The *Exploring for the Future* 2019 Barkly 2D Deep Crustal Reflection Seismic Survey: Key discoveries and implication for resources

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Introduction

The first phase of the Australian Government's *Exploring for the Future* (EFTF) was a $100.5 million, multi-year (2016–2020) Australian Government initiative to increase northern Australia's attractiveness as a destination for resource industry exploration and investment. Geoscience Australia, in collaboration with key State and Territory partners, has acquired a diverse range of pre-competitive geoscience datasets across northern Australia, focusing on frontier or 'greenfield' regions, ie areas under-evaluated for mineral, energy, and groundwater resource potential. In late 2019, the Barkly 2D Deep Crustal Reflection Seismic Survey (L212, Barkly seismic survey), jointly funded under the EFTF program and the Northern Territory Geological Survey's *Resourcing the Territory* initiative, acquired seismic data across the underexplored and (mostly) undercover South Nicholson and Barkly Tablelands regions in the northeastern Northern Territory (**Figure 1**). The Barkly seismic survey data images a complete seismic profile from the newly discovered Carrara Sub-basin (eg Carr *et al* 2019) to the eastern margins of the highly prospective Beetaloo Sub-basin (eg Williams 2019). The survey also links into the recently acquired EFTF South Nicholson 2D Deep Crustal Reflection Seismic Survey (L210, South Nicholson seismic survey; Henson *et al* 2018, Carr *et al* 2019, 2020) and the Camooweal 2D seismic survey, completed by the Geological Survey of Queensland in 2019. The seismic data from the Barkly seismic survey, in conjunction with a comprehensive range of other new datasets acquired across the Barkly and South Nicholson regions through the EFTF program[4], will greatly improve regional resource evaluations and stimulate greenfield exploration across this part of northern Australia.

Seismic acquisition and interpretation

Acquisition commenced on the Queensland–Northern Territory border near the town of Camooweal and finished over the Beetaloo Sub-basin to the northwest (**Figure 1**). The survey comprised five lines with a total acquisition length of 812.6 km. The lines are 19GA-B1 (434.6 km), 19GA-B2 (45.9 km), 19GA-B3 (66.9 km), 19GA-B4 (225.8 km), and 19GA-B5 (39.4 km), as shown on **Figure 1**. Interpretation of the Barkly seismic survey reveals previously unknown Palaeoproterozoic to Mesoproterozoic basin successions, as well as Proterozoic half-graben rifts and basement heterogeneity beneath the Barkly Tablelands. Importantly, it provides a continuous seismic profile linking the highly prospective Beetaloo Sub-basin (well known for its unconventional hydrocarbon potential) in the northwest to the newly discovered Carrara Sub-basin in the southeast (**Figure 1**).

For the purpose of presenting the seismic data, a Pre-Stack Depth Migration composite line (the Barkly composite line) has been constructed, comprising lines 19GA-B1, B3, and B4 (or parts thereof; **Figures 1** and **2**). For a complete description and interpretation of the survey, see Southby *et al* (in prep). Due to limited geological control from either wells or outcrop geology, and the persistent cover of Cambrian Georgina Basin sediments (Kruse 2008), interpretation is restricted to major stratigraphic sub-divisions, applying both lithostratigraphic packages (Rawlings *et al* 1999) and superbasin nomenclature (eg Jackson *et al* 1999, 2000). The interpretation is tied to the results of the South Nicholson seismic survey (Carr *et al* 2019, 2020) in the Carrara Sub-basin, and to existing geological interpretations from the well-studied Beetaloo Sub-basin (Williams 2019).

Based on our interpretation, we have subdivided the Barkly composite line into three informal geological domains, each defined by dominant structural elements and/or basin characteristics. These informal domains are, from southeast to northwest (**Figures 1** and **2**):

- Carrara domain
- Brunette Downs rift corridor
- Beetaloo-McArthur domain.

