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PESA Special Publication

VOLUME 1 | EXTENDED ABSTRACTS

Darwin Convention Centre
29 - 30 August 2022

The CABS IV Committee would like to acknowledge that this symposium was held on the traditional lands of the Larrakia people.

We pay our respects to elders past, present and emerging.

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Front Cover: *Karst towers of the Cambrian aged Tindall Limestone, exposed on the Stuart Highway in Katherine. Photo courtesy of Lachlan Hallett.*

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Editors' Foreword

This CABS Special Publication was prepared following PESA's Central Australian Basins Symposium (CABS) in Darwin on the 29th and 30th of August, 2022. This was the fourth 'CABS' conference, held ten years after the last one in Alice Springs in 2012.

Special Publication Volume 1 contains extended abstracts of presentations given at the symposium, and Volume 2 contains select technical papers. We hope that these volumes will provide a useful update for all geoscientists working in the central Australia region.

From the greater McArthur Basin in the north to the Officer, Pedirka and Cooper-Eromanga basins in the south, this volume covers the geological history of Australia's vast sedimentary record, dating back to around 2 billion years ago. These Australian basins provide some of the best-preserved early records of basin evolution on the planet, spanning multiple phases of super continent break-up, dispersal and amalgamation.

As with previous conference publications there is a substantial contribution on petroleum-related studies, from industry, academia, government bodies and research institutions. However, contributions on mineral and water resources are also covered, in addition to ideas on the energy transition, for which new information, innovative ideas and new technologies are required in order to meet net-zero targets in this modern world.

We hope that both volumes provide a suitable reminder of an excellent conference held at the best time of the year in the Top End, allowing the geoscience community to share knowledge and discuss the latest ideas and technological developments in central Australian basins.

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Borehole image features map depositional environment change in Mesoproterozoic deltas: insights from the Beetaloo Sub-Basin

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The Beetaloo Sub-Basin in the Northern Territory is a Proterozoic basin filled predominantly with siliciclastics rocks, the deeper sections only found in sub-crop (Munsen, 2016). The Beetaloo Sub-Basin hosts significant unconventional hydrocarbon resources within three identified shale reservoir intervals of the Mesoproterozoic Velkerri Formation (Close, 2016). The origin and mode of preservation of organic carbon in the Velkerri Formation is currently debated (Cox et al., 2016; Cox et al., 2022; Crombez et al., In Review). A greater understanding of the sedimentology and structural geology of the host formations is required to constrain plausible causal relationships within these units.

Borehole image logs were used to investigate the structural geology and sedimentology of the Beetaloo Sub-Basin ranging from the Velkerri Formation through to the Kyalla Formation in the following wells: Amungee NW-1, Beetaloo W-1, Kalala S-1, and Tanumbirini-1 (as of 2020). These wells provide control points within the present day basinal axes in the Beetaloo Sub-Basin East at an average correlation length of 55 km.

Sedimentary bed dip picking, image facies assignment, interpretation of image facies associations, and palaeocurrent analysis was carried out as part of a larger image log interpretation project (Wilson, 2020). In addition to these standard analyses, small-scale sedimentological features visible in the image logs were identified and mapped. Two features reported here are gutter casts and synaeresis crack fills.

Gutter casts are small-scale erosional features typically appearing as resistive or conductive downwards pointing triangular features in conductive formation with thicknesses

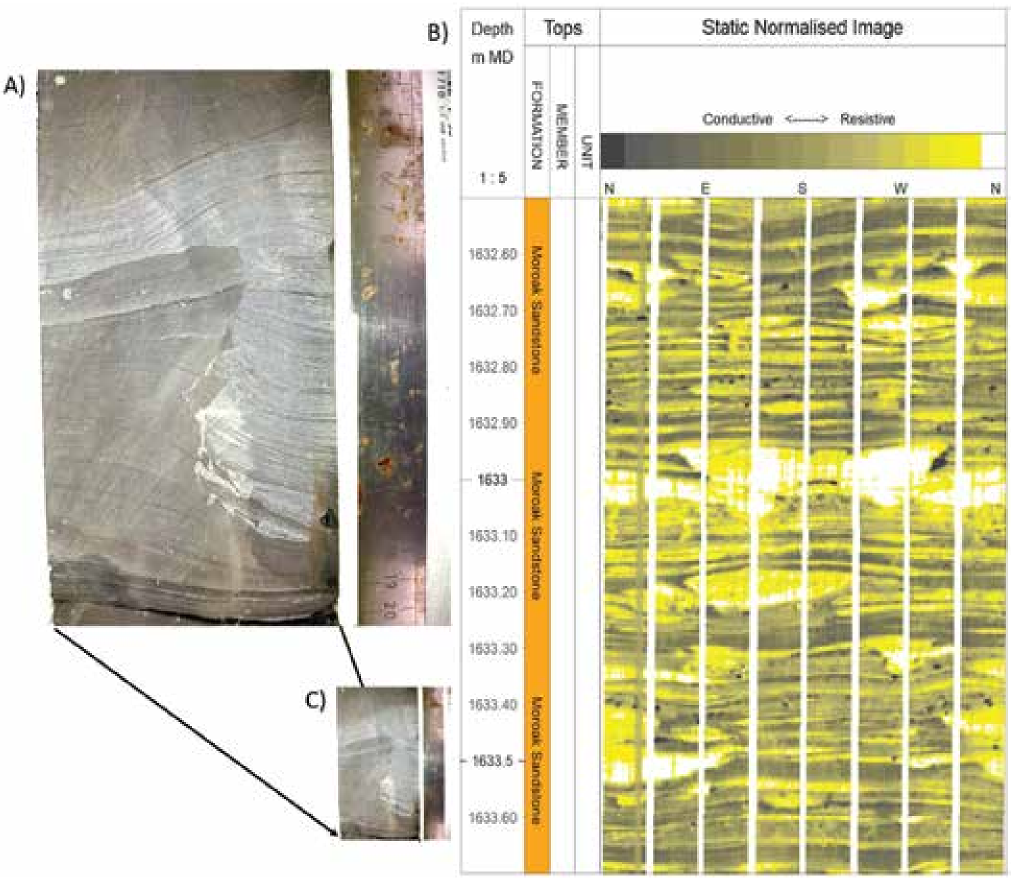

Figure 1. Sand-filled gutter casts. A) Sand-filled gutter casts in core from the Kyalla Shale of Beetaloo W-1. Note the erosive nature of the boundary scour, on-lapping of parallel-laminated sandstone fill and differential compaction. B) Sand-filled gutter casts in an FMI borehole image from the Moroak Sandstone in well Amungee NW-1. Static normalised FMI image shown. Bespoke resistivity colour scheme whereby sand (resistive) is yellow and mudstones (conductive) is green-grey. As the borehole image is an 'unwrapped' visualisation of the borehole wall a gutter cast crossing the borehole will appear twice, once on each side. The gutter casts at 1633 m MD has two triangular profiles and so is interpreted to cross the borehole. C) Image of core from A rescaled to the same scale as the borehole image.

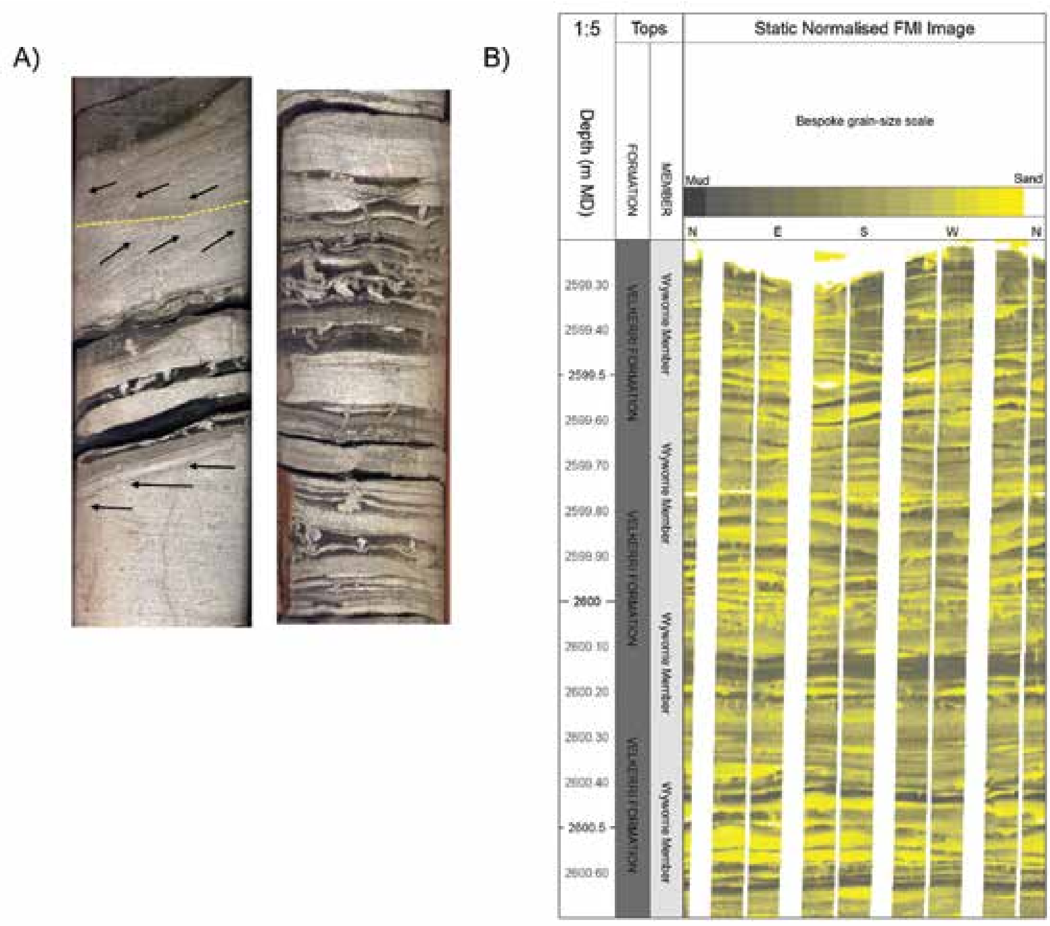

Figure 2. Synaeresis crack fills in core and image log. A) Synaeresis crack fills in core from the Kyalla Formation in well Elliott-1 (modified from Baruch, 2018). B) Static normalised FMI image from the Velkerri Fm. in Tanumbirini-1 with a bespoke resistivity colour scheme whereby sand (resistive) is yellow and mudstones (conductive) is green-grey. Synaeresis crack fills are clearly visible as short (~1 cm) vertical resistive (sand-filled) features in conductive formation (mudstone). Depth is in m MD.

of a few centimetres to a couple of decimetres (Figure 1). Comparison of core images shows that these are either mud-filled (conductive) or sand-filled (resistive) scours occurring in mudstone or muddy heterolithic sequences. Synaeresis crack fills are centimetre-scale, downward projecting resistive features visible in conductive formation (Figure 2). Turbidite fan, offshore/prodelta, lower shoreface/distal delta front, and upper shoreface/proximal delta front palaeodepositional environments were interpreted from image log analysis (Wilson, 2020). These describe a storm-dominated Moroak Delta that prograded NNW following deposition of the Wyworrie Mbr mudstones (Figure 3). These depositional environment interpretations build on and are broadly consistent with previous studies (e.g. Munsen, 2016; Johns et al., 2017). Turbidites are also considered by Crombez et al. (in review) from wireline log and sequence stratigraphic analysis.

Gutter casts first appear in abundance at the base of the Wyworrie Member of the Velkerri Formation (intervals interpreted as offshore/prodelta with turbidite fan deposits) and continue up into the base of the Moroak Sandstone (intervals interpreted as distal delta front) in all wells (Figure 3). Synaeresis crack fills first appear later than gutter casts in the upper part of the Wyworrie Member and continue up into the Moroak Sandstone intervals (interpreted as distal delta front) in all wells (*Figure 3*). Both gutter casts and synaeresis crack fills are no longer observed where the Moroak Sandstone becomes dominantly arenaceous. The mode in the frequency of gutter casts (by depth) in the Moroak Delta occurs lower (deeper) than the mode in the frequency of synaeresis crack fills in all wells (Figure 4).

This distribution of gutter casts and synaeresis crack fills is a new finding discovered through exceptional quality image logs over thick intervals of un-bioturbated, fully cemented strata. It is also, potentially, a feature of storm-flood dominated deltas more generally. This distribution is consistent with the basin-ward progradation of the storm-flood deltaic system. In the more distal position/deeper water depths erosional scours are formed by either storm-rip currents or hyperpycnal bottom-hugging currents that are then filled by sediment transported in these flows (sensu Collins et al., 2017). In the more proximal location/shallower water depths synaeresis crack fills form by the introduction of brackish water into a predominantly saline environment.

