA region

Source: Bradshaw et al. (2018c)

Data: Proterozoic solid geology map sourced from Bradshaw et al. (2018b). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)

Element: GBA-ISA-2-027

Future data acquisition would refine the solid geology interpretations. Data made available in recent years has resulted in differences between the solid geology map presented here and the solid geology map compiled earlier by the Geological Survey of Queensland (2011b). The differences include:

- a westward shift in the South Nicholson Basin boundary because Egilabria 4 (drilled in 2013) did not intersect South Nicholson Basin sediments. The basin subcrops the Carpentaria Basin at Beamesbrook 1
- the placement of the Term Supersequence as the subcrop unit in the hanging wall block of the Brinawa Fault System, due to the recent interpretations of seismic data by Bradshaw et al. (2018c).

Another difference is due to a variation in the stratigraphic placement of the Lawn Supersequence boundary. Krassay et al. (2000a) noted two different but valid placements of the Lawn Supersequence boundary, as follows:

- at the base Bulmung Sandstone, which represents a significant unconformity-bounded lowstand sandstone, and;
- the base of the Pmh 2 member, which represents a major change in sediment provenance to locally sourced volcaniclastic deposits.

The solid geology map of Figure 50 uses the former definition and so outlines a large outcropping area of the Term Supersequence in the south-western Isa GBA region.

4.4 Regional three-dimensional datasets and schematic sections

The depth-converted structure maps published by Bradshaw et al. (2018c) for the Isa Superbasin, South Nicholson and Carpentaria basins were used to generate a simplified three-dimensional geological model for the Isa GBA region. Two three-dimensional perspective views of this model are shown in Figure 51 and Figure 52, while example cross-sections are shown in Figure 53 and Figure 54. Faults and other geological structures have not been explicitly incorporated into the model structure, but major structural features are clearly evident in areas where stratigraphy shows significant disruption/displacement over relatively short distances.

The regional three-dimensional geological model for the Isa GBA region underpins Isa GBA region shale gas prospectivity assessment (Bailey et al., 2020) and hydrostratigraphic analysis (Buchanan et al., 2020).