Carrara domain

The *Carrara domain* extends from the Queensland–Northern Territory border to the northwest along seismic line 19GA-B1 (**Figure 1**). This domain includes the southwestern margins of the Carrara Sub-basin and a shoulder of shallow metamorphic basement where overlying Proterozoic sediments of the Carrara Sub-basin are absent (**Figure 2**). The Carrara Sub-basin is up to 10 000 m deep (Carr *et al* 2019, 2020) and is interpreted to comprise, from oldest to youngest, the Palaeoproterozoic Leichhardt (ca 1790–1750 Ma), Calvert (ca 1735–1690 Ma) and Isa (ca 1670–1575 Ma) superbasins, and the Mesoproterozoic Roper Superbasin (ca 1500–1400 Ma), following the nomenclature of Jackson *et al* (2000), Southgate *et al* (2000), and Abbott and Sweet (2000). These sequences overlie seismic basement characterised by diffuse, structureless, or otherwise amorphous, low amplitude seismic reflectors, which is interpreted as a composite metamorphic basement complex, possibly low-grade metamorphic and ca 1850 Ma felsic intrusive, equivalent to that of the Murphy and/or Warramunga provinces (eg Donnellan 2013, Ahmad *et al* 2013).

The Leichhardt Superbasin, characterised by medium amplitude discontinuous reflectors, reaches a thickness

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of 4000 m at around Common Depth Point (CDP) 9400 (**Figure 2**), then thins and onlaps shallowing basement at the sub-basin margin to the west at about CDP 18 000 (**Figure 2**). The Calvert Superbasin is interpreted as having a comparatively uniform thickness through the deepest parts of the Carrara Sub-basin; to the west, it thins and onlaps the basement flank (at around CDP 14 000), as well as thinning towards the east. The interpreted seismic character of the Calvert Superbasin is typically well-defined, sub-parallel, moderate to high amplitude reflectors in the east, typical of shallow marine sandstone packages. This is consistent with the reported character of Calvert Superbasin sedimentary rocks (eg Southgate *et al* 2000). The seismic character of this package changes to discontinuous and low amplitude reflectors in the western side of the sub-basin.

The overlying Isa Superbasin represents the thickest sedimentary package within the Carrara Sub-basin on the composite line, reaching up to 7400 m thick (at around CDP 8600, **Figure 2**). This represents a minimum thickness as there has been structural thickening due to gentle warping of all sequences and pre-Georgina erosion (cf CDP 7000–10 500, **Figure 2**). A basement-penetrating fault zone in the centre of the Carrara Sub-basin (at CDP 9000, **Figure 2**) disrupts the sedimentary successions with vertical displacements of up to 1500 m at the base of the