Combined with Gamma Ray values, the presence or absence of these features in image logs or core can be used as a predictive tool to quickly locate any study section within the larger-scale Moroak Delta architecture (Table 1).

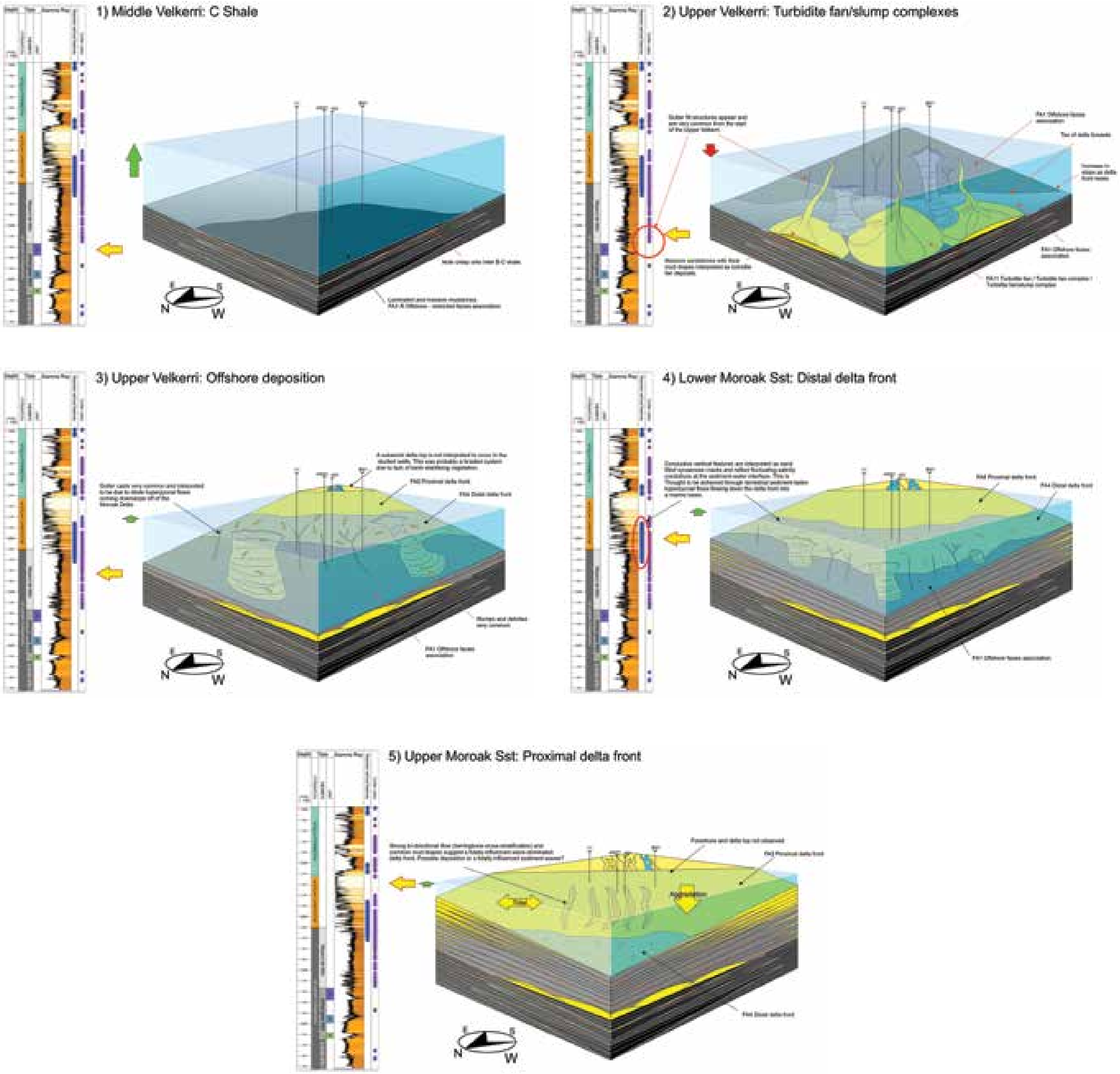

Figure 3. Oriented box models illustrating depositional environment interpretations and large-scale stratigraphic architecture for the Middle Velkerri (Wyworrie Mbr) to the Moroak Sandstone stratigraphic interval (modified from Wilson, 2020). Yellow arrows indicate the position in the stratigraphy for the box models shown. Green and red arrows indicate increase and decrease in relative sea-level respectively. Refer to figure text for explanation.

FACIES ASSOCIATION	SYNERESIS CRACK FILLS	GUTTER CASTS	COMBINATION	GR
Proximal delta front	Absent	Absent	AA	Low
Distal delta front	Present	Present	PP	Mid
Offshore/prodelta	Absent	Present	AP	High
Turbidite fan	Absent	Present	AP	Low
Offshore – restricted	Absent	Absent	AA	Very High

Table 1.

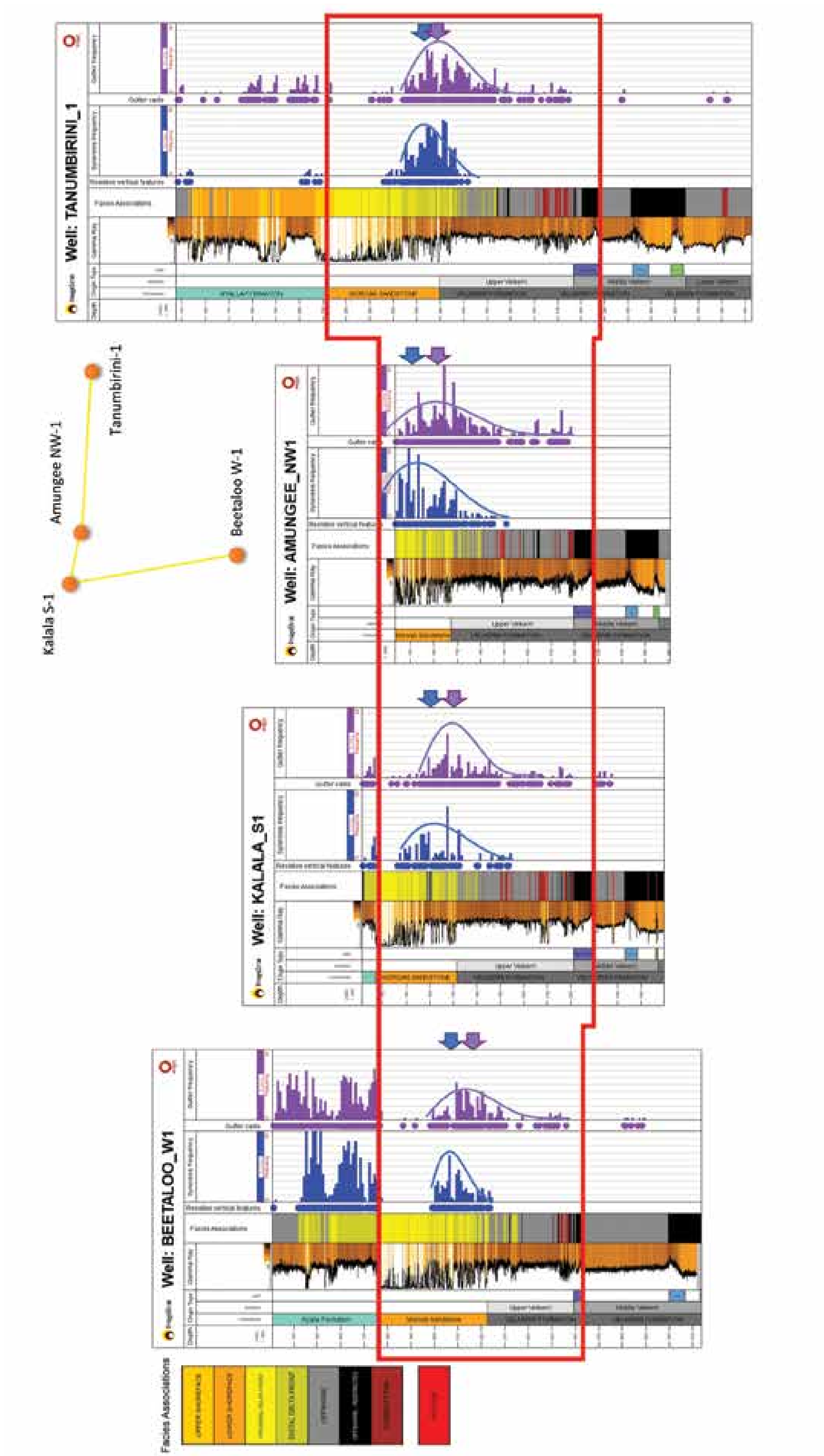

Figure 4. GR, synaeresis crack fill frequency histograms and gutter cast frequency histograms for wells Beetaloo W-1, Kalala S-1, Amungee NW-1 and Tanumbirini-1. Red box indicates the Moroak Delta and associated turbidite fans. Blue arrow indicates the mode in the histograms of synaeresis crack fills in the Moroak Delta, purple arrows indicate the mode in the frequency of gutter casts. Gutter casts always appear first and are most frequently occurring before synaeresis crack fills.

Acknowledgements

ImageStrat would like to thank Origin Energy and Falcon Oil & Gas for permission to present this work.

Keywords: Borehole image analysis, Beetaloo Sub-Basin, Velkerri Formation, Unconventionals.

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On the origin of quartz in the Velkerri Fm: implications for exploration and production in the Beetaloo Sub-basin and the Si cycle in the Mesoproterozoic

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The Beetaloo Sub-basin is a concealed, composite depocenter and a component of a group of intra-cratonic Paleoproterozoic to Mesoproterozoic sedimentary basins collectively described as the Greater McArthur Basin (Figure 1). The Sub-basin hosts unconventional and conventional petroleum resources, particularly in the uppermost Roper Group where stacked play opportunities include liquids rich shale, dry gas shale and hybrid/ tight gas plays (Côté et al. 2018; Altmann et al., 2020). The Mesoproterozoic (1.39 – 1.36 Ga) Velkerri Formation represents the most technically mature resource play for gas and liquids r Kalala, Amungee, and Wyworrie in ascending stratigraphic order (Munson and Revie, 2018). The Amungee Member is the main target for hydrocarbon exploration representing the deepest and most distal depositional environment and containing the highest proportion of fine-grained, organic-

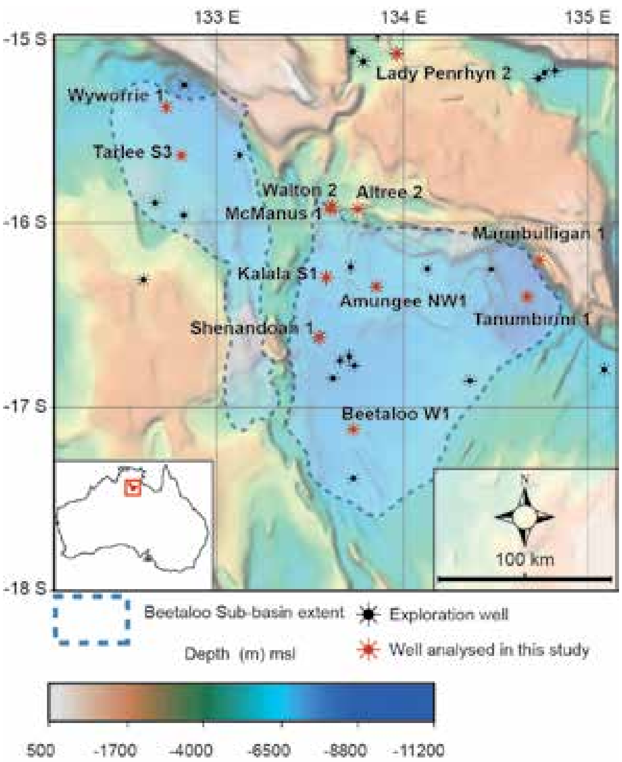

Figure 1. Extent of the Beetaloo Sub-basin overlaid on a basement depth map (Data from FROGTECH, 2018) and location of drill holes used in this study.

rich sediments. Mineralogical analyses, geo-mechanical laboratory tests, and down-hole fracture tests indicate a vertical heterogeneity in the organic-rich mudstones of the Amungee Member (e.g. Figure 2a) resulting in variations in reservoir and completion qualities (Close et al., 2017; Santos 2017).

