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Increasing the prospectivity of northern Australia; impacts from the recent Exploring for the Future seismic acquisition and regional geology studies in the South Nicholson Region, Northern Territory.

L.K. Carr
Geoscience Australia
lidena.carr@ga.gov.au

C. Southby
Geoscience Australia
chris.southby@ga.gov.au

C. Carson
Geoscience Australia
chris.carson@ga.gov.au

E. Grosjean
Geoscience Australia
emmaanuelle.grosjean@ga.gov.au

A. Bailey
Geoscience Australia
adam.bailey@ga.gov.au

J. Anderson
Geoscience Australia
jade.anderson@ga.gov.au

P. Henson
Geoscience Australia
paul.henson@ga.gov.au

SUMMARY

Exploring for the Future (EFTF) is a multiyear (2016–2024) initiative of the Australian Government, conducted by Geoscience Australia. This program aims to improve Australia's desirability for industry investment in resource exploration of frontier regions across Australia. This paper will focus on the science impacts from the EFTF program in northern Australia derived from the acquisition and interpretation of seismic surveys, the drilling of the NDI Carrara 1 and also complimentary scientific analysis and interpretation to determine the resource potential of the region. This work was undertaken in collaboration with the Northern Territory Geological Survey, the Queensland Geological Survey, AuScope and the MinEx CRC. These new data link the highly prospective resource rich areas of the McArthur Basin and Mt Isa Province via a continuous seismic traverse across central northern Australia. The Exploring for the Future program aims to further de-risk exploration within greenfield regions and position northern Australia for future exploration investment.

Key words: Northern Australian Basin, seismic surveys, South Nicholson Region, Barkly, NDI Carrara 1. Carrara Sub-basin.

INTRODUCTION

Exploring for the Future (EFTF) is a multiyear initiative of the Australian Government, conducted by Geoscience Australia aiming to accelerate investment in resource exploration across Australia. This paper will focus on the scientific impacts delivered by the acquisition of seismic surveys, the drilling of the NDI Carrara 1 drill hole and the complementary analyses of physical samples. This work has been undertaken in collaboration with the Northern Territory Geological Survey, the Queensland Geological Survey, AuScope and the MinEx CRC. The work across northern Australia has incorporated a multidisciplinary approach with the aim of providing new fundamental geological data to evaluate the energy mineral and groundwater resource potential of the region.

The L210 South Nicholson 2D Deep Crustal Seismic Survey undertaken in 2017 consists of five linked seismic lines (17GA-SN1 to SN5) totalling ~1100 line-km (Figure 1). This survey links directly to legacy Geoscience Australia seismic lines 06GA-M1 and 06GA-M2. To complement this data across the underexplored and mostly undercover South Nicholson and Barkly regions, a second seismic survey (L212) was acquired in 2019. The L212 Barkly 2D Deep Crustal Reflection Seismic Survey comprises five intersecting lines (19GA-B1 to B5), totalling ~813 line-km, extending from the Northern Territory–Queensland border in the southeast, near Camooweal, to the highly prospective Beetaloo Sub-basin in the northwest. The seismic program was complemented by regional geological studies, including the collection and analysis of geological, geochemical and geochronology data, all of which led to the drilling of NDI Carrara 1 (Figure 1).