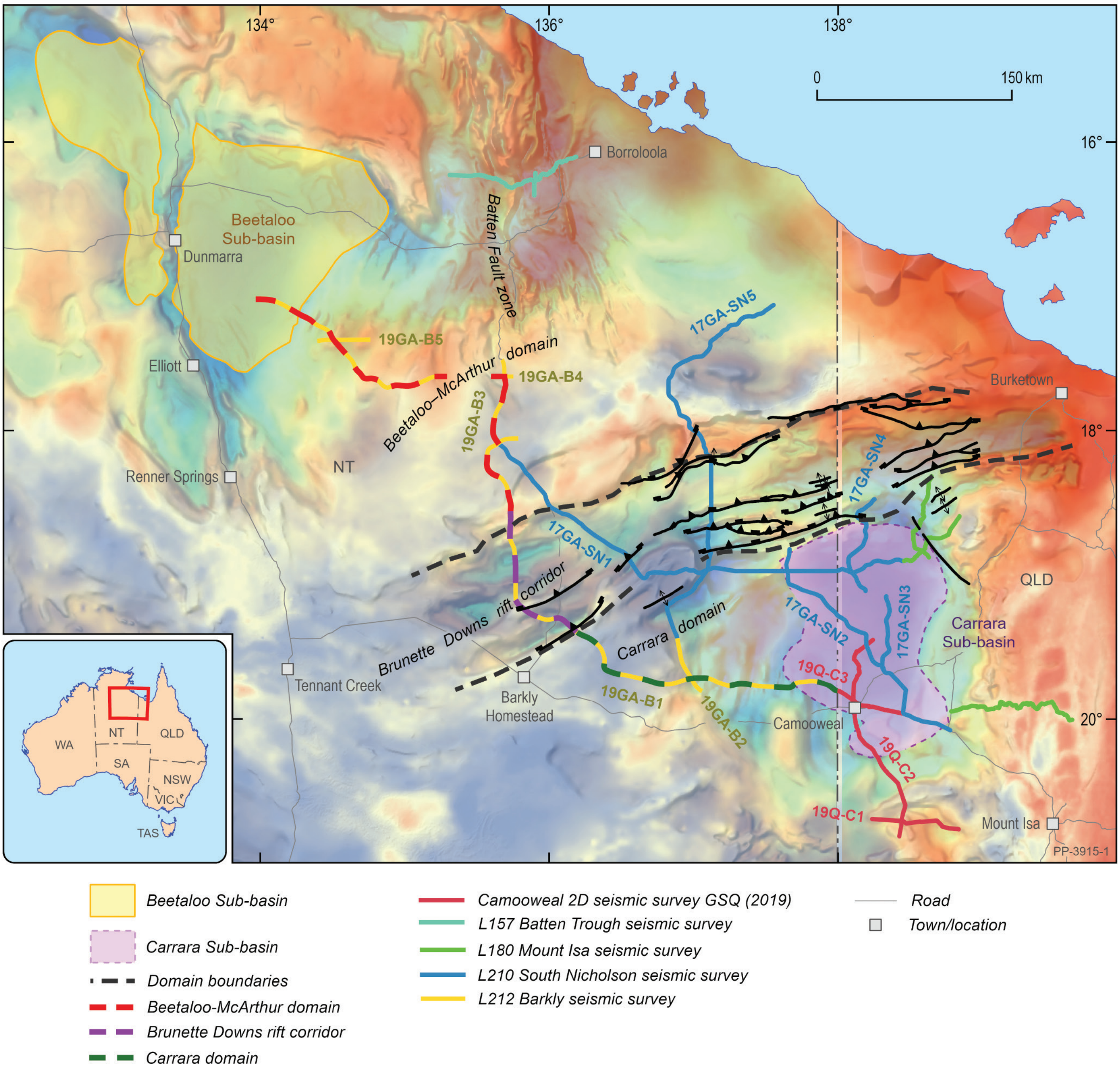

Figure 1. Location map of northeastern Northern Territory and the Mount Isa region of northwestern Queensland, showing the location of the Barkly seismic survey (L212). The coloured dashed segments of the Barkly seismic survey lines indicate that component of the seismic line residing within one of the three informal domains as described in the text. The South Nicholson seismic survey (L210), acquired in 2017, also shown for reference. Note, in particular, the Brunette Downs rift corridor, which extends from the eastern Tennant Creek region to the Lawn Hill Platform in western Queensland (only major faults indicated; see text for further detail). Background is a Bouguer gravity anomaly image (National Gravity Compilation 2019) overlain by a partly transparent layer of the Northern Territory SEEBASE® (Northern Territory Geological Survey and Geognostics Australia Pty Ltd 2021) and National SEEBASE (Geognostics Australia Pty Ltd 2020) images.