Here we investigate the factors responsible for this vertical heterogeneity by establishing links between the effects of diagenesis (quartz cementation) and the geomechanical and petrophysical properties of the Velkerri Formation. The results indicate that intervals with the highest organic content are associated with pervasive quartz cementation in sediments dominated by diagenetic rather than detrital components and consistent with a distal depositional environment characterised by quiescent waters and low clastic dilution of organic material. These organic- and quartz-rich intervals have distinct elastic and geomechanical characteristics from those of the organic-lean intervals (*Figure 2b*). Petrographic and isotopic measurements at the of nano- and micro-scale indicate the presence of two types of diagenetic quartz: a widespread microcrystalline (ca. 500 nm in diameter) quartz with euhedral habit occurring in the matrix as tight clusters of crystals interspersed with illite clay and engulfed by bitumen filling the intercrystalline space (Figure 3a). The second diagenetic quartz type is identified as silt-sized crystals aggregated in elongated and flattened clusters that can reach ca. 0.5 mm in length and 100-200 µm in thickness and display a close spatial association between quartz, pyrite, and calcium phosphate spheroids (*Figure 3b*). The diagenetic nature of the latter quartz type is confirmed by in-situ isotopic measurements returning strongly positive values of δ18OVSMOW of 20.8 ± 1.4 ‰ (1σ, N = 23) consistent with those reported for Pre-Cambrian cherts (e.g. Jaffrés et al., 2007) suggesting precipitation from a low-temperature pore fluid. Vertical co-variations of organic content and diagenetic quartz abundance are regionally consistent and suggest a depositional environment control induced by eustatic level fluctuations resulting in stratigraphic stacking patterns interpreted as fourth-order transgressive-regressive sequences (Figure2a and Crombez et al., under review). The microscale distribution of diagenetic quartz imparts stiffness to the sediments and provides intercrystalline pore space now filled with bitumen therefore improving both reservoir

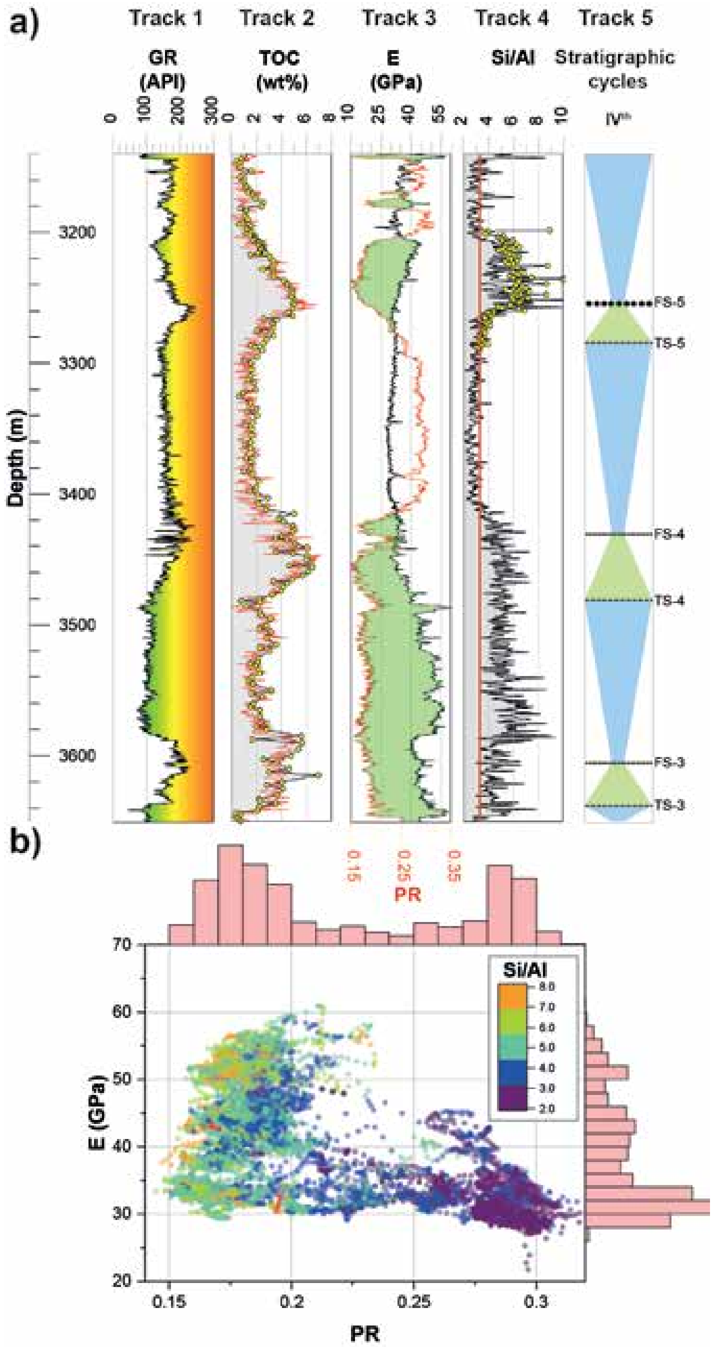

Figure 2. Petrophysical and geochemical character of the Amungee Member of the Velkerri Formation a) Wireline logs through the Amungee Member in well Tanumbirini 1.
Track 1: Gamma ray (GR). Track 2: total organic carbon (TOC) from elemental capture spectroscopy log (continuous lines) and laboratory measurements (yellow filled circles). Track 3: dynamic elastic moduli calculated from density, P- and S-wave velocities (E = Young's modulus; PR = Poisson's ratio); green areas show overlap in the two moduli representing favourable geomechanical properties for fracture reservoir stimulation. Track 4: geochemical values from elemental capture spectroscopy log (continuous lines) and laboratory measurements (yellow filled circles). illustrating the abundance of diagenetic quartz expressed by the ratio of Si and Al. Red vertical line shows the Post Archean Australian Shale Si/Al ratio (3.3), and values above 3.3 represent silica from non-detrital sources. Track 5: Stratigraphic surfaces from Crombez et al. under review, FS = flooding surface; TS = transgressive surface. b) Cross-plot of dynamic elastic moduli E (Young's modulus) and PR (Poisson's ratio) colour coded by Si/Al, note the bi-modal distribution of PR resulting in two clusters of data: one with low PR and a wide range of E (4<Si/Al<8) and one with high PR and low E (2<Si/Al<4). Wireline logs and geochemical data from wells in the Beetaloo Sub-basin discussed in this study are available through Northern Territory Geoscience Exploration and Mining Information System.

and completion qualities of the cemented intervals. The volumetrically significant amount quartz cement implies an early precipitation in a porous and relatively uncompacted mud and bears implications for the mechanisms of Si-removal from seawater and the marine silicon cycle in the Proterozoic. Our petrographic, isotopic and geochemical observations suggest an interplay between sedimentary and biogeochemical processes indicating that a significant proportion of quartz in the Velkerri is possibly due to bacterially mediated precipitation of primary biogenic opal. This represents a new and overlooked mechanisms of Si-removal from seawater in Pre-Cambrian sediments and has implications for the interpretation of similarly massive microquartz in certain organic-rich Phanerozoic mudrocks.

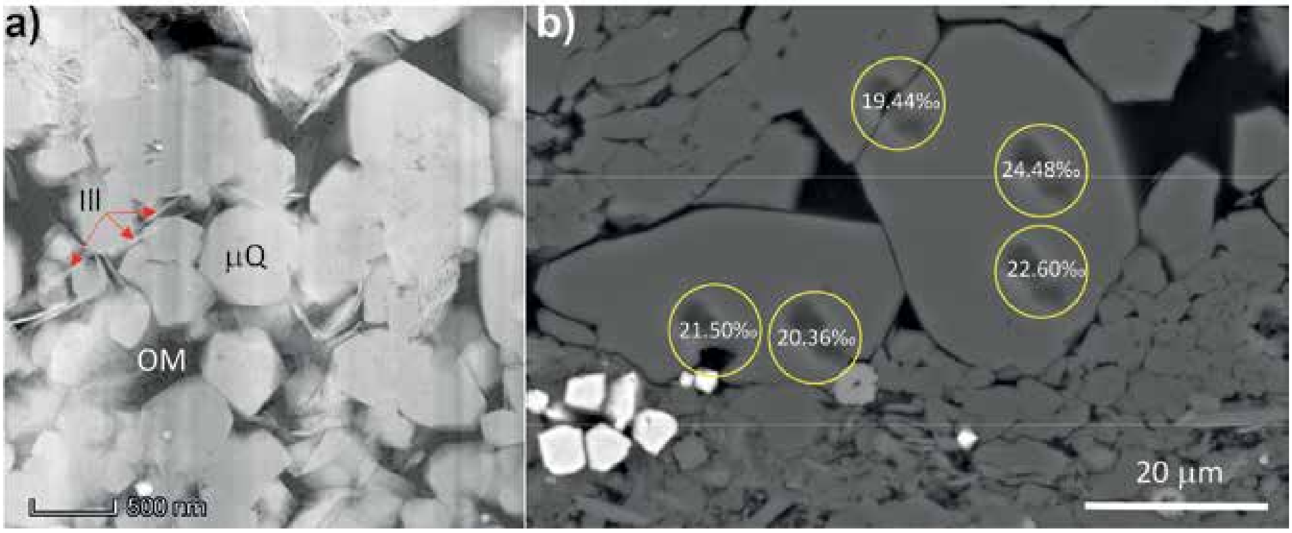

Figure 3. 3 Petrographic characteristics of two types of diagenetic quartz in the Velkerri Formation. a) Transmission electron microscopy image of the fine grained, quartz dominated matrix. Ill = illite; OM = organic material; μQ = diagenetic, micro-crystalline quartz, note the euhedral crystal shape of the quartz and the pore filling distribution of organic material (migrated bitumen). b) Scanning electron microscope detail of a quartz aggregate composed of silt-sized grains analysed by secondary ion mass spectrometry (SIMS). Yellow circles show SIMS pit locations, enclosed numbers are the measured δ18O values.

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Low-temperature thermal history of the McArthur Basin: Influence of the Cambrian Kalkarindji Large Igneous Province on hydrocarbon maturation

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The greater McArthur Basin of the North Australian Craton is one of the very few places on Earth where extensive hydrocarbons are preserved that were generated from Mesoproterozoic source rocks, prior to the development of extensive multicellular life (e.g. Cox et al., 2022). It is, however, unclear precisely when hydrocarbons from these source rocks matured, and if this occurred as a singular event or multiple phases (e.g. Crick et al., 1988; Dutkiewicz et al., 2007). In this study we present new apatite fission track data from a combination of outcrop and sub-surface samples from the McArthur Basin (Figure 1) to investigate the post-depositional thermal history of the basin, and explore the timing of potential hydrocarbon maturation.

Modelled thermal histories across the McArthur Basin predict varying Palaeozoic thermal evolutions across the basin. The Tanumbirini 1 well near the Beetaloo sub-basin (Figure 1) exhibits a rapid heating event following the emplacement of the Kalkarindji LIP at ca. 510 Ma (e.g. Jourdan et al., 2014; Figure 2). Kalkarindji basaltic lavas extend across the northern and western Australia (Figure 1), and reach a maximum preserved thickness of ~1100 m in the West Australian Craton (Mory and Beere, 1988), and ~440 m in the Beetaloo sub-basin (Hibbird, 1993), although in the McArthur Basin the lavas are characterised by a regional unconformity. The modelled heating event in the Tanumbirini 1 well was geologically short-lived, and consistent with heating of the shallow subsurface to depths of ~1 km below hot extruded lavas ~750–500 m in thickness (Figure 3). Once cooled, lavas must have been largely eroded from this region in the subsequent ~20 million years to allow rebound to the pre-eruption thermal state. Consequently, any hydrocarbon generation linked to this event in the Tanumbirini 1 well is likely to have been short lived.

Thermal reconstructions for the Broughton 1, WE1 and Manbulloo S1 wells and field sample 91779025 similarly place heating beginning at ca. 510 Ma (Figure 2), although at a much slower rate than seen in the Tanumbirini 1 well. We propose that these regions were overlain by thinner Kalkarindji lava flows than the Beetaloo sub-basin, but which were not rapidly eroded. Together with subsequently overlying sedimentary rocks of the Cambrian–Devonian Georgina Basin, low thermal conductivity basalts would have served to thermally insulate the underlying McArthur Basin (Gard et al., 2019) with a lower magnitude of heating but for a much longer duration (Figure 2). McArthur Basin rocks would only have cooled once Georgina Basin and Kalkarindji overburden was removed, which in modelled wells appears coeval with the ca. 390–360 Ma Pertnjara-Brewer Event (Jones, 1972; Bradshaw and Evans, 1988; Ahmad and Munson, 2013) of the Alice Springs Orogeny. No major structural reactivation is observed in the McArthur Basin at this time, so it appears most likely this event reflects gentle regional uplift and termination of sedimentation in the northern Georgina Basin.