GEOLOGICAL BACKGROUND

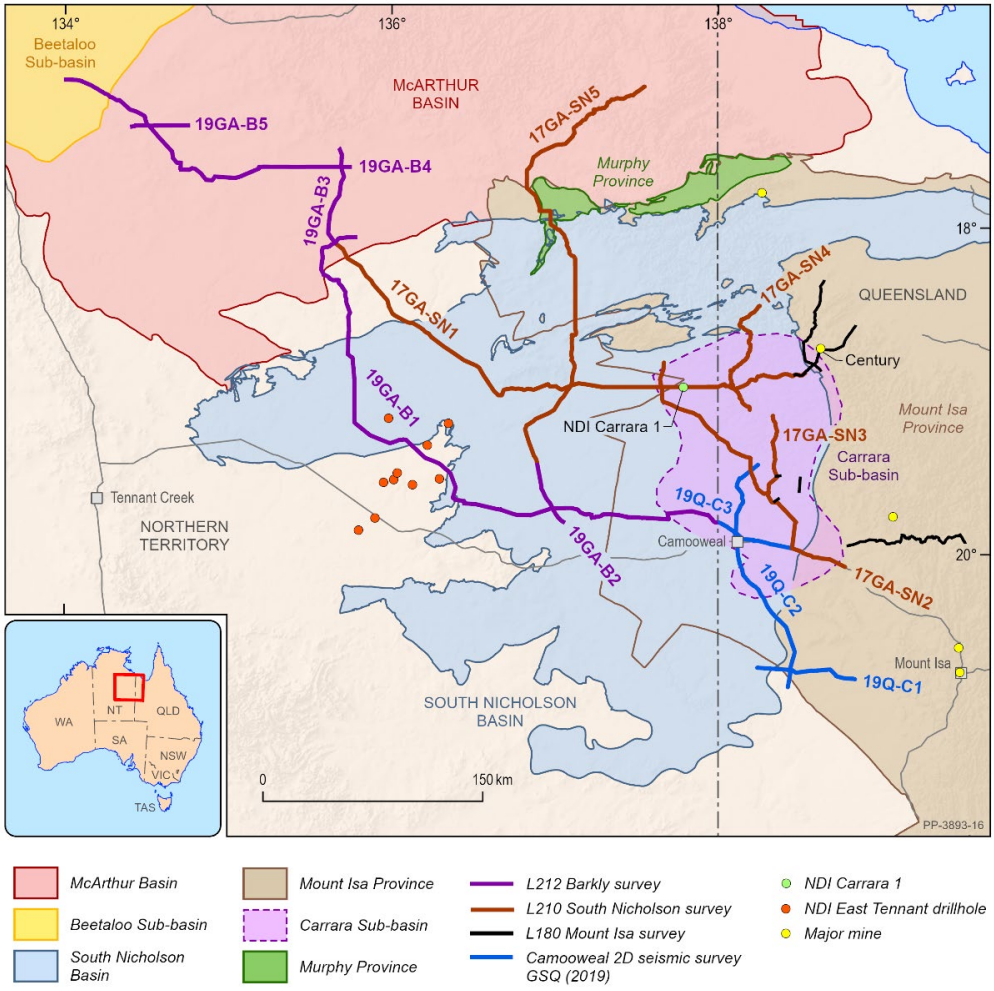

Figure 1 Map of the study area showing the geological regions and the location of seismic lines and drill hole NDI Carrara 1.

Three major geological regions in central northern Australia are included in the area of study; the Mount Isa Province, South Nicholson Basin, and McArthur Basin (Figure 1). These regions are described by various authors using lithostratigraphic, sequence stratigraphic, and petroleum supersystem approaches (summarised in Carr et al. (2019).

The Paleoproterozoic–Mesoproterozoic Mount Isa Province is a complex terrane in western Queensland (Withnall and Hutton, 2013) and the eastern Northern Territory, characterised primarily from surface mapping (e.g. Blake, 1987). Historically, the Mount Isa Province has been of interest due to its world-class base and precious metal mineralisation; and consists of sedimentary, volcanic and plutonic rocks that have undergone multiple phases of deformation and varying extents of metamorphism (e.g. Withnall and Hutton, 2013). Deposition in the Mount Isa Province is preserved within the stacked Leichhardt, Calvert and Isa superbasins (e.g. Jackson et al., 2000 and summarised in Carr et al., 2019). These Paleoproterozoic metasedimentary and metavolcanic units formed between *ca* 1790 and 1590 Ma (e.g. Betts et al., 2006; Withnall and Hutton, 2013).

The Paleoproterozoic–Mesoproterozoic McArthur Basin is a sedimentary basin with an area over approximately 180 000 km^2 in the northeastern Northern Territory (e.g. Plumb et al., 1980) and western Queensland. Stratigraphic correlations between the McArthur Basin and both the Birrindudu Basin and the Tomkinson Province in western and central Northern Territory, respectively, have been proposed previously (e.g. Plumb and Wellman, 1987) and are supported by recent seismic, drilling and geochronology data (e.g. Dunster et al., 2000; Carson, 2013; Carr et al., 2016). The McArthur Basin predominantly consists of relatively undeformed, terrigenous siliciclastic and carbonate rocks. The sedimentary successions in the basin are up to 10–12 km thick and include minor intercalated mafic and felsic volcanics and shallow intrusives (e.g. Munson, 2014). The McArthur Basin unconformably overlies the Paleoproterozoic Pine Creek Province to the west, the Murphy Province to the south, and the Arnhem Province to the northeast (Carr et al., 2016). In the southeast, the basin succession extends into the Mount Isa Province in Queensland (Carr et al., 2016). The

McArthur Basin is unconformably overlain by the Neoproterozoic to Devonian Georgina Basin, as well as the Mesozoic Carpentaria Basin in the southwest and the Arafura Basin in the north.