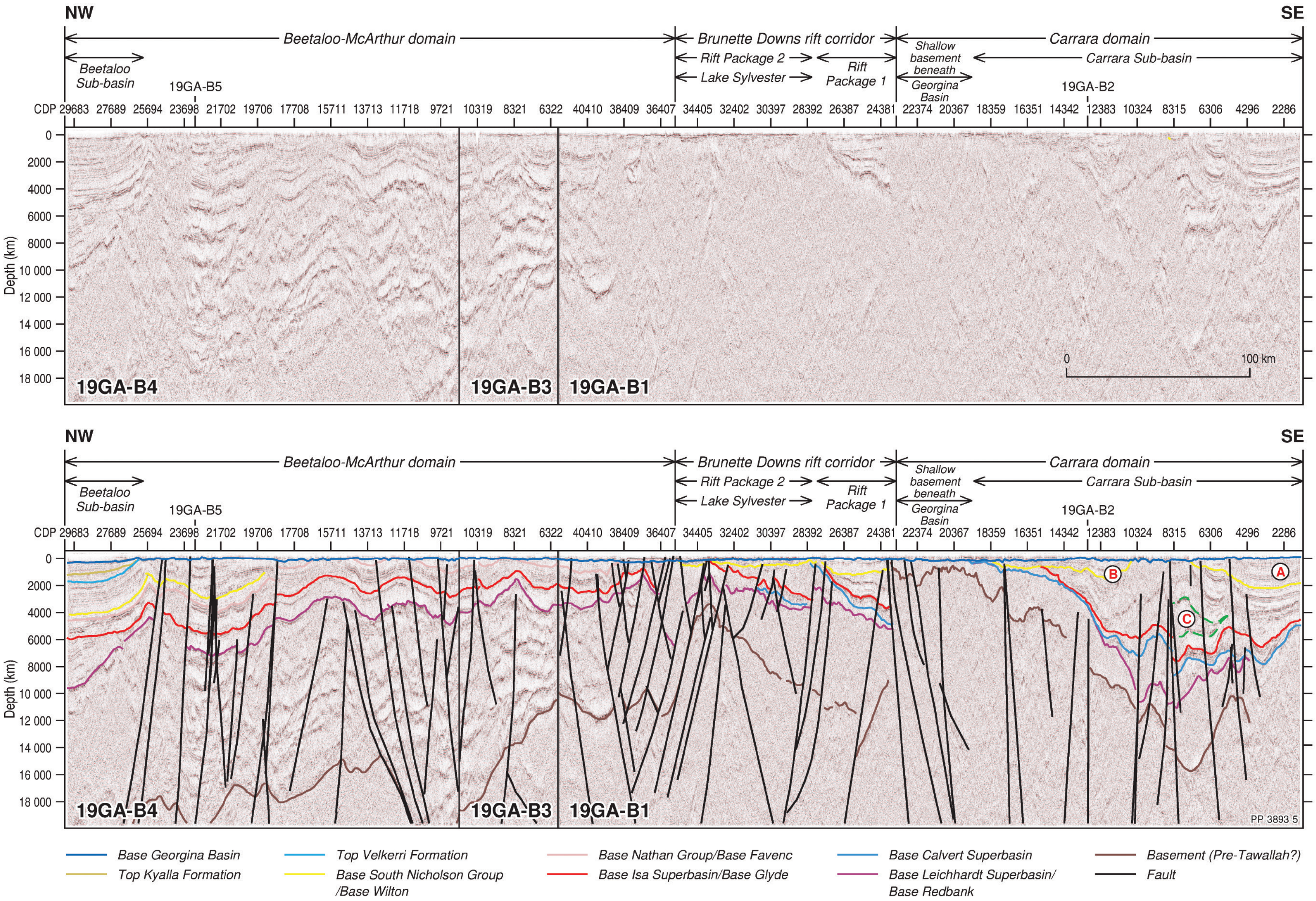

Figure 2. Pre-Stack Depth Migration composite seismic profile of the Barkly seismic survey incorporating lines 19GA-B1, -B3 and -B4, extending from the recently discovered Carrara Sub-basin in the east (right hand side of profile) to the southeastern margins of the Beetaloo Sub-basin (left hand side). Top figure shows the uninterpreted seismic profile; lower figure shows the geological interpretation as discussed in text. The three informal domains and other features, such as the unusual seismic 'basement' under the Beetaloo-McArthur domain and the locations labelled 'A', 'B' and 'C', are discussed in the text. Vertical exaggeration ~12×.