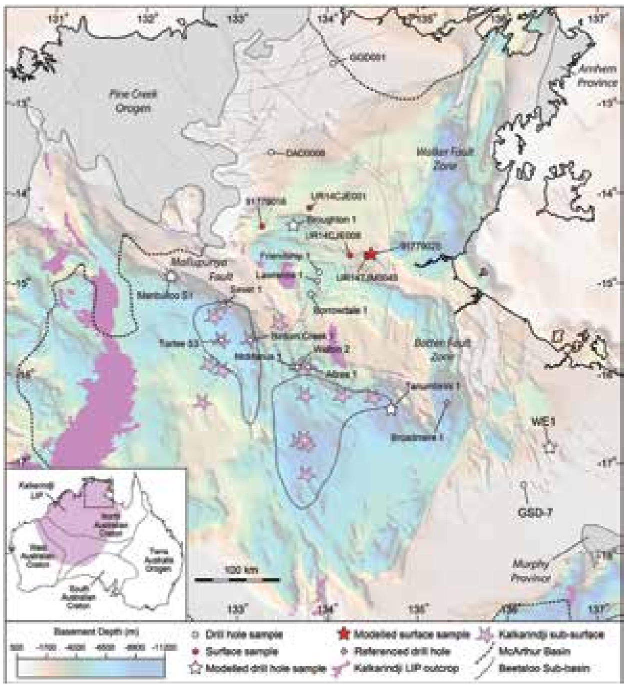

Figure 1. Sample locations collected for apatite fission track study within the McArthur Basin. The base of this overview is the SEEBASE depth to basement map showing depocentres and major structural highs (after Frogtech Geoscience, 2018). The overlain McArthur Basin extent includes the surface expression of McArthur sediments and the inferred sub-surface extent of strata from the Mesoproterozoic Wilton Package (Munson, 2016).

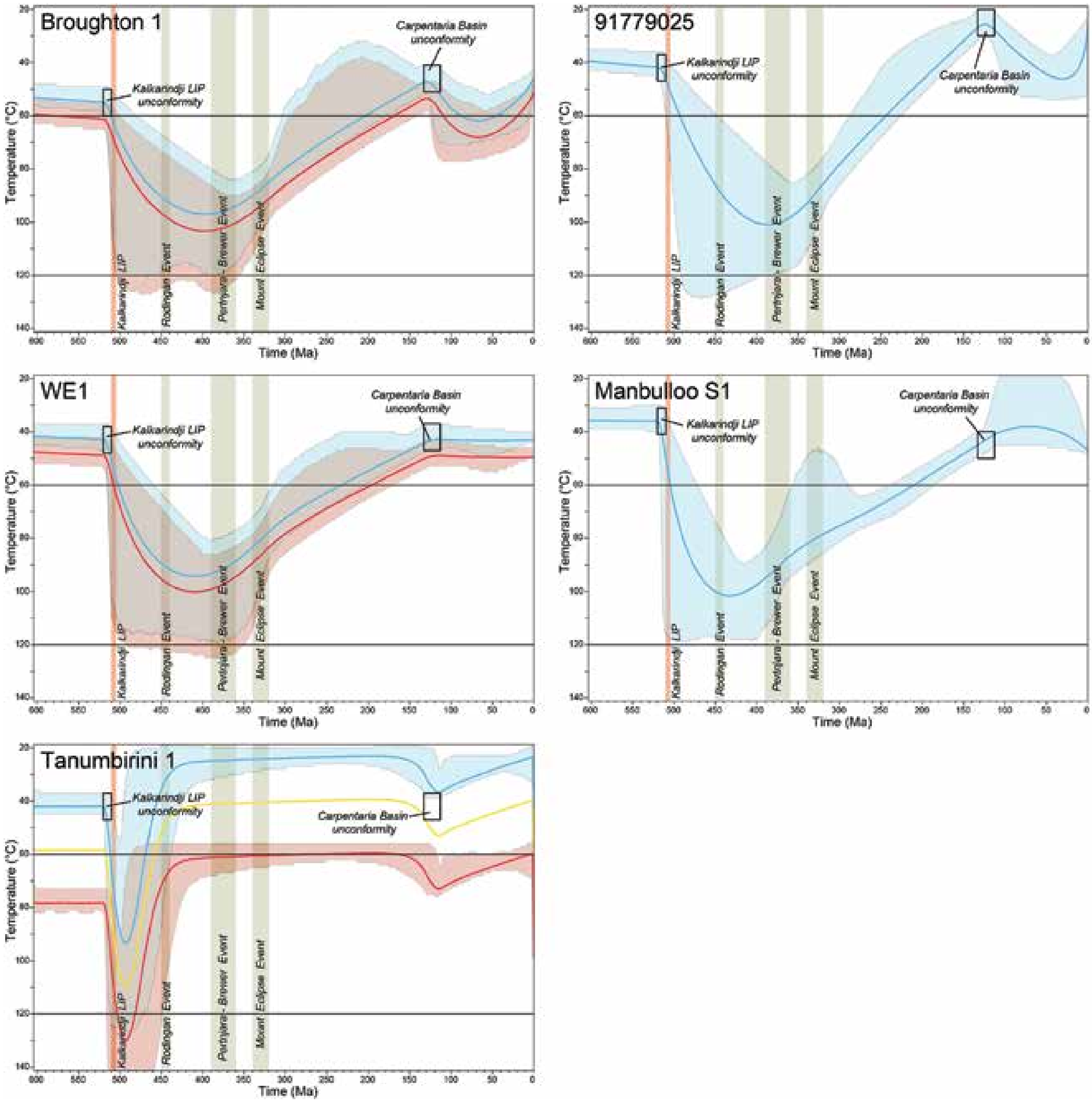

Figure 2. Low-temperature thermal history models for the McArthur Basin, produced using QTQt software (Gallagher, 2012). Solid lines denote the 'expected' thermal history, while associated envelops provide the 95% confidence interval. Blue paths represent the modelled thermal history of the shallowest sample, orange the intermediate and red the deepest (where applicable). The timing of magmatism of the Kalkarindji LIP (ca. 510 Ma) has been indicated, as well as the durations of deformational episodes of the Alice Springs Orogeny. The apatite partial annealing zone between temperatures of 120–60 °C (Gleadow et al., 1986) is indicated on each model.

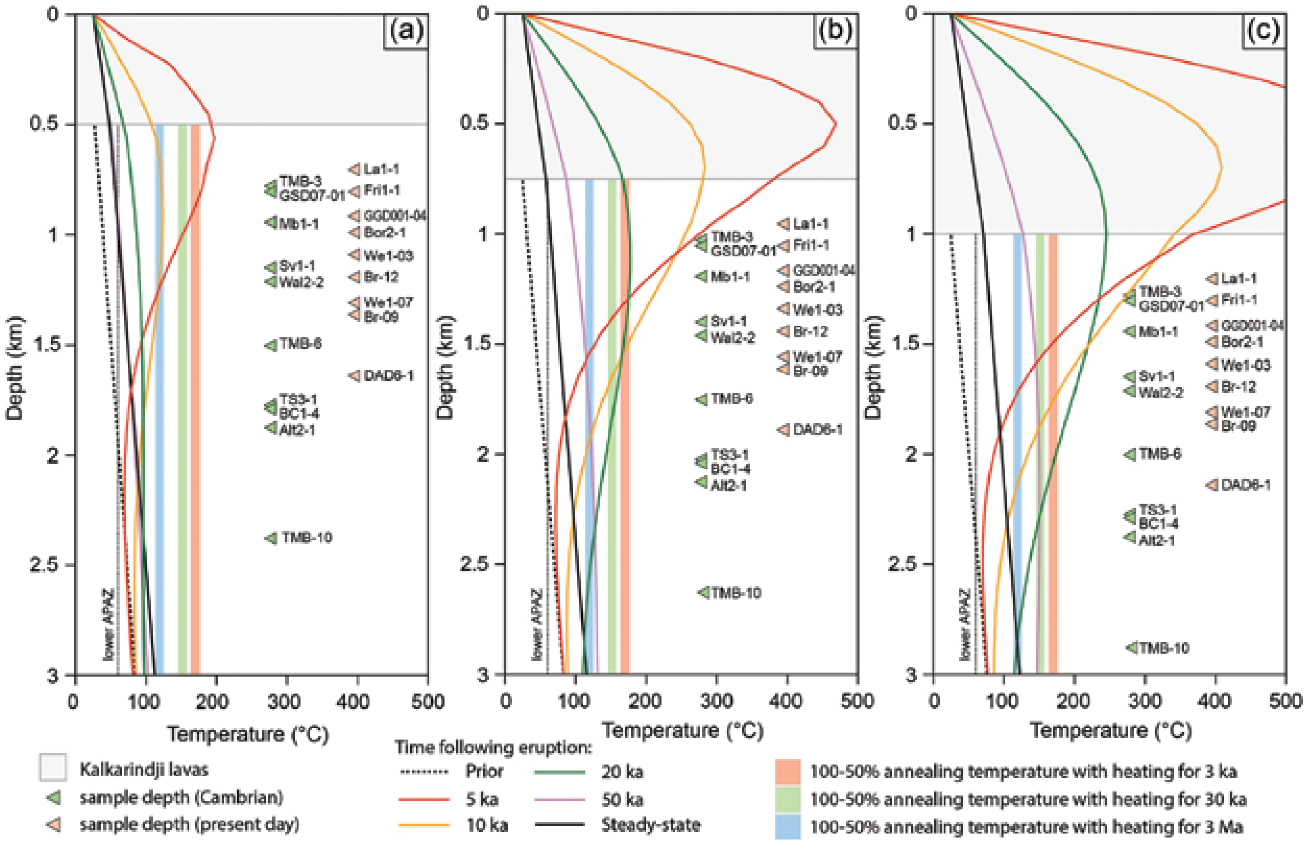

Figure 3. One-dimensional transient thermal modelling of McArthur Basin sediments in response to Kalkarindji LIP emplacement for lava thicknesses of (a) 500 m, (b) 750 m, and (c) 1000 m. Temperature ranges required for 100–50% annealing of tracks in apatite have been provided for multiple time durations, as calculated from fanning Arrhenius annealing model (Green et al., 1986; Laslett et al., 1987).

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Geothermal parameters of *in situ* Rb–Sr dating on Proterozoic shales and its applications

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Recent developments in tandem laser ablation-mass spectrometer technology have been shown to be capable of separating parent and daughter isotopes of the same mass online. Consequently, beta decay chronometers can now be applied to the geological archive in situ as opposed to through traditional whole-rock digestions. This new technique provides quicker and cheaper acquisition of geochronological and geochemical data whilst still maintaining a sample's petrographic context. One novel application of this technique is the in situ Rb–Sr dating on Proterozoic shales that are dominated by authigenic clays. This method can provide a depositional window for shales by differentiating signatures of early diagenetic processes versus late-stage secondary alteration. However, the thermal sensitivity of the Rb–Sr isotopic system across geological timescales in shale-hosted clay minerals is not well understood. As such, we dated the Mesoproterozoic Velkerri Formation from the Altree 2 well in the Beetaloo Sub-basin (greater McArthur Basin) using *in situ* Rb–Sr geochronology and constrained its thermal history using common hydrocarbon maturity indicators. Furthermore, thermal modelling of the Derim Derim Dolerite intrusion that crosscut the unit was also constructed to help define these parameters.

Our study found that the *in situ* Rb–Sr dating of mature, oil-prone shales in the diagenetic zone from the Velkerri Formation (Figure 1) yielded ages of 1470 ± 102 Ma, 1457 ± 29 Ma, and 1421 ± 152 Ma. These results agree with previous Re–Os dating of the unit at 1417 ± 29 Ma, constraining its depositional age. Conversely, overmature, gas-prone shales in the anchizone sourced from stratigraphically deeper within the succession (*Figure 1*) were dated at 1318 ± 105 Ma and 1332 ± 67 Ma. These ages are younger than the expected depositional interval for the Velkerri Formation. Instead, they are consistent with the age of the Derim Derim Dolerite mafic intrusion intersected 800 m below the unit, dated twice at 1313 ± 1 Ma and 1328 ± 24 Ma respectively.