The South Nicholson Basin, defined by Smith and Roberts (1963), straddles the border of the Northern Territory and Queensland (e.g. Sweet et al., 1981, Carr et al., 2016). It covers an area of 91 000 km^2 (Raymond et al., 2018) and is bounded in the north by the Paleoproterozoic Murphy Province (Jackson et al., 1999). In the east it unconformably overlies the Mesoproterozoic–Paleoproterozoic Lawn Hill Platform of the Mount Isa Province and is overlain by the Georgina Basin (e.g. Rawlings et al., 2008). It is the intent of this study to explore the links between the well-defined Paleoproterozoic–Mesoproterozoic Mount Isa Province and McArthur Basin, with the less well known South Nicholson Basin. A more in-depth summary of the geology of these regions is available in Carr et al. (2019).

DATA ACQUISITION AND RESULTS

South Nicholson seismic survey (L210)

The acquisition of the L210 South Nicholson 2D Deep Crustal Seismic Survey in the region between the southern McArthur Basin and the Mt Isa western succession, crossing the South Nicholson Basin and Murphy Province, was completed in August 2017 with the aim of understanding the relationship between these two highly prospective areas (Figure 1). Prior to this survey the region contained no seismic data, minimal well data and the subsurface geology was mostly unknown (Carr et al, 2016; Carr et. al, 2019). This new dataset was made publically available in Alice Springs at the 2018 Annual Geoscience Exploration Seminar (Henson et al., 2018).

The South Nicholson seismic survey included five seismic lines in an orientation to best image geological features identified in outcrop and as subsurface geophysical anomalies on gravity and magnetics data (Figure 1). The acquisition was designed to explore both exposed and undercover sedimentary basins to better understand the region's crustal architecture and the location and scale of potential resources. The seismic study was undertaken in tandem with surface geochemistry (Bastrakov et al., 2018) and petroleum and mineral systems geochemistry (Jarrett et al., 2018a; 2018b).

This acquisition revealed a previously unknown sedimentary basin that straddles the Northern Territory and Queensland boarder, northwest of Mount Isa (Figure 1). This newly discovered basin, now termed the Carrara Sub-basin, is ~120 km E-W by ~190 km N-S, with a maximum depth of ~8 km. The interpretation by Carr et al. (2019) suggests that the Carrara Sub-basin contains a thick undeformed late Paleoproterozoic (equivalent to the McNamara Group or Isa Superbasin) sedimentary succession overlain by a relatively thin succession of the South Nicholson Group.

Geochronology and stratigraphic correlations for the South Nicholson Region

To complement the South Nicholson seismic survey and build on the new geological understanding delivered by the seismic data, a comprehensive U–Pb SHRIMP zircon and xenotime geochronology program was undertaken. This helped to better understand the basin evolution and stratigraphy of the South Nicholson Region and its relationship to the adjacent and overtly prospective Mount Isa Province and McArthur Basin (Carson et al., 2020).

The Paleoproterozoic to Mesoproterozoic rocks of the South Nicholson Basin and western Mount Isa Province may correlate temporally to the same aged sediments of the McArthur Basin to the northwest, and the Mount Isa Province farther east. These later regions are better understood and host base-metal mineralisation and rocks with hydrocarbon prospectivity, making them of particular interest for this study. In comparison, the basin evolution and stratigraphy of the South Nicholson Region remains poorly understood, largely due to the undercover nature of many of the rocks and paucity of existing data. The South Nicholson Group has been correlated with the Roper Group of the McArthur Basin (Plumb et al., 1980), with the timing of deposition of the South Nicholson Group inferred to be *ca* 1500–1320 Ma based on the age of the Roper Group (e.g. Jackson et al., 1999; Rawlings et al., 2008). However, prior to EFTF this correlation was speculative as published U–Pb age constraints from the South Nicholson Group only comprise detrital zircon dates older than *ca* 1569 Ma (e.g. Jackson et al., 1999; Carson et al., 2011). A substantial amount of age data exists for the older Paleoproterozoic basin units (e.g. McNamara Group) of the Mount Isa Province in Queensland, however, the stratigraphic relationships of these units going west into the Northern Territory have been uncertain. In an attempt to resolve these stratigraphic uncertainties new geochronology has been obtained in the South Nicholson Region (Figure 2).