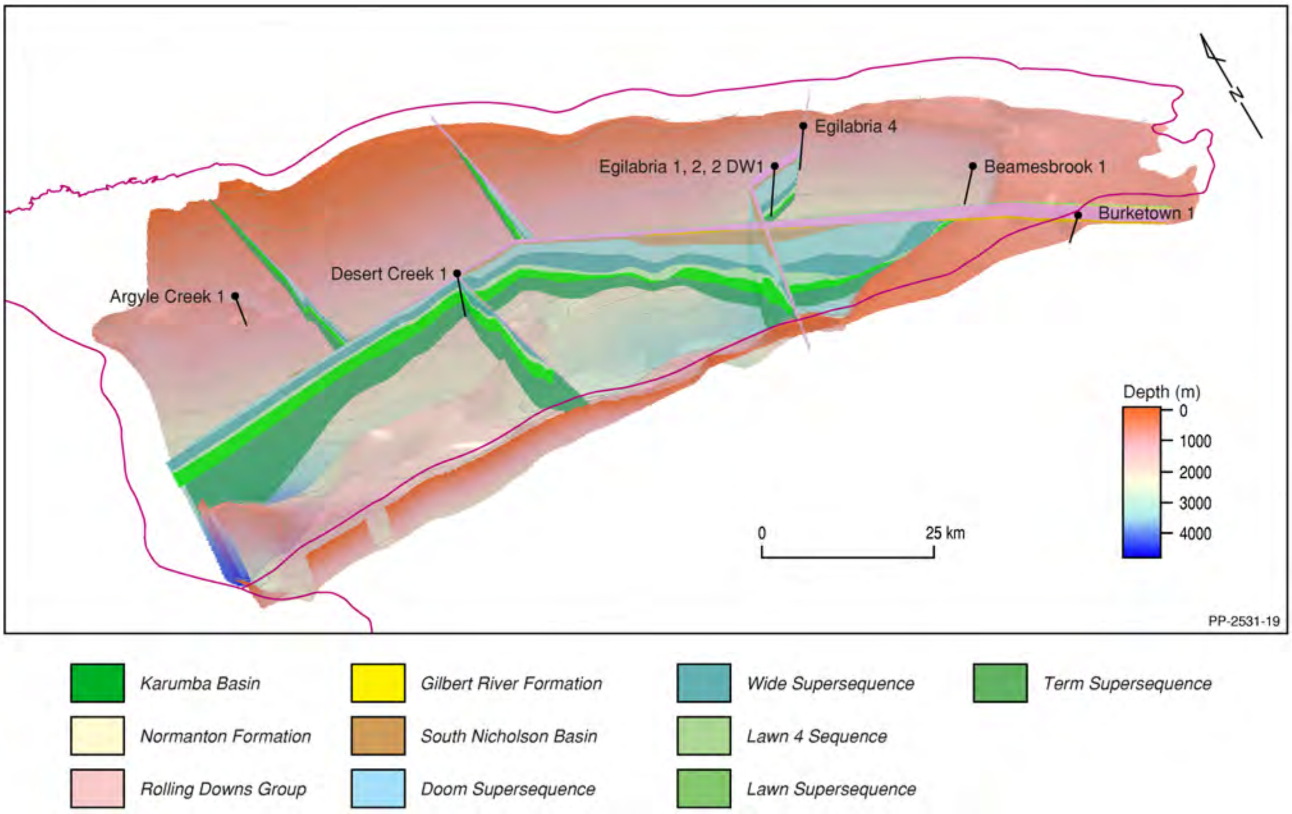


Figure 51 Oblique view of the regional three-dimensional geological model for the Isa GBA region (looking north)

The structural surface shown is the Base Term Supersequence. Depth is in metres below mean sea level. The locations of key petroleum wells are also shown. The three-dimensional geological model is available from the GBA data repository.
Source: Based on the grids of Bradshaw et al. (2018b)
Element: GBA-ISA-2-120