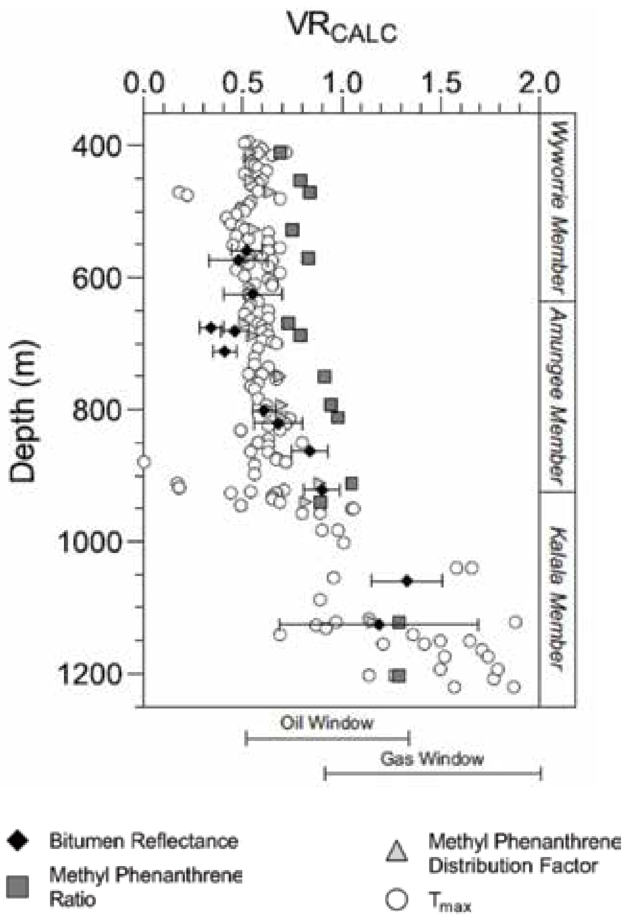

Figure 1. Calculated vitrinite reflectance (VRCALC) data down-hole modelled from TMax, MPR, MPDF, and bitumen reflectance data compiled in this study (NTGS, 1989, 2009, 2010, 2012; Cox et al., 2016; Lemiux, 2011; Revie, 2014; Capogreco, 2017; Revie et al., 2022; Jarrett et al., 2019). VRCALC from all proxies all indicate an elevation in thermal maturity into the gas window at depths ca. 900 m.

Computational modelling suggests that a single intrusion of 75 m thickness would have been capable of producing this significant hydrothermal perturbation radiating from the sill top (Figure 2). This is in agreement with similar Derim Derim Dolerite sill thicknesses found elsewhere in the McArthur Basin. The extent of this hydrothermal aureole coincides with the point in which kerogen from the Velkerri Formation becomes overmature. As a result, the mafic intrusion is interpreted to have driven the kerogen in these shales into the gas window, as well as induced fluids that mobilise trace elements and reset the Rb–Sr chronometer (Figure 2).

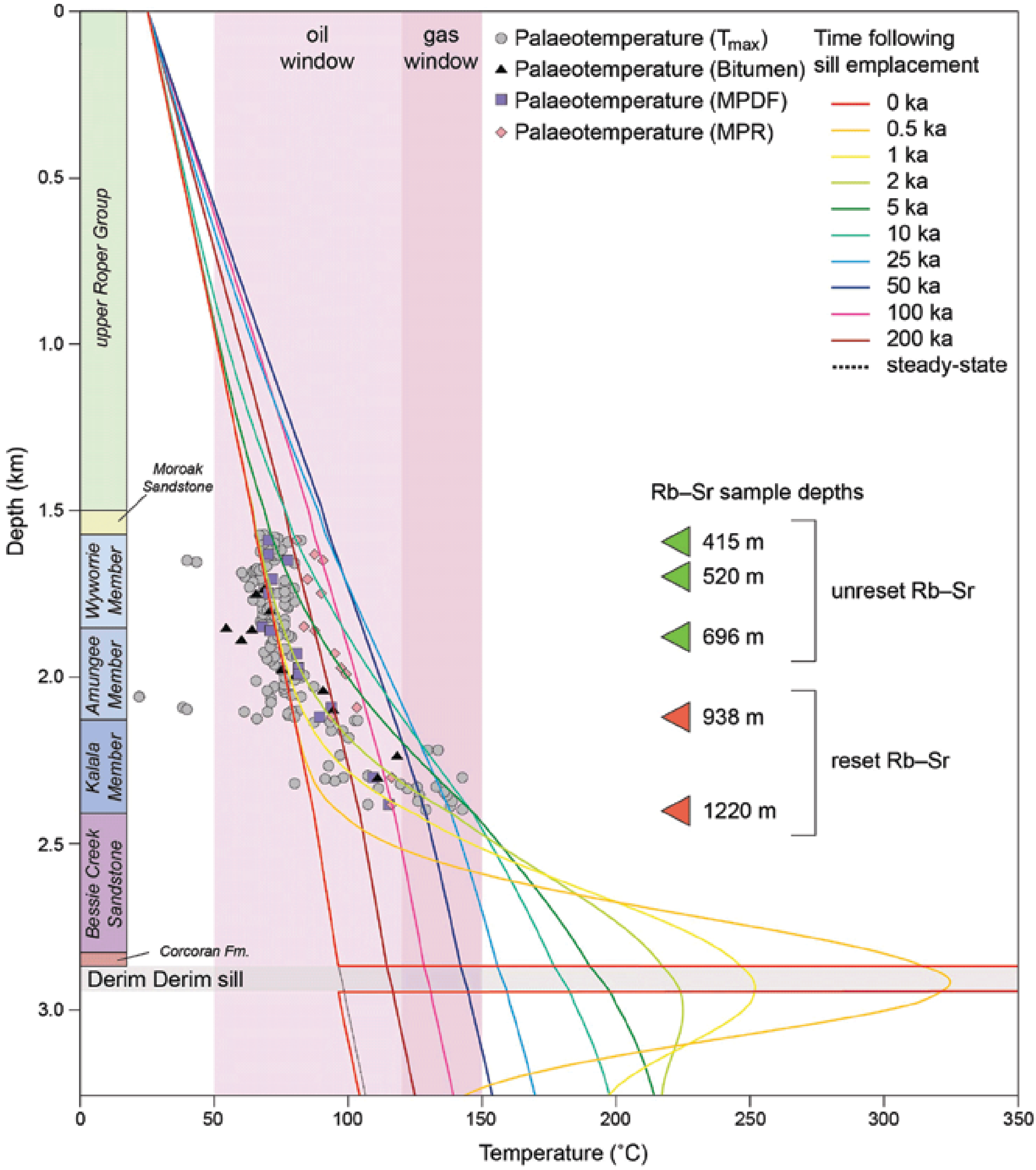

Figure 2. One-dimensional thermal model for sill intrusion of 75 m thickness within the Altree 2 well depicting time steps following emplacement at 0 ka. Sill intrusion and Rb–Sr sample depths have been normalised to palaeodepths with 1.5 km of additional Mesoproterozoic sediments (Hall et al., 2021). Median palaeotemperature estimates from VRCALC data from the Altree 2 well have been included for comparison to modelled temperatures.

Consequently, we propose that the Rb–Sr chronometer in shales may be sensitive to temperatures of ca. 120°C in hydrothermal reactions, but can withstand temperatures of more than 190°C in thermal reactions not dominated by fluids. As such, we show that this technique can aid hydrocarbon exploration, as the parameters of fluid-assisted resetting of shale hosted Rb–Sr systems in hydrothermal settings could overlap with the maturation of kerogen into the gas window.

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The Proterozoic greater McArthur Basin – New ways of looking at a frontier resource-rich basin

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The greater McArthur Basin of northern Australia is a vast frontier exploration province for basin-hosted resources, both hydrocarbons (oil and natural gas) and metals (critical metals [e.g. rare earth elements, Co], Cu, Pb, Zn and Au). This basin system covers much of northern Australia and may have included much of North China that lay off northern Australia when the basin formed—ca. 1820–1325 Ma. Hydrocarbon and metal deposits in the basin are largely controlled by host sediment composition and 'redox traps' related to ancient water chemistry, which, in-turn, are modulated by biological activity, tectonism and relative sea level change. None of these controls are fully understood or constrained throughout the basin.

In order to better understand the basin evolution we follow a number of approaches, including:

1. Developing new techniques to date shales, rapidly and economically, to assist with intra-basinal correlation, thermal and hydrothermal overprint history, and to help build a basin chronostratigraphic framework (e.g. Subarkah et al. 2021; 2022).

Innovations in laser mass spectrometry have been used to date shales from the McArthur Basin and triage the resulting data to separate ages interpreted as dating deposition or early diagenesis, from those reflecting later hydrothermal overprints. These are coupled with campaign-style detrital mineral geochronology and targeted high-precision U–Pb thermal ionisation mass spectrometry to build a basin chronostratigraphy.

2. Characterising the source areas for the basin system through detrital petrochronology and shale geochemistry (e.g. Yang et al. 2020; 2022).

Detrital minerals (zircon, rutile, muscovite) from the main 'packages' in the greater McArthur Basin have been dated and their trace element compositions determined to build a spatial and temporal database of source material that has been interpreted based on the tectonic evolution of the basement terranes around the greater McArthur Basin during the amalgamation of the Australian continents within Nuna/Columbia.

3. Investigating the ancient basin water chemistry through chemical proxies that relate to bio-productivity, salinity/restriction, and redox—temporally and spatially (e.g. Cox et al. 2019; 2022).

Proterozoic basin waters were extremely heterogeneous in dissolved oxygen. We are developing and building basin-wide elemental (e.g. U, V, Cu, Co, Mo, Fe, organic geochemistry) and isotopic (Cr, Cd) proxies for the reconstruction of paleoredox and paleobioproductivity conditions at different sites in the ambient water columns. These will be coupled with elemental and isotopic proxies for restriction/salinity (including coupled $^{87}Sr/^{86}Sr$ and $^{88}Sr/^{86}Sr$ datasets from carbonates) and proxies for biological activity (e.g. Cr/Cd, as well as C and N isotopes). These are being interpreted in a sequence stratigraphic framework to understand the dynamics between basin water chemistry, tectonics and basin water level variations.

4. Building a reconstruction of the basin, and of the tectonic geography of the basin and its environs through the ca. 1.8–1.32 Ga history of its existence (e.g. Figure 1). This has been facilitated by constructing a full-plate tectonic reconstruction for the Proterozoic.

Here we present a full-plate tectonic reconstruction from 1.8 Ga to present, focussed on the region of the Australian continental lithosphere. The greater McArthur Basin is considered as part of the McArthur-Yanliao Gulf of Nuna/Columbia and the nature of the basin will be addressed at different times and in different places.

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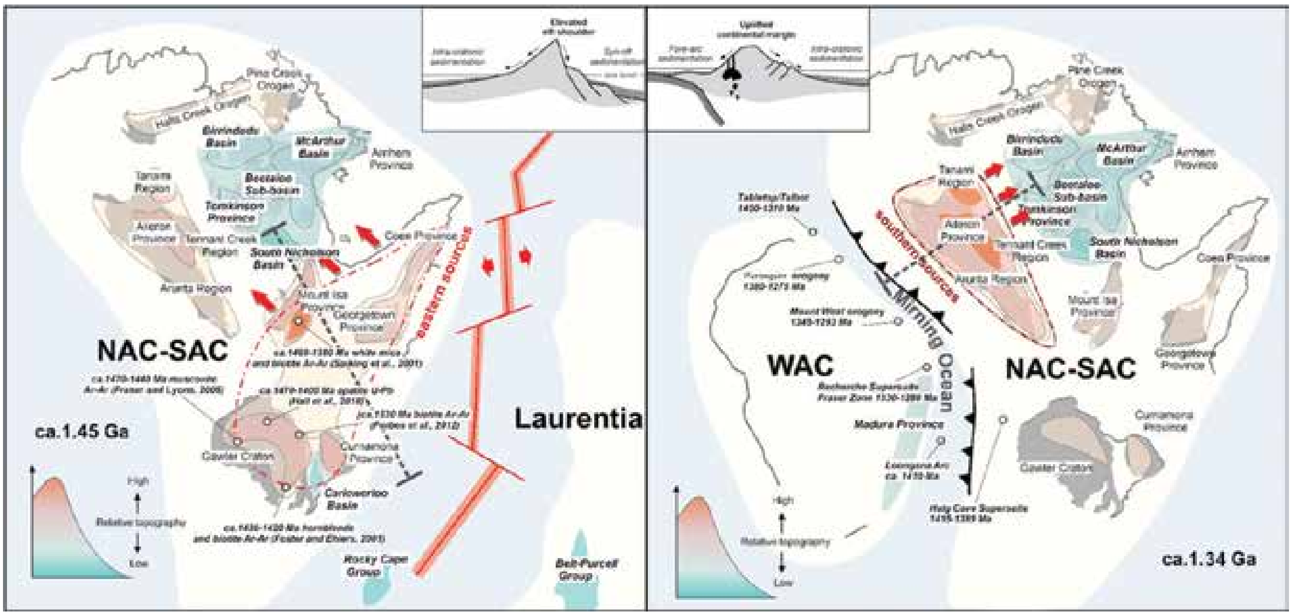