Results from these U–Pb zircon and xenotime geochronological analyses confirm that the South Nicholson Group is temporally equivalent to the Roper Group of the McArthur Basin, with a depositional age bracket of *ca* 1480–1266 Ma. We hypothesise that an episode of fluid-flow through the South Nicholson Group occurred during the middle Mesoproterozoic, constrained by U–Pb xenotime data to *ca* 1266 Ma. The study also resulted in a revision of the Carrara Range Group, which now incorporates the Surprise Creek Formation and the Drummond Formation, representing a tectonostratigraphic package of *ca* 1725 Ma immature siliciclastic and bimodal volcanics. Some units in the Benmara region, previously assigned to the Mesoproterozoic South Nicholson Group, are reassigned into a revised and expanded late Paleoproterozoic Benmara Group, the mid- to upper units of which were deposited during crustal

extension at *ca* 1640 Ma (= 'River' event). An increased geographic extent of highly prospective, late Paleoproterozoic stratigraphy (the revised Benmara Group) is recognised, extending westward beneath the Georgina Basin for an unknown distance and enhancing the resource potential across the South Nicholson Region, particularly for MVT and SEDEX style base metal occurrences. Renaming of some stratigraphic units across the South Nicholson Region will be necessary based on the new geochronological data.

The new geochronological data and resulting conclusions (Carson et al., 2020) have improved regional stratigraphic correlations between Proterozoic basins, resulting in better understanding of commodity prospectivity, and enhances exploration targeting strategies across central northern Australia.

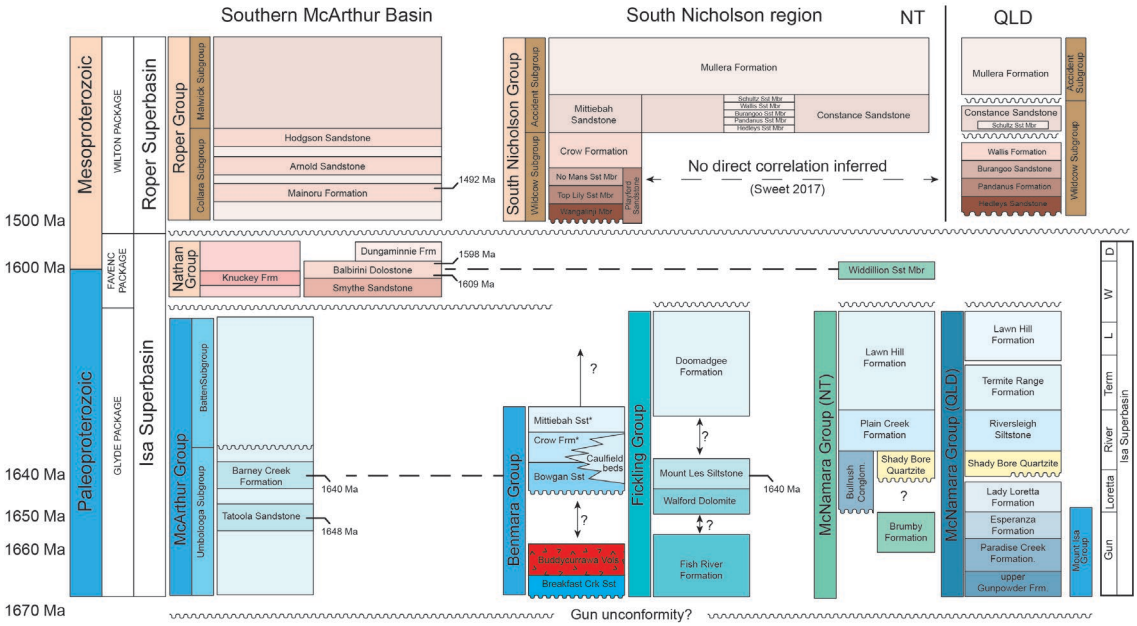

Figure 2 Revised stratigraphy for the South Nicholson Region (Carson et al., 2020)