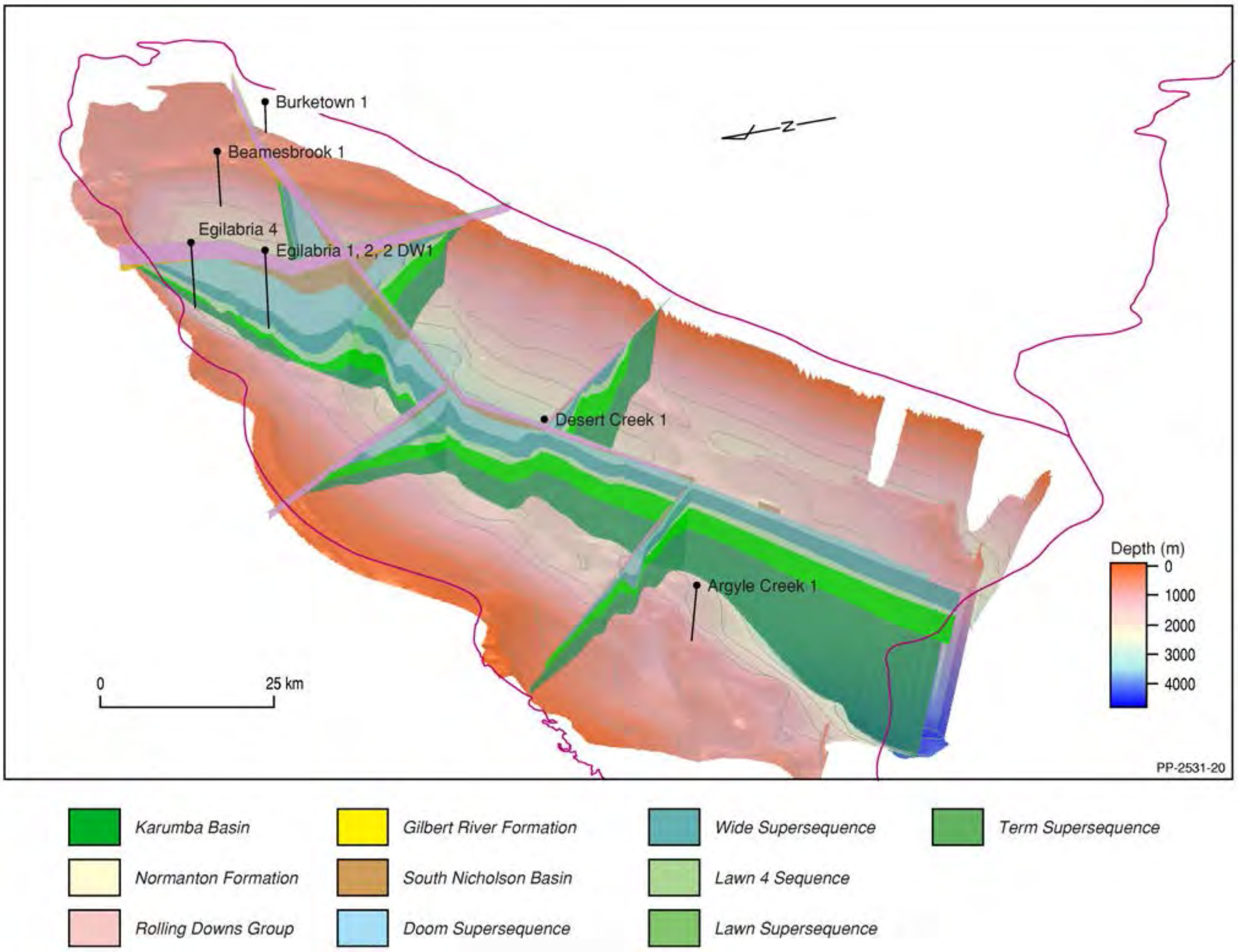


Figure 52 Oblique view of the regional three-dimensional geological model for the Isa GBA region (looking east)

The structural surface shown is the Base Term Supersequence. The locations of key petroleum wells are also shown. The three-dimensional geological model is available from the GBA data repository.
Source: Based on the grids of Bradshaw et al. (2018b)
Element: GBA-ISA-2-121