Figure 1. Reconstructed tectonic geography model of the combined North Australia Craton (NAC) and South Australia Craton (SAC) and Western Australia Craton (WAC) at ca. 1.45 Ga and ca. 1.34 Ga, showing the elevation of the eastern basement terranes during the separation between the Proterozoic Australia and Laurentia followed by topography creation to the south as the WAC collides with the combined SAC-NAC during the final stages of Nuna closure (after Yang et al. 2023)

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Understanding the interplay between basin architecture, depositional environments and sediment pathways in the Cooper Basin

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The late Carboniferous to Middle Triassic Cooper Basin is Australia's premier onshore petroleum province hosting a range of conventional and unconventional resources (Hall et al., 2019). Despite being considered a mature petroleum basin with over 1900 wells drilled and over 104,000 km of seismic surveys shot (Resources, 2022), many aspects of the Cooper Basin remain enigmatic with very different structural and sedimentary histories between the eight troughs and intervening ridges (Kulikowski et al., 2022). There is no consensus on the overall tectonic regime during the basin's formation. Interpretations include intracratonic (Hill and Gravestock, 1995; Kapel, 1972), contractional tectonism (Apak et al., 1997; Kuang, 1985), extensional (Stanmore and Johnstone, 1988) and dextral strike-slip tectonics (Kantsler et al., 1983). New perspectives on the tectonostratigraphic and depositional evolution of the basin are suggested by an integrated study of legacy 2D seismic lines, well logs, cores, 1D burial history models and backstripping of 2-D seismic sections

Seismic interpretations suggest that the basin architecture (Fig. 1) is similar to the Viking Graben in the North Sea and the southern Red Sea Basin. The major depocentres, including the Patchawarra and Nappamerri Troughs, are interpreted as half-grabens that developed during an early episode of rifting with elevated subsidence during the early Permian. The lack of substantial original topographic relief on the basin floor together with concordant-parallel geometries of pre-Patchawarra strata suggests that the basin highs and lows are entirely structural in origin as proposed by Thornton and Hudson (1979) (*Fig. 1*), rather than the infilling of a glacially eroded topography suggested by Kuang (1985) and Wopfner (1969). 1D burial history models of the Cooper and the overlying Eromanga Basin are inconsistent with an intracratonic tectonic setting as there was a short-lived (<20 Ma) period of elevated subsidence during the early Permian, several episodes of tectonic uplift (3 to 5 Ma) and prolonged passive thermal subsidence that persisted from the Early Jurassic through to the mid-Cretaceous. The Patchawarra, Roseneath, Epsilon and Murteree strata most likely represent the syn-rift phase of the Cooper Basin indicated by differential subsidence between the troughs and the thickening of these units against the hanging wall of the Gidgealpa–Merrimelia–Innamincka (GMI) ridges. In contrast, the overlying Toolachee Formation, Nappamerri Group and Eromanga basin units, which lie above the Daralingie Unconformity, exhibit thick onlapping stratigraphic sections suggesting the infilling of basin relief which is consistent with post-rift tectonostratigraphic architectures. These interpretations are similar to those of Hall et al. (2019) who suggested the Cooper-Eromanga Basin experienced a polyphase tectonic regime influenced by both contractional and extensional events during its evolution.

Measured sections through the early Permian Patchawarra Formation reveal the complex interplay of tectonic and depositional environments with a diverse range of facies within and between the depositional troughs/half grabens. Lacustrine facies dominate in the deeper parts of half-grabens/troughs whereas more fluvial and/or thicker coal beds developed on the basin margins. During periods when sediment supply exceeded the rate of creation of accommodation, rivers developed in the centre of troughs and likely flowed parallel to structural highs. In contrast, when the rate of creation of accommodation exceeded the rate of sediment supply, fluvial sediment was trapped on the basin margin and extensive lakes developed within the basin. These interpretations contrast with those of Beeston (1995) and Strong et al. (2002) who suggested a north-easterly flowing fluvial system over large parts of the basin. The preservation of extensive coal beds, up to 30 m thick suggests periods when tectonic subsidence rates were relatively stable.

Present-day structures and deformation are largely a consequence of post-Cretaceous uplift as opposed to earlier tectonic events recorded in the basin. This is most prominent in strata above the GMI Ridge which continues to be uplifted following the cessation of sedimentation in the Eromanga Basin after the mid-Cretaceous.

These interpretations may better constrain paleogeographic reconstructions, provide insights into the location of new petroleum plays in lesser explored regions of the basin and enhance the Cooper Basin's resource prospectivity.

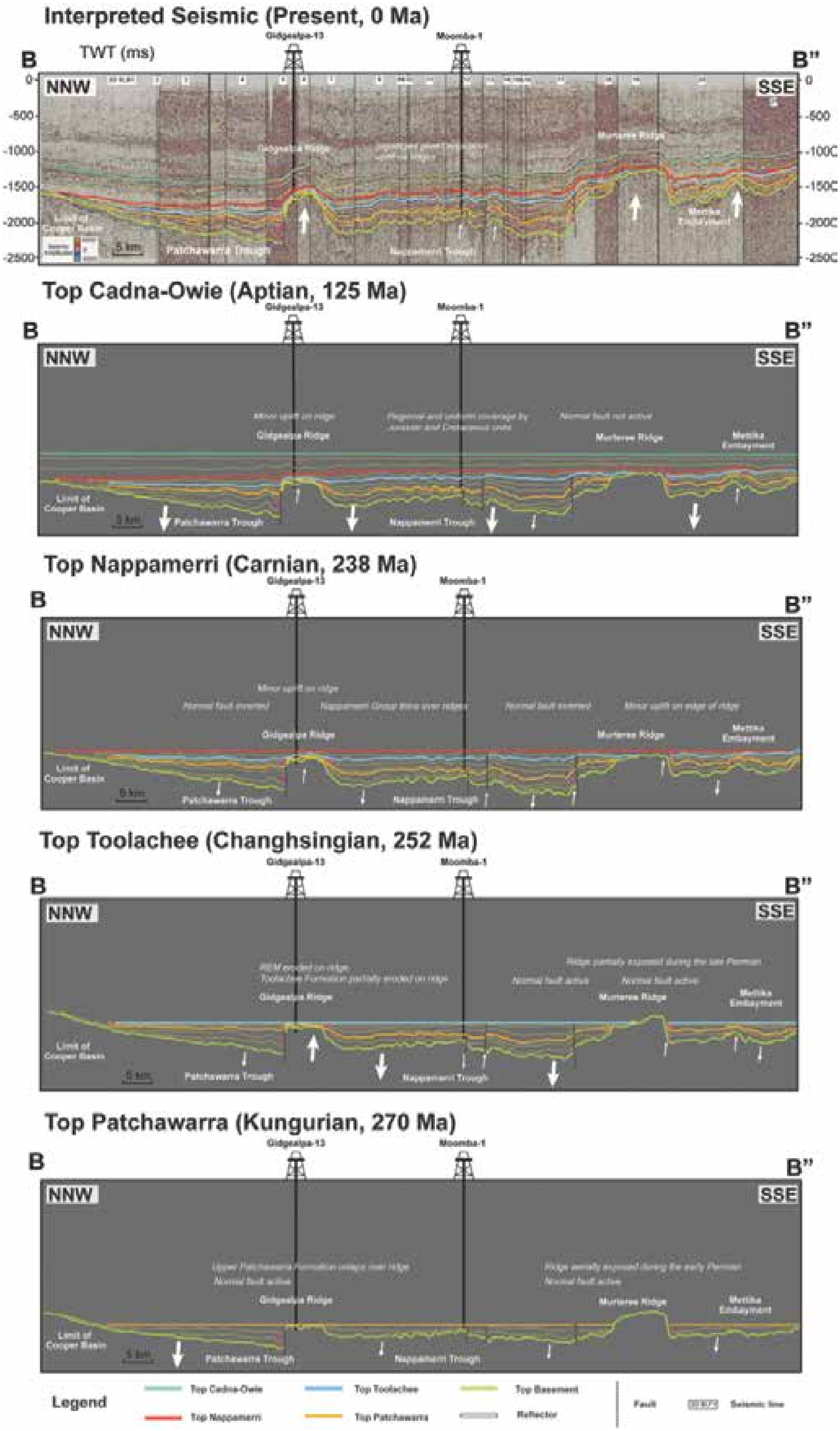

Figure 1: Regional NNW-SSE cross-section B–B" flattened on the Top Cadna-Owie Formation (sag Phase), Top Nappamerri Group (sag Phase, Top Toolachee Formation (sag phase) and the Top Patchawarra Formation (rift phase) respectively showing how basin architecture varied between these two tectonic phases). Interpreted on composite 2D seismic lines in two-way time.

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Quick-look core-logging, a cost-effective way to develop a regional depositional model, Patchawarra Formation, Cooper Basin

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The early Permian Patchawarra Formation is one of the principal gas producing intervals of the South Australian Cooper Basin (Government of South Australia., 2022), (Figure 1). The gross depositional environment (GDE) for this interval is reported to be dominantly fluvial plain (Strong et al., 2002 and Stephens et al., 2014). However, recent logging and interpretation of 296 m of the Patchawarra Formation from seven wells (Dullingari 39, Fly Lake 2, Halsam 1, Le Chiffre 1, Moomba 194, Pando 1 and Talaq 1), from the South Australian Cooper Basin, indicate the presence of significant lacustrine depositional environments, including shoreface, possible lacustrine turbidites and potential incised valleys, all of which may alter exploration and development strategies.

This core-based study grew out of the PESA (SA/NT) core workshop held at the South Australian government's core facility at Tonsley in early November 2021. Cores were logged over a 15-day period followed by a series of peer reviews. All cores were logged with no reference to literature to maintain independence. To see stratigraphic and areal changes, the Patchawarra Formation was informally divided into lower, middle, and upper intervals, based upon changes in wireline and core characteristics.

Patchawarra core logging revealed some surprising results not the least being the presence of syneresis cracks (Figure 2a), an indicator of salinity flux in sub-aqueous conditions (Reineck and Singh, 1980). In all cases the syneresis cracks occur in upper, lacustrine/deltaic

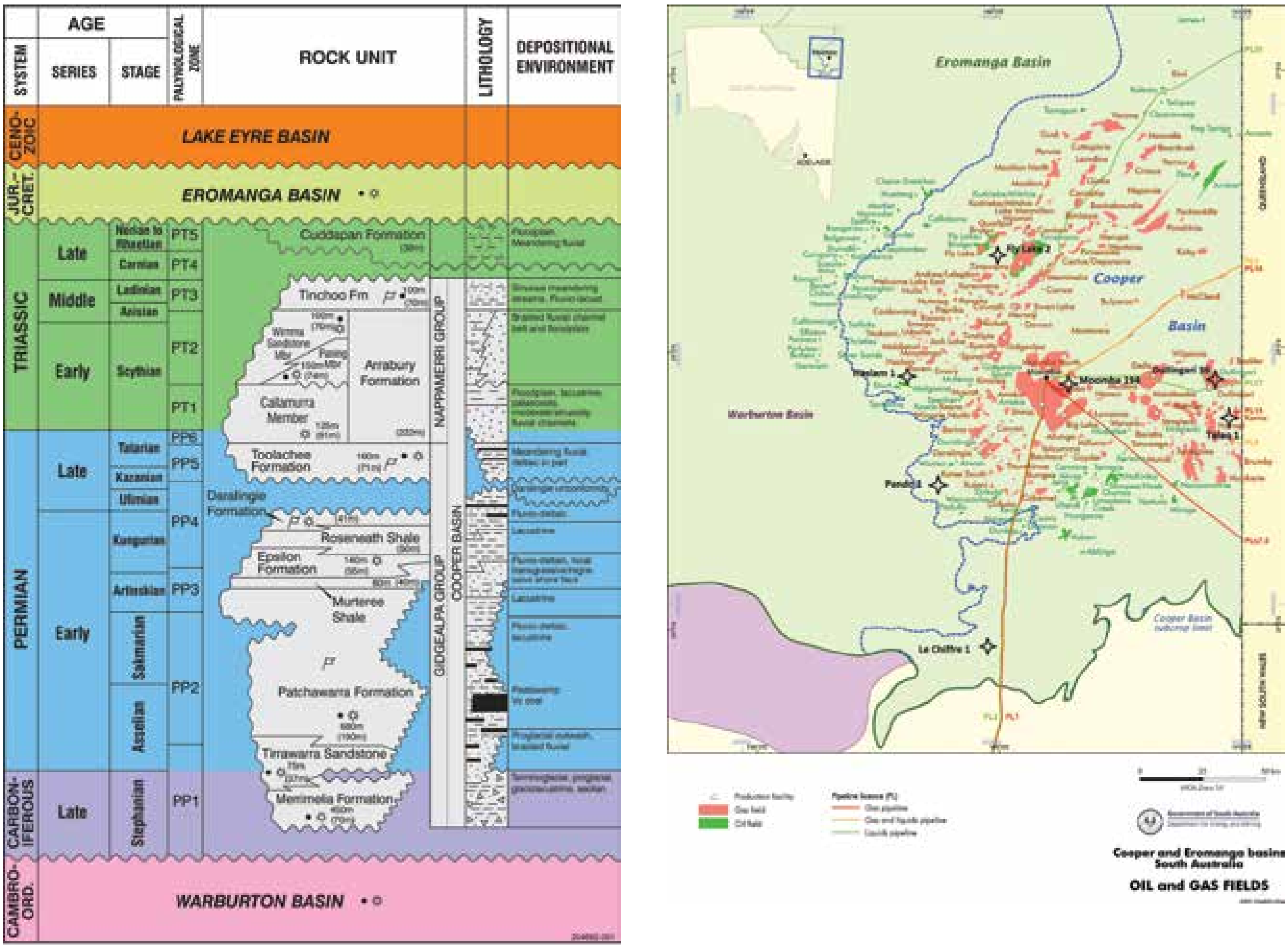

Figure 1: Cooper Basin stratigraphy study well location map (After DEMIRS 2022).

dominated intervals and are possibly formed due to salinity fluctuations, associated with glacial freshwater melts. Additionally, diverse, and at times, intense trace fossil assemblages were also observed including Skolithos and Cruziana (Figure 2b and Figure 2c) ichnofacies. Looking at all wells (Figure 3) reveals the spatial variation of key sedimentary features.