Barkly seismic survey (L212)

To complement the South Nicholson seismic survey across the underexplored South Nicholson and Barkly regions the L212 Barkly 2D Deep Crustal Reflection Seismic Survey was undertaken. In 2019 acquisition commenced on the Northern Territory–Queensland 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). Interpretation of the Barkly seismic survey (Figure 3) reveals previously unknown Paleoproterozoic 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 (Southby et al., 2021 and 2022).

The interpretation of the Barkly seismic survey is tied to those of the South Nicholson seismic survey (Carr et al., 2019, 2020) in the Carrara Sub-basin, and to the well-studied Beetaloo Sub-basin (Williams, 2019). Further geological control on the interpretation is limited due to a persistent cover of Cambrian Georgina Basin sediments, limited outcrop geology and sparse well control. The imaged basin successions are subdivided into major stratigraphic intervals, applying both lithostratigraphic package (e.g. Rawlings et al., 1999) and superbasin nomenclature (e.g. Jackson et al 2000). Figure 3 presents a composite line, comprising lines 19GA-B1, -B3 and -B4. Based on the interpretation, the Barkly composite line is divided into three informal geological domains, each defined by dominant structural elements and/or basin characteristics (Southby et al., 2022). These informal domains are, from southeast to northwest (Figure 3): the Carrara domain, the Brunette Downs rift corridor and the Beetaloo-McArthur domain.

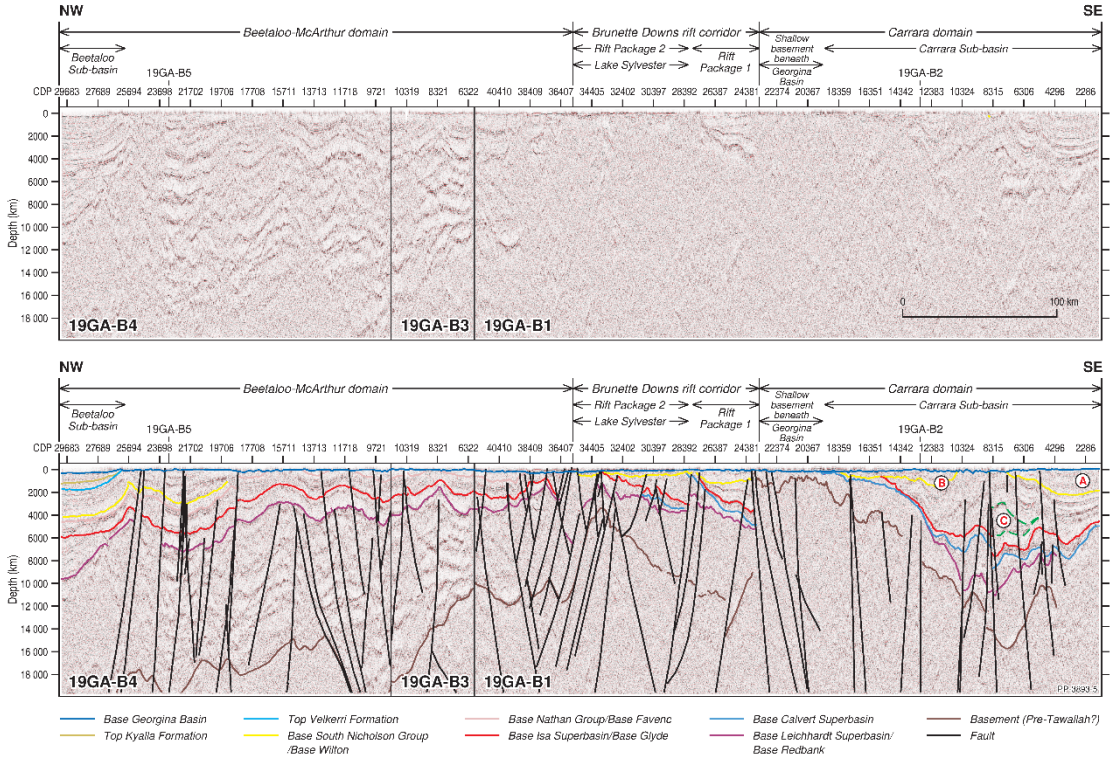

Figure 3. Pre-Stack Depth Migration composite seismic profile of the Barkly seismic survey, incorporating lines 19GA-B1, -B3 and -B4, extending from the recently discovered Carrara Sub-basin in the east (right hand side of profile) to the southeastern margins of the Beetaloo Sub-basin (left hand side). Top panel shows the uninterpreted seismic profile; lower panel 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 Southby et. al., 2022. Vertical exaggeration ~12×.