Isa Superbasin. On the eastern side of this fault zone, there is evidence of west-directed stratal thickening into this fault (labelled 'C', **Figure 2**), suggesting crustal extension during Isa Superbasin deposition, probably during the 'River' extension event at ca 1640 Ma (Carr *et al* 2019), an event first reported on the Lawn Hill Platform to the northwest (Southgate *et al* 2000, Bradshaw *et al* 2000, 2018, Palu *et al* 2020). The western margin of the Isa Superbasin thins and onlaps the underlying Calvert Superbasin sequences as the basement shallows, and is truncated and overlain in an apparent erosional unconformity by the Mesoproterozoic South Nicholson Basin (Roper Superbasin equivalent) at around CDP 16 000 (**Figure 2**).

The South Nicholson Group appears to have been deposited in a flexural subsidence or 'sag' type geometry ('A' and 'B', **Figure 2**), similar to that described in Carr *et al* (2019). It is absent due to erosion from CDP 7900 to 11 000 (**Figure 2**) where the Isa Superbasin directly underlies the Cambrian Georgina Basin.

Brunette Downs rift corridor

The *Brunette Downs rift corridor* (**Figures 1** and **2**) is separated from the *Carrara domain* to the east by a steeply dipping, basement-penetrating fault (CDP 24 300, **Figure 2**), and to the west by a complex fault zone (CDP 36 200, **Figure 2**) that, in turn, marks the southeastern limit of the *Beetaloo–McArthur domain*. The *Brunette Downs rift corridor* is characterised by two southeasterly deepening half-grabens controlled by steeply dipping, extensional half-graben bounding faults and a number of sub-parallel subsidiary faults. We have divided the rift corridor into two rift packages (**Figure 2**).

Rift package 1 (CDP 24 300–28 200) and rift package 2 (CDP 28 200–36 400) are both interpreted to contain all four superbasin sequences: the Palaeoproterozoic Leichhardt, Calvert and Isa superbasins, and the Mesoproterozoic Roper Superbasin. In both rift packages, Leichhardt Superbasin unconformably overlies undifferentiated, seismically featureless basement. In both rift packages, the Leichhardt Superbasin shows stratal thickening to the northwest away from the half-graben bounding fault, whereas the Calvert Superbasin and, in particular, the Isa Superbasin, show marked southeast-directed stratal thickening into the half-graben bounding fault. This suggests at least two major episodes of syn-depositional growth faulting: a) during initial opening of the Calvert Superbasin at ca 1725 Ma; and b) during the ca 1640 Ma River extensional event within the Isa Superbasin. Both episodes are consistent with rifting events reported elsewhere in the region (eg Bradshaw *et al* 2000, 2018, Carson *et al* 2020).

The Mesoproterozoic South Nicholson Group (Roper Superbasin equivalent) unconformably overlies the Palaeoproterozoic superbasins across both rift packages (**Figure 2**). In rift package 1, the South Nicholson Group overlies the Isa Superbasin with a sag-style geometry, whereas in rift package 2, the South Nicholson Group is thinner, relatively flat-lying and deposited on a low angle unconformity with the underlying Isa Superbasin successions.

The two main half-graben bounding faults described here coincide with linear, northeast-trending, high gravity anomalies that are clearly visible in gravity data (see **Figure 1**); these basement trends are consistent with other datasets, including 2D tomography and airborne electromagnetic data (Rollet *et al* 2021). Furthermore, these half-grabens occur along strike from a half-graben structure identified in seismic line 17GA-SN1 (**Figure 1**; Carr *et al* 2019) and three well-defined, north-dipping half-graben structures described in seismic line 17GA-SN5 in the South Nicholson region on MOUNT DRUMMOND (Carr *et al* 2019, Carson *et al* 2020). These half-grabens also align with east-west trending extensional fault systems described on the Lawn Hill Platform in Queensland (eg Scott *et al* 1998, Bradshaw *et al* 2000, 2018, Rollet *et al* 2021). We conclude that the concealed half-grabens identified in this study represent a western continuation of an extensional structural 'corridor' ranging over 400 km from the Lawn Hill Platform in the east (**Figure 1**). The regional tectonic implications of this discovery remain to be established.