The core logs in all seven wells reveal depositional trends and a succession of GDE's. For example, two wells, Haslam 1 (west) and Talaq 1 (east), illustrate the stratigraphic changes in fluvial and lacustrine successions. The Haslam 1 example (Figure 4) shows a progression of peat swamp deposition and lacustrine/shoreface cycles. Completing the depositional continuum, peat production recommenced upwards. It should be noted that the Figure 4 and Figure 5 maps, are single well, GDE sketches (quick look concepts). More wells would need to be added, in a similar manner, to constrain and finalise predictive GDE maps. Moreover, seismic data should be incorporated into this (and the Haslam 1) depositional models to better understand sediment packaging and lateral equivalence. The scale of these depositional features, however, may be an issue for seismic facies work with waveform seismic processing most likely the best way forward.

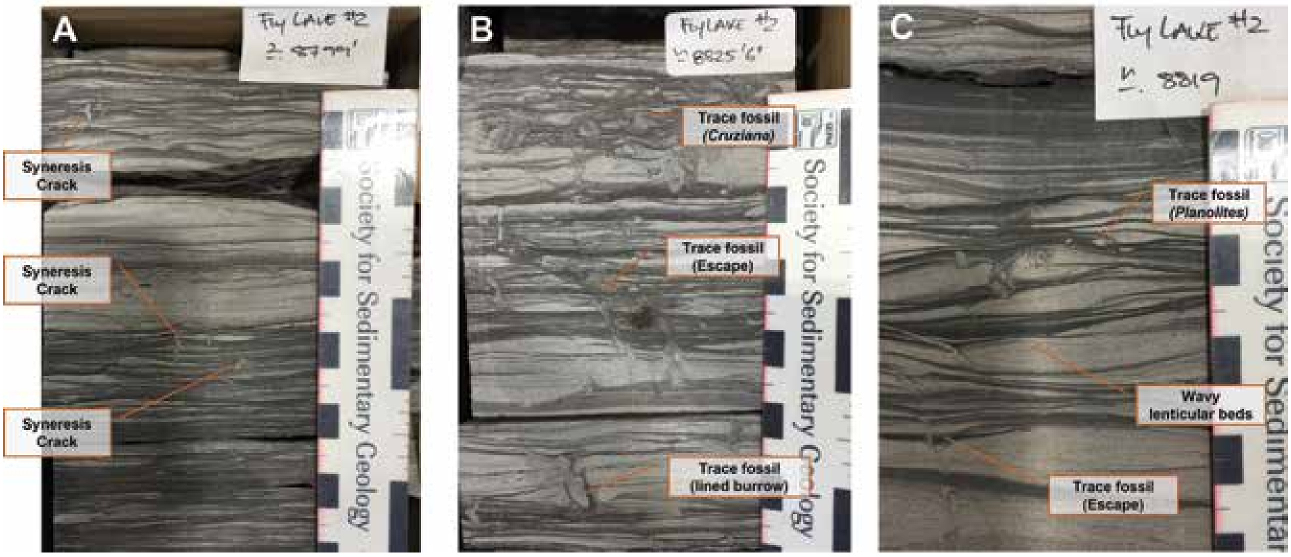

Figure 2: Key Patchawarra Formation sedimentary features. (A) Fly Lake 2 (8799' ~ 2681.3 m wireline depth) syneresis dominated heterolithic [GDE – lower delta plain]. (B) Fly Lake 2 (8825' 6" ~ 2689.4 m wireline depth) Skolithos-dominated trace fossil dominated heterolithic [GDE – lower delta plain]. (C) Fly Lake 2 (8819' ~ 2687.4m wireline depth) Wavy lenticular bedded heterolithic with simple Planolites trace fossils [GDE – lower delta plain].

All interpreted depositional environments were defined by a standardised set of criteria using sedimentary features, grainsize trends and depth-matched wireline curves. For example, the "Fluvial (Anastomosing)" depositional environment is defined as a series of stacked fining upward-to-aggradation sandstone packages, with truncated abandonment sections common. Additionally, this depositional environment shows bedding styles that range from massive to planar with occasional trough cross bedding present (an example of this is given in Figure 5).

In all nineteen depositional environments and six GDEs were identified. The dominant GDEs include, lacustrine (45%), fluvial plain (33%), coastal plain (17%) with various minor GDEs (including shoreface) accounting for 5%. Fluvial plain GDEs were most developed in the lower to middle Patchawarra Formation, whereas the lacustrine, coastal plain, delta and shoreface GDEs were observed in the upper Patchawarra Formation. In contrast, lacustrine, rather than fluvial plain deposition was observed in the lower/middle interval at Le Chiffre 1. These results question the notion that the Patchawarra Formation is dominantly a (fluvial) meander/swamp succession. Notably a change in GDEs, to more lacustrine-dominated intervals, may change exploration strategies regarding stratigraphic traps, in the upper Patchawarra Formation, especially on the Western Flank.

In contrast to Haslam 1, a fluvial dominated succession was cored in the Talaq 1 well. At the base of the core a meander channel system is interpreted complete with the abandonment lacustrine fill and peat swamp formation (Figure 5). Upwards the peat swamp is eroded by high energy bedload conglomerates and stacked, aggradational, sandstones, interpreted to form a set of anastomosing fluvial channels. However, is there an alternative to this anastomosing channel interpretation? For example, does this upper most package represent an anastomosing fluvial channel system that is switching with time (autocyclic) or incised valley fill (IVF) that formed in response to tectonic uplift (allocyclic)? If the latter, then such events should be traceable elsewhere in the Cooper sub-basins.

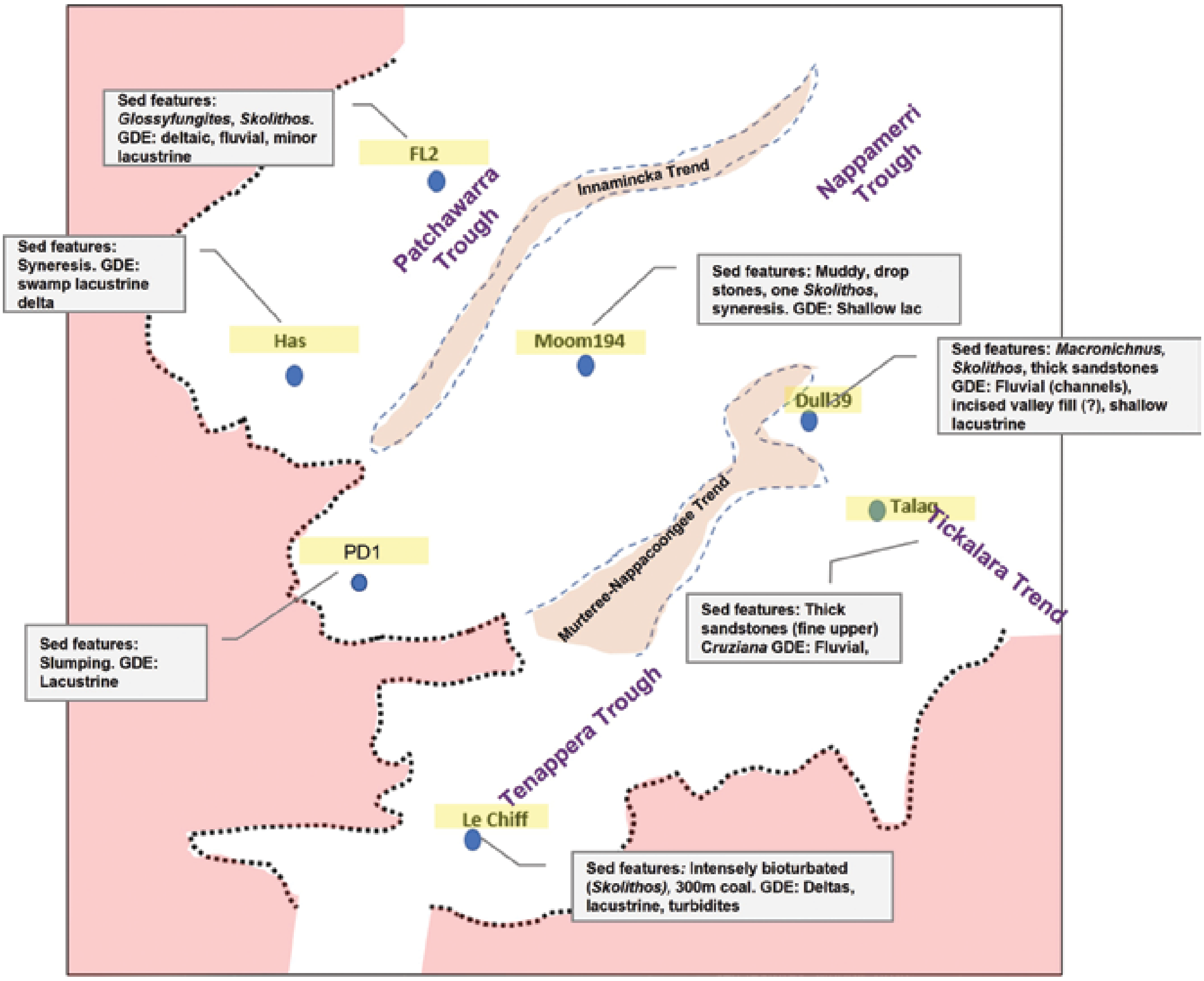

Figure 3: Subset of the study wells with some key sedimentological feature and depositional environment interpretations. Note: Dull39 (Dullingari 39), FL2 (Fly Lake 2), Has (Halsam 1), Le Chiff (Le Chiffre 1), Moomba194 (Moomba 194), PD1 (Pando 1) and Talaq (Talaq 1).

This study has suggested that the Patchawarra should not be universally regarded as a meander-fluvial system but rather the stratigraphic and geographic position need to be considered before assigning dominant DEs and associated reservoir types and geometries. This work illustrates the value of quick-look core logging to build a regional dataset upon which significant information regarding reservoir type, development and quality can be determined. Such a workflow could impact future drilling locations if the work is undertaken during the de-risking timeframe. This is a key component of quick look core logging, as often, regional studies can be out of sync with drilling decision timing.

Acknowledgements

The authors would like to thank Dave Groom and team at South Australia's DEMIRS (Tonsley) core facility for providing accelerated core layouts. The authors would also like to thank Rhodri Johns and Carmine Wainman for the many productive core review sessions.