For a complete description, interpretation and discussion of the Barkly seismic survey refer to Southby et al. (2022). Key findings of the survey include:

- The identification of a shallow platform of metamorphic basement representing the western shore of the Carrara Sub-basin that is most likely Murphy Province or Warramunga Province, immediately below the Cambrian Georgina Basin. The presence of these basement rocks has been recently confirmed by the MinEx CRC East Tennant drilling program. Further the identification of a fault-bounded horst of Murphy Province, coinciding with a northeast trending ridge of a gravity high that, in turn, links with known surface outcrops of the Murphy Province to the northeast.
- The identification of a major structural domain of north-east trending Proterozoic half-graben. These half-graben form part of a rift corridor, characterised by half-graben with markedly similar geometry, extending from the Barkly Tablelands in the southwest to the South Nicholson Region to the east, and into western Queensland onto the Lawn Hill Platform in the northeast, a distance of over 400 km. We have informally termed this structural feature the Brunette Downs rift corridor. Crustal extension episodes recorded by the half-graben likely correlate with extensional events at *ca* 1725 Ma and *ca* 1640 Ma previously identified in the South Nicholson Region and the Lawn Hill Platform.
- The identification of a basement component with an unusual seismic character was also identified in the South Nicholson Deep Crustal Reflection Seismic Survey (L210) and only observed north of the rift corridor in both surveys. The coincidence of the Brunette Downs rift corridor with the southern limit of the unusual seismic basement suggests the rift corridor represents a major crustal boundary, suture or tectonic feature, the nature and significance of which remains to be determined.
- A near-continuous, concealed succession of Proterozoic sediments extending from the highly prospective Beetaloo Sub-basin to the, as yet unevaluated, Carrara Sub-basin greatly expands the known extent of Proterozoic rocks across the region, enhancing the regions potential for both hydrocarbon and base-metal occurrences.
- Structural evidence of Phanerozoic tectonism and reverse faulting (possibly associated with the *ca* 400-300 Ma Alice Springs Orogeny) affecting the Cambrian Georgina Basin, which is also identified in the South Nicholson Seismic Survey and historical mapping.

NDI Carrara 1 drill hole

NDI Carrara 1 is a deep stratigraphic drill hole completed in 2020 as part of the MinEx CRC National Drilling Initiative in collaboration with Geoscience Australia and the Northern Territory Geological Survey. The drilling of NDI Carrara 1 was built on the success of the seismic and regional geology programs in earlier stages of the EFTF program. It is the first stratigraphic test of the Carrara Sub-basin, a depocentre discovered in the South Nicholson Region based on interpretation from seismic surveys discussed above (Figure 1). The drill hole intersected ~1120 m of Proterozoic sedimentary rocks, unconformably overlain by 630 m of Georgina Basin carbonate rocks. Continuous cores were recovered from 284 m to total depth at 1750.85 m. A comprehensive analytical program designed to investigate the resource prospectivity of this newly discovered depocentre has been conducted on more than 400 NDI Carrara 1 physical samples.