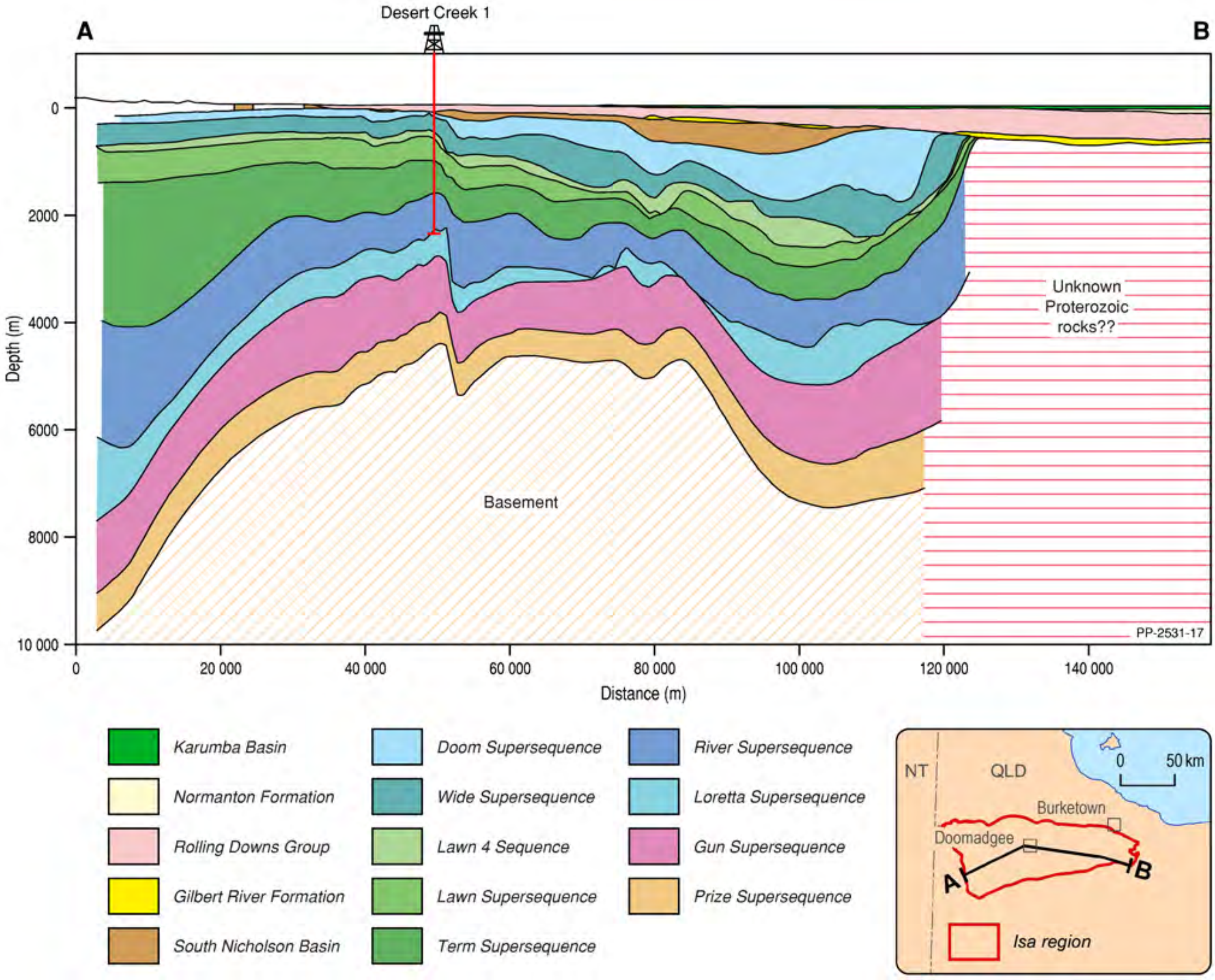


Figure 53 Schematic east to west cross-section through the Isa GBA region generated from the three-dimensional geological model showing the along-strike structural architecture of the northern Lawn Hill Platform

Both the Isa GBA region and the line location are shown on the inset map. The three-dimensional geological model is available from the GBA data repository.
Source: Based on the grids of Bradshaw et al. (2018b).
Element: GBA-ISA-2-122