Beetaloo-McArthur domain

The *Beetaloo-McArthur domain* (**Figures 1** and **2**) extends northwest from the northern limit of the *Brunette Downs rift corridor* to the southeast margin of the well-characterised Beetaloo Sub-basin (eg Ahmad *et al* 2013, Williams 2019*). The Beetaloo-McArthur domain* is separated from the *Brunette Downs rift corridor* by a fault-bounded horst of Proterozoic basement rocks with featureless seismic character (36 200–36 450 CDP, **Figure 2**), and which is overlain by a thin, faulted veneer of Georgina Basin. This basement horst likely represents Murphy Province basement as the horst coincides with a southwest-trending, linear, elevated gravity response reflecting a concealed south-western extension of known Murphy Province (**Figure 1**).

For the *Beetaloo-McArthur domain*, we use the lithostratigraphic package nomenclature of Rawlings (1999), as commonly applied in the Beetaloo Sub-basin and McArthur Basin. The *Beetaloo-McArthur domain* contains near continuous, gradually westward deepening sequences (from 3000–6000 m depth) of Palaeoproterozoic Redbank, Glyde, and Favenc packages (**Figure 2**). The Mesoproterozoic Wilton Package is largely absent across much of the *Beetaloo-McArthur domain* but is present west of a major, steeply dipping, normal fault at CDP 18 000 (Line 19GA-B4, **Figure 2**). The formal eastern basin margin of the Beetaloo Sub-basin, defined by the 400 m depth contour of the top of the Kyalla Formation (Roper Group; Williams 2019), occurs at around CDP 26 000 (**Figure 2**); all Proterozoic successions deepen markedly to the west into the Beetaloo Sub-basin to a depth of around 10 000 m at the end of the Barkly composite line. At CDP 24 800 (**Figure 2**), Palaeoproterozoic and Mesoproterozoic successions on the western hanging wall side of steeply west-dipping, basement-penetrating reverse faults show fault-propagated roll-over anticlines, which suggests that the eastern margin of the Beetaloo Sub-basin is structurally disrupted by post-Mesoproterozoic basin inversion. Incidentally, we also note that some of the post-Mesoproterozoic faults within the *Beetaloo-McArthur* *domain,* the *Brunette Downs rift corridor* and elsewhere, clearly offset the overlying Cambrian Georgina Basin. This suggests that basin inversion, in part, may be attributed to the Phanerozoic Alice Springs Orogeny.

The Redbank Package of the *Beetaloo-McArthur domain* directly overlies an unusual and distinctive seismic package, characterised by anastomosing, arcuate and overlapping, moderate amplitude reflectors, reaching as much as 20 000 m depth (**Figure 2**). This distinctive acoustic package is also observed at the northern end of seismic line GA17-SN5 from the EFTF South Nicholson seismic survey, where it is tentatively interpreted as a '*pre-Tawallah*' package (Carr *et al* 2019). It is also reported in a legacy seismic dataset across the Batten Fault Zone of the southern McArthur Basin (**Figure 1**; Rawlings *et al* 2004). In both cases, this unusual seismic package overlies presumably crystalline basement. This distinctive package is only observed north of the rift structures identified on the Barkly and the South Nicholson seismic surveys; it is not observed south of these features.