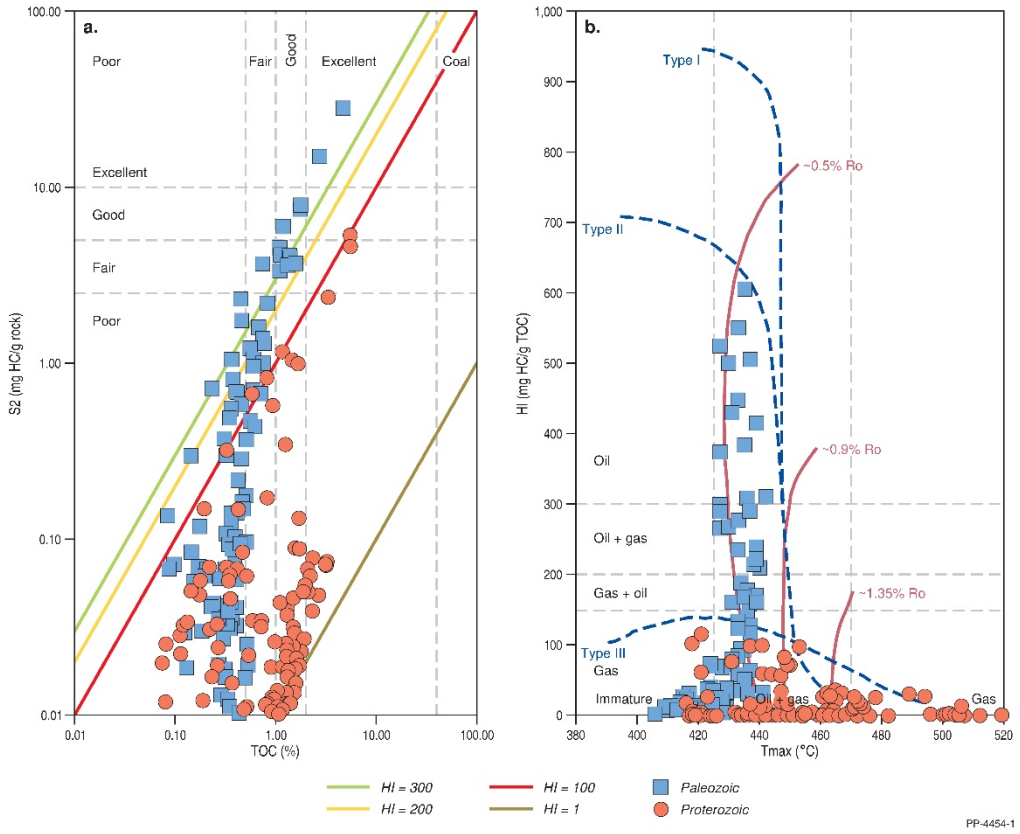

Figure 4 Organic geochemistry plots for NDI Carrara 1 rocks. (a) TOC versus S2 (logarithmic scale). (b) Tmax versus HI

Recent analyses of the NDI Carrara 1 rocks have constrained the age of the succession within the Carrara Sub-basin and better defined the stratigraphy at this location (text above and in Carson et al., 2022). SHRIMP zircon U–Pb geochronology has revealed that the stratigraphic interval between 1012 and 1653 m was deposited between *ca* 1590 and 1612 Ma and is coincident with felsic volcanism. Thus, this interval is stratigraphically equivalent to the middle to upper Lawn Hill Formation, host to the world-class Pb-Zn Century Mine in the Lawn Hill Platform in western Queensland, and to the upper McArthur and Nathan groups in the southern McArthur Basin (Carson et al., 2022). Analyses of a lithic tuff at 706 m resulted in a maximum depositional age of *ca* 1595 Ma; therefore, uncertainty remains regarding the age of the stratigraphic section between the unconformity at 630 m and 1012 m.

The hydrocarbon-generating potential of sedimentary rocks intersected by NDI Carrara 1 was evaluated based on screening by Rock-Eval pyrolysis. Based on total organic carbon (TOC) contents, several organic-rich sections are identified within both the Cambrian and the Proterozoic intervals. Oil-prone source rocks occur in the Georgina Basin section and two organic-rich intervals are present within Proterozoic black siltstones and shales (Figure 4). Three petroleum supersystems were initially defined within the Proterozoic (Bradshaw et al 1994): the Palaeoproterozoic McArthur Supersystem, the Mesoproterozoic Urapungan Supersystem (now renamed the Beetaloo Supersystem; Jarrett and Munson, 2022), and the Neoproterozoic Centralian Supersystem. Two more have recently been defined by Jarrett et al. (2022): the Palaeoproterozoic Redbank Supersystem and the Palaeo- to Mesoproterozoic Lawn Supersystem.