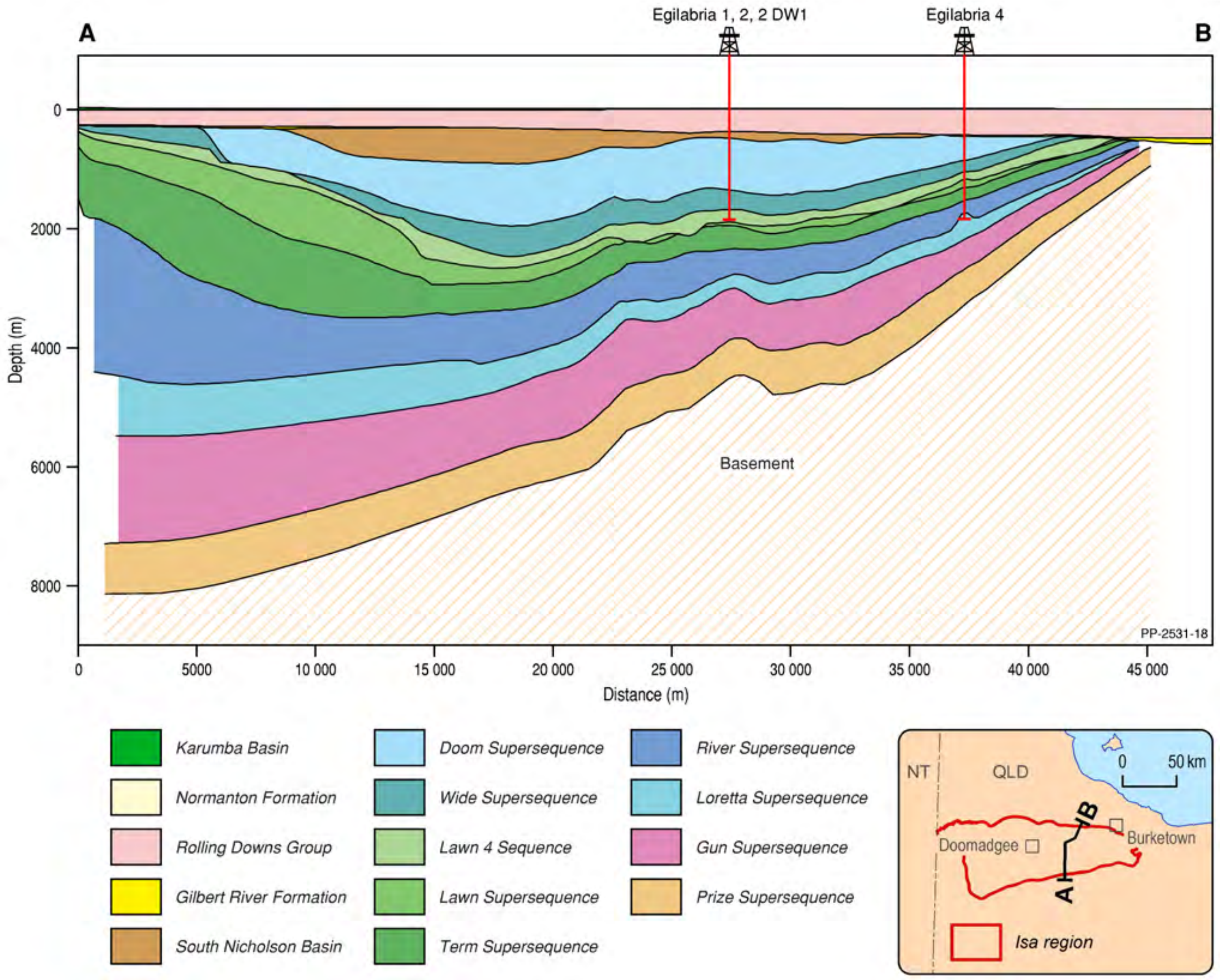


Figure 54 Schematic north to south cross-section through the Isa GBA region generated from the three-dimensional geological model showing the cross-dip structural architecture of the northern Lawn Hill Platform

Both the Isa GBA region and the line location are shown on the inset map. The three-dimensional geological model is available from the GBA data repository.
Source: Based on the grids of Bradshaw et al. (2018b)
Element: GBA-ISA-2-123

4.5 Interpretation confidence

The structural and stratigraphic interpretations presented here remain limited by the small number of seismic surveys and well data available over the northern Lawn Hill Platform (Figure 55). The variability in data coverage and quality corresponds to different degrees of confidence in the interpreted subsurface horizons and structural element maps derived from these data (Figure 56) (Bradshaw et al., 2018c).

An elongate area from just east of Argyle Creek 1 to just west of Beamesbrook 1 has good quality seismic data with well ties, allowing confident interpretation and mapping of seismic horizons (Figure 56) (Bradshaw et al., 2018c). In contrast, data coverage and quality are greatly reduced to the north and south of Argyle Creek 1, to the north of Desert Creek 1, to the south of the Egilabria 1 and 2 wells, and in the area surrounding Beamesbrook 1 (Figure 56). Consequently, interpretation confidence becomes low to very low in the areas extending to the southern flanks of the Murphy Inlier in the north and in the southern Isa GBA region (Figure 56).

This variability in data coverage and quality impacts both the accuracy of the interpreted surfaces and that of all derived products. Future additional data acquisition would add detail and accuracy to the geological characterisation of the Isa GBA region.