Implications for resource prospectivity

A key finding from the Barkly Seismic survey has been the identification of a concealed, near-continuous sequence of Palaeoproterozoic to Mesoproterozoic successions extending from the newly discovered Carrara Sub-basin of the South Nicholson region (Carr *et al* 2019) to the highly prospective Beetaloo Sub-basin of the McArthur Basin. While the Carrara Sub-basin is, as yet, unevaluated for energy and mineral potential, the similarities in basin architecture and sedimentary successions with the Beetaloo Sub-basin are compelling, suggesting that the Carrara Sub-basin may be similarly prospective. The identification of extensive Palaeoproterozoic successions between the Carrara and Beetaloo sub-basins improves the regional potential for sediment-hosted base metal mineralisation. Although unavailable at the time of writing, the highly anticipated outcomes of the MinEx CRC deep stratigraphic drillhole Carrara-1 on the western margin of the Carrara Sub-basin will better constrain our stratigraphic interpretation and conclusions. The release of the EFTF Barkly Seismic dataset and accompanying report will contribute towards expanding exploration interest across this frontier region, building on the success of the EFTF South Nicholson seismic survey.

Acknowledgements

The Barkly seismic survey is a product of the Australian Government *Exploring for the Future* initiative (phase one 2016–2020), conducted in collaboration with, and co-funded by, the Northern Territory Geological Survey under its *Resourcing the Territory* initiative. We would like to extend our thanks all the land owners and custodians who facilitated on-ground access. We also wish to thank Darwun Chau, Chris Evenden, and Bianca Reese for drafting the figures. Andrew McPherson and Tehani Palu (both Geoscience Australia) provided positive and constructive reviews. Geoscience Australia authors publish with the permission of the CEO, Geoscience Australia (eCat 145107).

References

Abbott ST and Sweet IP, 2000. Tectonic control on third-order sequences in a siliciclastic ramp-style basin: An example from the Roper Superbasin (Mesoproterozoic), northern Australia. *Australian Journal of Earth Sciences* 47(3), 637–657.

Ahmad M, Dunster J and Munson TJ, 2013. Chapter 15 - McArthur Basin: in Ahmad M and Munson TJ (compilers). '*Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publication* 5.

Ahmad M, Munson TJ and Wygralak AS, 2013. Chapter 8 - Murphy Province: in Ahmad M and Munson TJ (compliers), *'Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey Special Publication* 5.

Bradshaw BE, Lindsay JF, Krassay AA and Wells AT, 2000. Attenuated basin-margin sequence stratigraphy of the Paleoproterozoic Calvert and Isa Superbasins: the Fickling Group, southern Murphy Inlier, Queensland. *Australian Journal of Earth Sciences* 47, 599–623.

Bradshaw BE, Orr ML, Bailey AHE, Palu TJ and Hall LS, 2018. Northern Lawn Hill Platform depth structure and isochore mapping update. *Geoscience Australia, Record* 2018/047.

Carr LK, Southby C, Henson P, Costello R, Anderson JR, Jarrett AJM, Carson CJ, MacFarlane SK, Gorton J, Hutton L, Troup A, Williams B, Khider K, Bailey AHE and Fomin T, 2019. Exploring for the Future: South Nicholson Basin geological summary and seismic data interpretation. *Geoscience Australia, Record* 2019/21.

Carson CJ, Henson PA, Doublier MP, Williams B, Simmons J, Hutton L and Close D, 2020a. Structural evolution of the South Nicholson region: insight from the 2017 L210 reflection seismic survey: in Czarnota K, Roach I, Abbott S, Haynes M, Kositcin N, Ray A and Slatter E (editors). *'Exploring for the Future: Extended Abstracts'*. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/133051.

Carson CJ, Kositcin N, Anderson JR, Cross A and Henson PA, 2020b. New U–Pb geochronology for the South Nicholson region and implications for stratigraphic correlations: in Czarnota K, Roach I, Abbott S, Haynes M, Kositcin N, Ray A and Slatter E (editors). '*Exploring for the Future: Extended Abstracts'*. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/132876.