Hydrocarbon shows were observed at several depths in NDI Carrara 1. A thick and viscous black oil stain was identified in the Georgina Basin section at 528.33 m in carbonate rocks with vuggy porosity; and two dark oil patches were identified in grey micritic limestones of the Proterozoic section at 763.1 and 765.4 m. Additionally, there were notable levels of gas recorded by the Pason gas detector of up to 2%, or 2000 units associated with black Paleoproterozoic shales which consisted primarily of methane with trace ethane, propane, and butane. Carbon isotopic and biomarker data of the oil stain present at 528 m indicate that it is related to other oil stains of the Georgina Basin, representing evidence for an active Larapintine petroleum system in the Carrara Sub-basin. In contrast, the geochemistry of oil stains in the Proterozoic section of NDI Carrara 1 differs significantly from that of the Georgina Basin oil stain, pointing to a possible different petroleum system. These oil stains share many characteristics with other known Proterozoic source rocks and demonstrate the presence of a Proterozoic petroleum system in the Carrara Sub-basin. The gas shows detected in Paleoproterozoic shales between 1150 and 1500 m are likely sourced from the local, thermally mature Paleoproterozoic Lawn Hill Formation, and indicate a Lawn Petroleum Supersystem (Jarrett et al.,2022) is effective in the South Nicholson Region of the Northern Territory. For a full discussion of the results of the organic geochemical analyses of hydrocarbon shows and rocks collected from NDI Carrara 1 and their implications for the hydrocarbon prospectivity of the Carrara Sub-basin refer to Grosjean et al. (2022).

Summary of work in Northern Australia

Prior to Geoscience Australia's Exploring for the Future program the geological knowledge across northern Australia was limited and in places lacking in data. The EFTF program has conducted an array of data acquisition activities delivering a wealth of new geological data and interpretations including seismic surveys, regional geology, age dating and geochemical analysis.

The most significant results from this program include:

- discovery of the Carrara Sub-basin, coinciding with a gravity low in the southeastern South Nicholson Region and linking of prospective stratigraphy of the Isa Superbasin (Lawn Hill Formation and Riversleigh Siltstone from the Lawn Hill Platform) into the Carrara Sub-basin.
- extension of the Mount Isa Province further in to the Northern Territory from Queensland and expansion of the spatial extent of the South Nicholson Region to approximately two and a half times the size proposed originally.
- new stratigraphic geochronology confirming the South Nicholson Group is temporally equivalent to the Roper Group of the McArthur Basin, with a depositional bracket of *ca* 1480–1266 Ma. Identification of an episode of fluid-flow through the South Nicholson Group during the middle Mesoproterozoic, constrained by U–Pb xenotime data to *ca* 1266 Ma.
- revision of units previously assigned to the Mesoproterozoic South Nicholson Group into a revised and expanded late Paleoproterozoic Benmara Group. The revision, based on geochronological and structural data, represents an increased geographic extent of the highly prospective late Paleoproterozoic stratigraphy (the revised Benmara Group) extending it westward beneath the Georgina Basin for an unknown distance and enhancing the resource prospectivity across the South Nicholson Region, particularly for MVT and SEDEX style base metal occurrences.
- Barkly seismic survey revealing previously unknown Paleoproterozoic to Mesoproterozoic basin successions, as well as a Proterozoic half-graben rift corridor and basement heterogeneity beneath the Barkly Tablelands. Importantly, the new data provides a continuous seismic profile linking the newly discovered Carrara Sub-basin in the southeast to the highly prospective Beetaloo Sub-basin in the northwest.
- geochemistry results from NDI Carrara 1 indicating oil stains in the Proterozoic section differ significantly from that of the oil stain from the Georgina Basin section, pointing to the presence of multiple petroleum systems. These Proterozoic oil stains share many characteristics with Proterozoic source rocks observed/known/characterised elsewhere and demonstrate the presence of a Proterozoic petroleum system in the Carrara Sub-basin.

CONCLUSIONS

The fundamental result from the program in central northern Australia was the discovery of the prospective Carrara Sub-basin, interpreted to contain late Paleoproterozoic to Mesoproterozoic rocks with strong affinities to the adjacent Mount Isa Province and Lawn Hill Platform. The multidisciplinary results include revisions to the known stratigraphy of the mapped geological surface units for the region, as well as the identification of petroleum systems within the Carrara Sub-basin. A key outcome of the studies is a step change in understanding of the resource potential of northern Australia, providing a significant building block for future work.

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