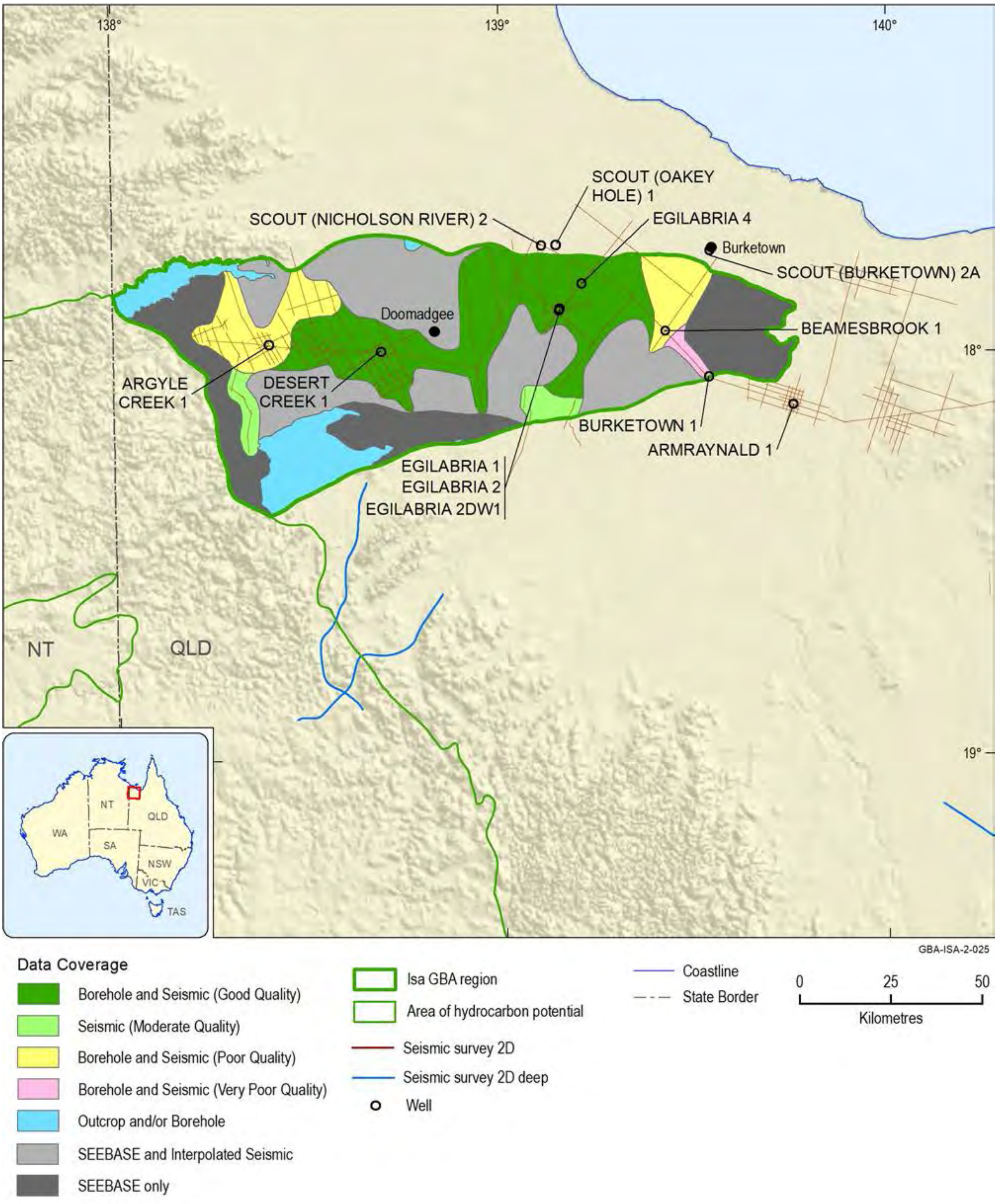


Figure 55 Data coverage and data quality for interpretation of Isa Superbasin horizons within the Isa GBA region

Data: Data coverage map from Bradshaw et al. (2018a). Two-dimensional seismic survey line locations from Department of Natural Resources (2017b), deep crustal seismic line locations from Department of Natural Resources (2017c), petroleum well locations from Department of Natural Resources (2017a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-025