Donnellan N, 2013. Chapter 9 - Warramunga Province: in Ahmad M and Munson TJ (compilers). *'Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publication* 5.

Geognostics Australia Pty Ltd, 2020. *OZ SEEBASE® 2020 (Version 1, May 2020).* Geognostics Australia Pty Ltd. https://www.geognostics.com/oz-seebase-2020.

Geophysical Acquisition & Processing Section, 2020. *National Gravity Compilation 2019 (CSCBA 1VD grid).* Geoscience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/144790.

Henson PA, Carr LK, Fomin T, Gerner E, Costelloe R, Southby C, Anderson JA, Bailey AHE, Lewis C, Champion D, Huston D, the Northern Territory Geological Survey and the Queensland Geological Survey, 2018. Exploring for the Future - Discovering the South Nicholson Basin region with new seismic data: in *'Annual Geoscience Exploration Seminar (AGES) Proceedings', Alice Springs, Northern Territory, 20–21 March 2018'*. Northern Territory Geological Survey, Darwin, 52–54.

Jackson MJ, Scott DL and Rawlings DJ, 2000. Stratigraphic framework for the Leichhardt and Calvert Superbasins: review and correlations of the pre-1700 Ma successions between Mt Isa and McArthur River. *Australian Journal of Earth Sciences* 47, 381–403.

Kruse PD, 2008. Georgina Basin stratigraphic drilling 2002–2006 and petrography 2000–2007. *Northern Territory Geological Survey, Record* 2008-001.

Northern Territory Geological Survey and Geognostics Australia Pty Ltd, 2021. Northern Territory SEEBASE® and GIS. *Northern Territory Geological Survey, Digital Information Package* DIP 030.

Palu TJ, Jarrett AJM, Orr ML, Bradshaw BE, Hall LS, Boreham CJ and MacFarlane SK, 2020. Burial and thermal history analysis of the northern Lawn Hill Platform, Isa Superbasin, Part A. *Geoscience Australia, Record* 2020/38, Canberra.

Rawlings DJ, 1999. Stratigraphic resolution of a multiphase intracratonic basin system: The McArthur Basin, northern Australia. *Australian Journal of Earth Sciences* 46(5), 703–723.

Rawlings DJ, Korsch RJ, Goleby BR, Gibson GM, Johnstone DW and Barlow M, 2004. The 2002 Southern McArthur Basin Seismic Reflection Survey. *Geoscience Australia, Record* 2004/017, Canberra.

Rollet N, Doublier M, Southby C, Carson CJ, Costelloe R, Fomin T, Ley Cooper Y, Carr LK, Bonnardot M-A, Wilford J, Wong S, Nicoll M and Czarnota K, 2021. 3D model of the South-Nicholson Basin region, Northern Australia, for mineral, energy and groundwater assessment. *Australasian Exploration Geoscience Conference 2021, Extended Abstracts*.

Scott DL, Bradshaw BE and Tarlowski CZ, 1998. The tectonostratigraphic history of the Proterozoic Northern Lawn Hill Platform, Australia: an integrated intracontinental basin analysis. *Tectonophysics* 300, 329–58.

Southby C, Rollet N, Carson CJ, Fomin T, Henson PA, Carr LK and Doublier MP, in prep. Exploring for the Future - The 2019 Barkly Reflection Seismic Survey (L212). *Geoscience Australia, Record*.

Southgate PN, Bradshaw BE, Domagala J, Jackson MJ, Idnurm M, Krassay AA, Page RS, Sami TT, Scott DL, Lindsay JF, McConachie BA and Tarlowski C, 2000. Chronostratigraphic basin framework for Paleoproterozoic rocks (1730–1575 Ma) in northern Australia and implications for mineralisation. *Australian Journal of Earth Sciences* 47, 461–485.

Williams B, 2019. Definition of the Beetaloo Sub-basin. *Northern Territory Geological Survey, Record* 2019-015.