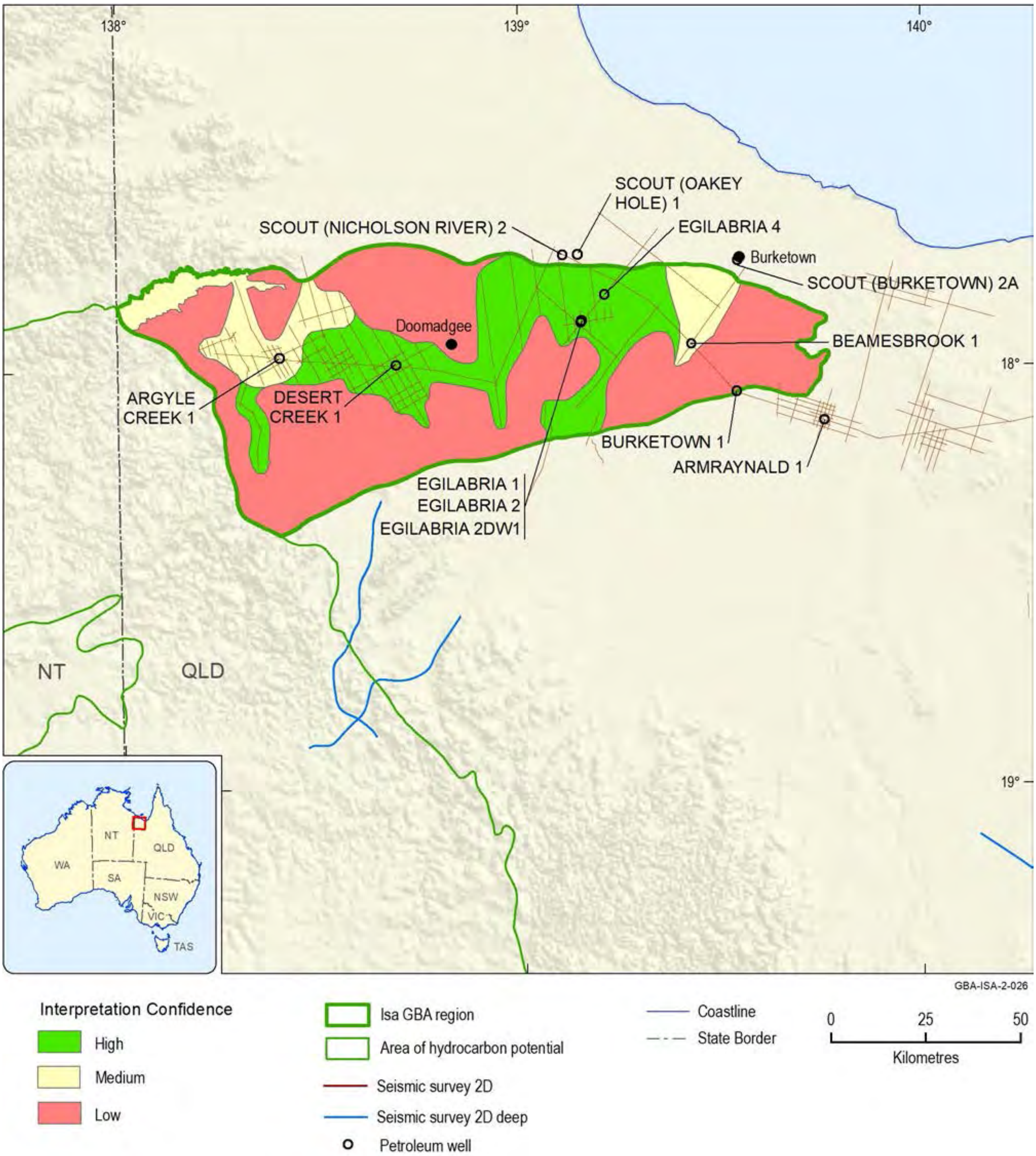


Figure 56 Interpretation confidence for the Isa Superbasin grids generated over the Isa GBA region

Data: Interpretation confidence map from Bradshaw et al. (2018a). Two-dimensional seismic survey line locations from Department of Natural Resources (2017b), deep crustal seismic line locations from Department of Natural Resources (2017c), petroleum well locations from Department of Natural Resources (2017a). Background image is the GEODATA 9-second digital elevation model, version 3 (hillshade) (Hutchinson et al., 2008)
Element: GBA-ISA-2-026

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Glossary

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

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

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

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

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

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

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

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

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

carbonaceous shale: organic-rich shales that contain less total organic carbon (TOC) than coals (50 wt.% TOC) clastic: sedimentary rock that consists of fragments or clasts of pre-existing rock, such as sandstone or shale

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

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

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

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

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

context: the circumstances that form the setting for an event, statement or idea

continental crust : the part of the Earth's crust that underlies the continents and continental shelves

conventional gas: conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock, with the gas trapped by buoyancy. The gas can often move to the surface through the gas wells without the need to pump.

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

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

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

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

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

depocentre: an area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin deposition: sedimentation of any material, as in the mechanical settling of sediment from suspension in water, precipitation of mineral matter by evaporation from solution, and accumulation of organic material

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

development: a phase in which newly discovered oil or gas fields are put into production by drilling and completing production wells

dolomite: a rhombohedral carbonate mineral with the formula $CaMg(CO_3)_2$

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

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

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

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

1. exploration: the search for new hydrocarbon resources by improving geological and prospectivity understanding of an area and/or play through data acquisition, data analysis and interpretation. Exploration may include desktop studies, field mapping, seismic or other geophysical surveys, and drilling.

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

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

fairway: a term used in geology to describe a regional trend along which a particular geological feature is likely to occur, such as a hydrocarbon fairway. Understanding and predicting fairways can help geologists explore for various types of resources, such as minerals, oil and gas.

fault: a fracture or zone of fractures in the Earth's crust along which rocks on one side were displaced relative to those on the other side field: in petroleum geoscience, a 'field' refers to an accumulation, pool, or group of pools of hydrocarbons or other mineral resources in the subsurface. A hydrocarbon field consists of a reservoir with trapped hydrocarbons covered by an impermeable sealing rock, or trapped by hydrostatic pressure.

fluvial: sediments or other geologic features formed by streams

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

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

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

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

geothermal gradient: the rate of increase in temperature with depth in the Earth

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

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

groundwater system: see water system

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

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

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

immature: a hydrocarbon source rock that has not fully entered optimal conditions for generation of hydrocarbons impact: the difference between what could happen as a result of activities and processes associated with extractive industries, such as shale, tight and deep coal gas development, and what would happen without them. Impacts may be changes that occur to the natural environment, community or economy. Impacts can be a direct or indirect result of activities, or a cumulative result of multiple activities or processes.

intrusion: the process of emplacement of magma into pre-existing rock

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

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

lithosphere: the outermost shell of the solid Earth, consisting of approximately 100 km of crust and upper mantle

material: pertinent or relevant

mature: a hydrocarbon source rock that has started generating hydrocarbons

mudstone: a general term for sedimentary rock made up of clay-sized particles, typically massive and not fissile

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

normal fault: a fault in which the hanging wall appears to have moved downward relative to the footwall, normally occurring in areas of crustal tension

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

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

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

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

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

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

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

potential source rock: a gas- or oil-prone, organic-rich rock that has not yet generated petroleum. A potential source rock becomes an effective source rock when it generates microbial gas at low temperatures or when it reaches the level of thermal maturity necessary to generate petroleum.

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

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

progradation: movement of the shoreline into a sedimentary basin when clastic input exceeds the accommodation space, as might occur due to reduced basinal subsidence or increased erosion and sediment supply

prospectivity assessment: the assessment of an area to determine the likelihood of discovering a given resource (e.g. oil, gas, groundwater) by analysing the spatial patterns of foundation datasets. The key objective is to identify areas of increased likelihood of discovering previously unrecognised potential. Sometimes referred to as ‘chance of success’ or ‘common risk segment’ analysis.

regression: the retreat or contraction of the sea from land areas, and the consequent evidence of such withdrawal (such as enlargement of the area of deltaic deposition). Also, any change (such as fall of sea level or uplift of land) that brings nearshore, typically shallow-water environments to areas formerly occupied by offshore, typically deep-water conditions, or that shifts the boundary between marine and nonmarine deposition (or between deposition and erosion) toward the center of a marine basin.

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

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

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

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

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

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

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

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

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

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

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

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

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

siliciclastic: clastic, non-carbonate rocks dominated by quartz or silicate minerals

siltstone: a sedimentary rock composed of silt-sized particles (0.004 to 0.063 mm in diameter) source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Under the right conditions, source rocks may also be reservoir rocks, as in the case of shale gas reservoirs.

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

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

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

structure: a geological feature produced by deformation of the Earth's crust, such as a fold or a fault; a feature within a rock, such as a fracture or bedding surface; or, more generally, the spatial arrangement of rocks

subcrop: 1 - A subsurface outcrop, e.g. where a formation intersects a subsurface plane such as an unconformity. 2 - In mining, any near-surface development of a rock or orebody, usually beneath superficial material.

subsidence: the sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved.

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

tectonics: the structural behaviour of the Earth's crust

tectonostratigraphic: relating to the correlation of rock formations with each other in terms of their connection with a tectonic event

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

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

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

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

transgression: any change (such as rise of sea level or subsidence of land) that brings offshore, typically deep-water environments to areas formerly occupied by nearshore, typically shallow-water conditions, or that shifts the boundary between marine and nonmarine deposition (or between deposition and erosion) outward from the center of a marine basin.

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

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

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

water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

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

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