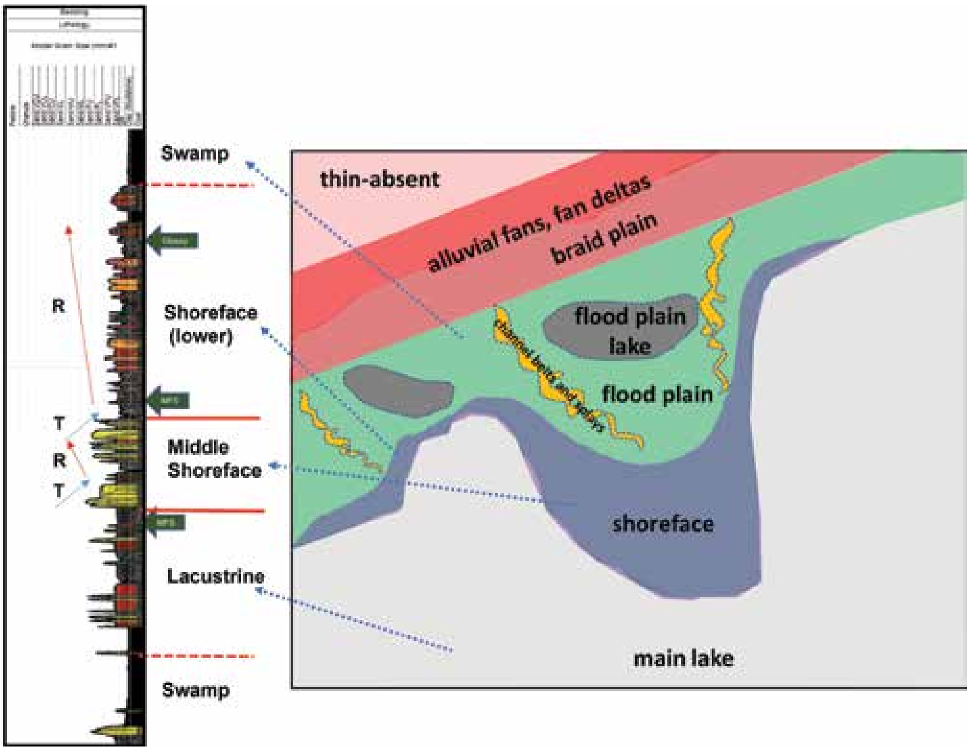

Figure 4: Haslam 1 core log extract and GDE maps and progression of GDE's upwards.

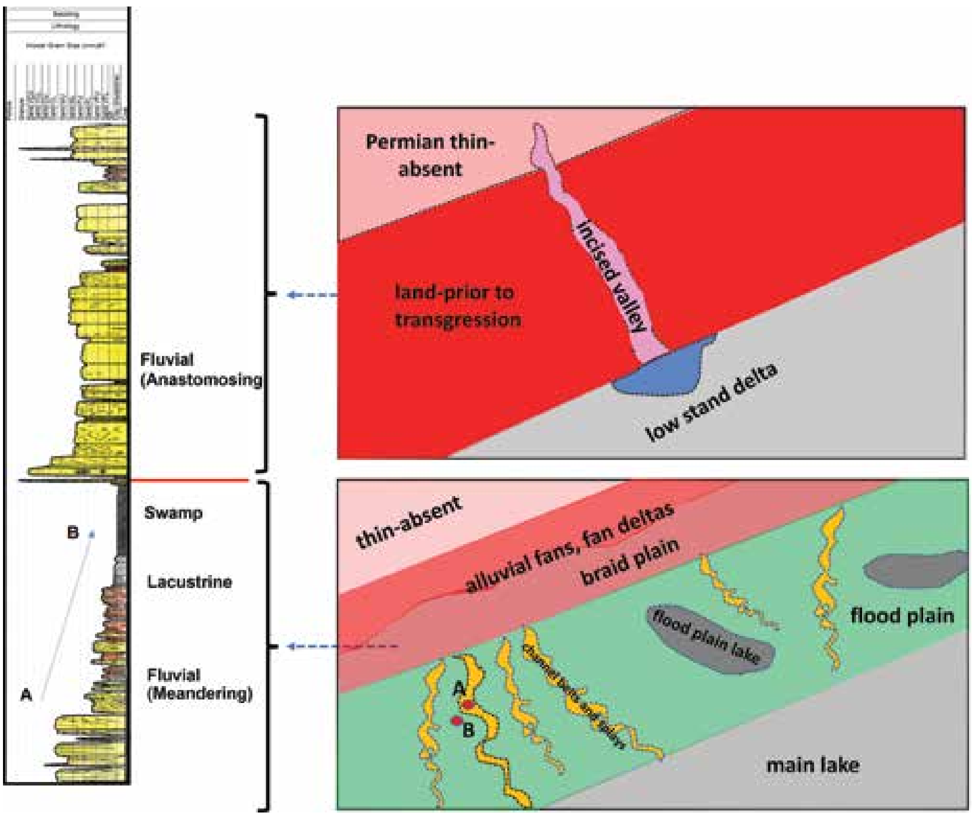

Figure 5: Talaq 1 core log extract and GDE maps and progression of GDE's up section.

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New metal isotope techniques to explore past depositional environments of the Centralian Superbasin, Australia

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The Centralian Superbasin (CSB) is a ~ 2 million km^2 Neoproterozoic to early Palaeozoic (ca. 850–400 Ma) intracratonic depositional system, which stretches across four states (WA, NT, SA and QLD) and is of fundamental scientific and economic significance to Australia. Sedimentary sequences within the CSB, comprising the Amadeus/Warburton, Georgina and Officer Basins, record a critical phase of Earth history (Figure 1), encompassing the Neoproterozoic rise of atmospheric oxygen, major reorganisations in the global carbon cycle and the emergence of the first complex life. Importantly, the formation and distribution of sediment-hosted energy and mineral resources within the CSB is controlled by several factors, including (i) the evolving basin palaeogeography, which in turn determines the CSB's bathymetry and hydrological connectivity, and (ii) the progressive oxygenation of the ocean-atmosphere system through time, impacting the basin's redox structure and thus local/regional 'redox traps' conducive to metals and hydrocarbon accumulation in the CSB.

This contribution will introduce selected alkaline earth metal isotope proxies (stable and radiogenic Sr isotopes, stable Ca) and their potential to reconstruct past changes in depositional environments in the CSB, including parameters such as (i) hydrological connectivity and basin restriction with respect to an open ocean, (ii) palaeo-salinity variations, and (iii) past changes in carbonate precipitation/burial vs dissolution/weathering linked to local mineral saturation (Figure 2). These processes will be illustrated on reconnaissance studies and Ca and Sr isotope datasets collected from the Neoproterozoic (Bitter Springs Gr., Ringwood Mb, Olympic Fm) and Cambrian (Goyder, Shannon, Giles Creek, Chandler Fms) carbonate/evaporite sequences, sampled from drill cores and outcrops, in the Amadeus Basin, NT, complemented also by data from modern marine/coastal systems (Shao et al 2018, 2021) for the proxy calibration.

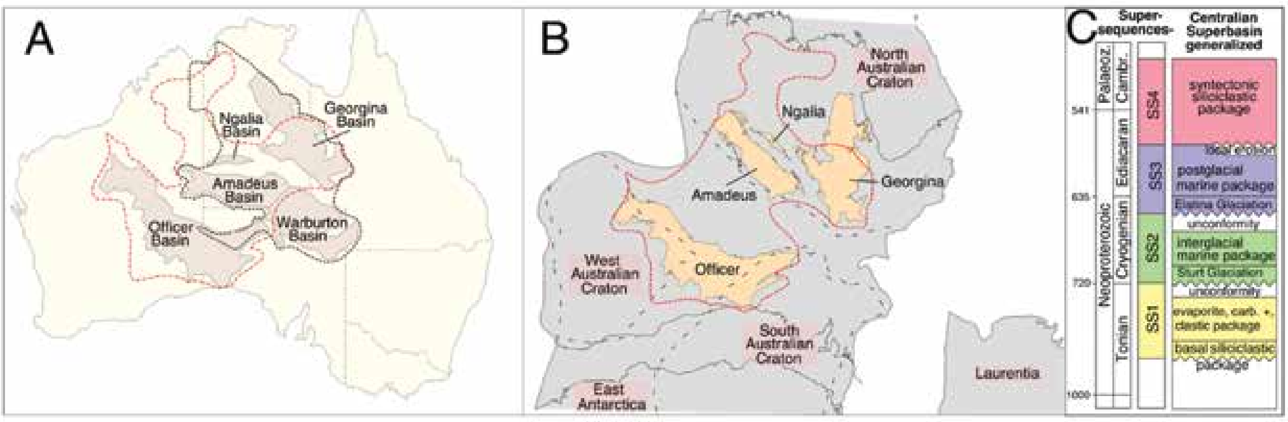

Figure 1: (A): Neoproterozoic (red) and Cambrian (black outline) extent of the Centralian Superbasin (CSB). (B): Reconstructed areas (red) and palaeogeography of CSB during Neoproterozoic (ca. 700 Ma), adapted from Lloyd et al. (2020), where grey areas denote continental crust. (C): Generalised stratigraphy of CSB from Munson et al (2013).

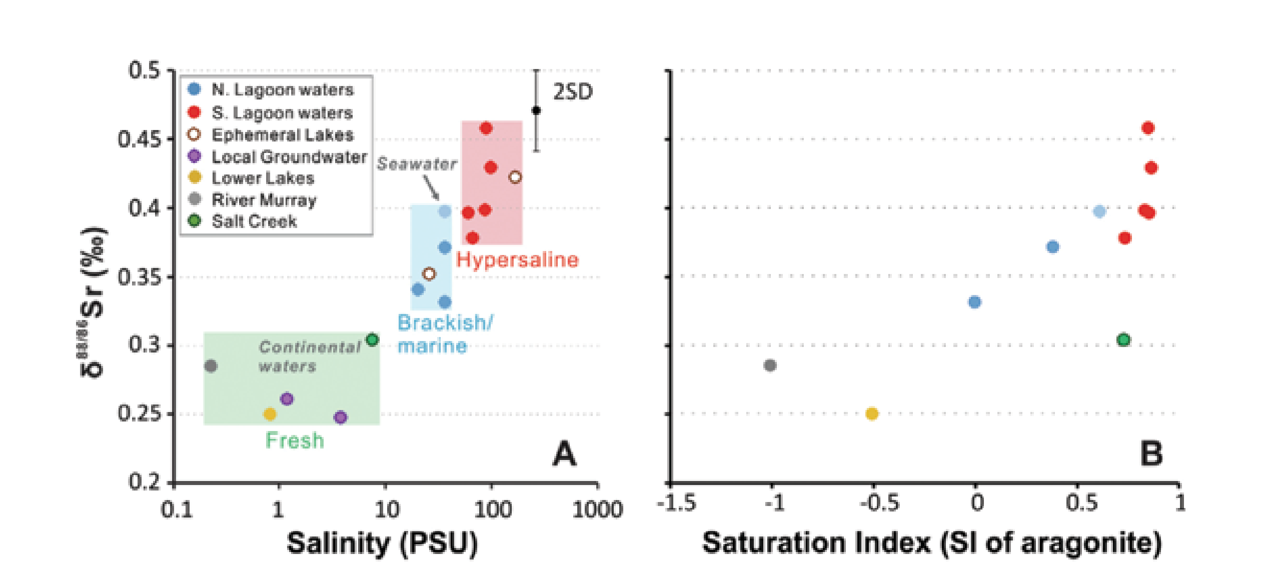

Figure 2: Stable Sr isotope variations ($\delta^{88/86}Sr$) in waters from a modern carbonate-producing coastal/marine system in South Australia, plotted as a function of (A) salinity (fresh, brackish to hypersaline) and (B) carbonate ($CaCO_3$) saturation of local waters (ranging from undersaturated to oversaturated).

The application of such a novel approach, which combines stable ($\delta^{88/86}Sr$) and radiogenic ($^{87}Sr/^{86}Sr$) strontium isotopes, measured in marine carbonate archives from the CSB could thus reveal changes in palaeo-salinity and local carbonate fluxes in the CSB or its individual depositional systems.

This is illustrated on pilot data $\delta^{88/86}Sr$ and $^{87}Sr/^{86}Sr$ from the Amadeus Basin measured in carbonates (Figure 3), including the late Tonian Bitter Springs Gr, Cryogenian Ringwood Mb, and the early Ediacaran Olympic Formation (cap carbonates).

Finally, this contribution will also introduce and present data from a new analytical approach for metal isotopes, using a TIMS-ATONA setup (a thermal ionisation mass spectrometry with a 'signal amplification' ATONA technology from IsotopX) available at the University of Adelaide (see also Yardley et al. 2020). This state-of-the-art analytical setup—the first of its kind in Australia—allows a high-precision metal isotope analysis of extremely small sample sizes (i.e., nanogram levels of metals) relevant to various applications in basin exploration and the Earth's system evolution studies. Briefly, our preliminary testing of the TIMS-ATONA system preformed on Sr isotopes confirmed that data from carbonates, silicates or waters can be measured with ultra-high precision of less than 3 ppm (2SD), corresponding to uncertainties on $^{87}Sr/^{86}Sr$ ratios of around +/- 0.000002. In addition, relatively high-precision data can be also collected from samples / loads of only few nanograms of Sr, which thus opens up new opportunities for improved Sr isotope stratigraphy (SIS) applications in the CSB, based on the TIMS-ATONA analyses of selected marine carbonate or phosphatic phases and/or suitable micro fossils (conodonts, brachiopods, etc).

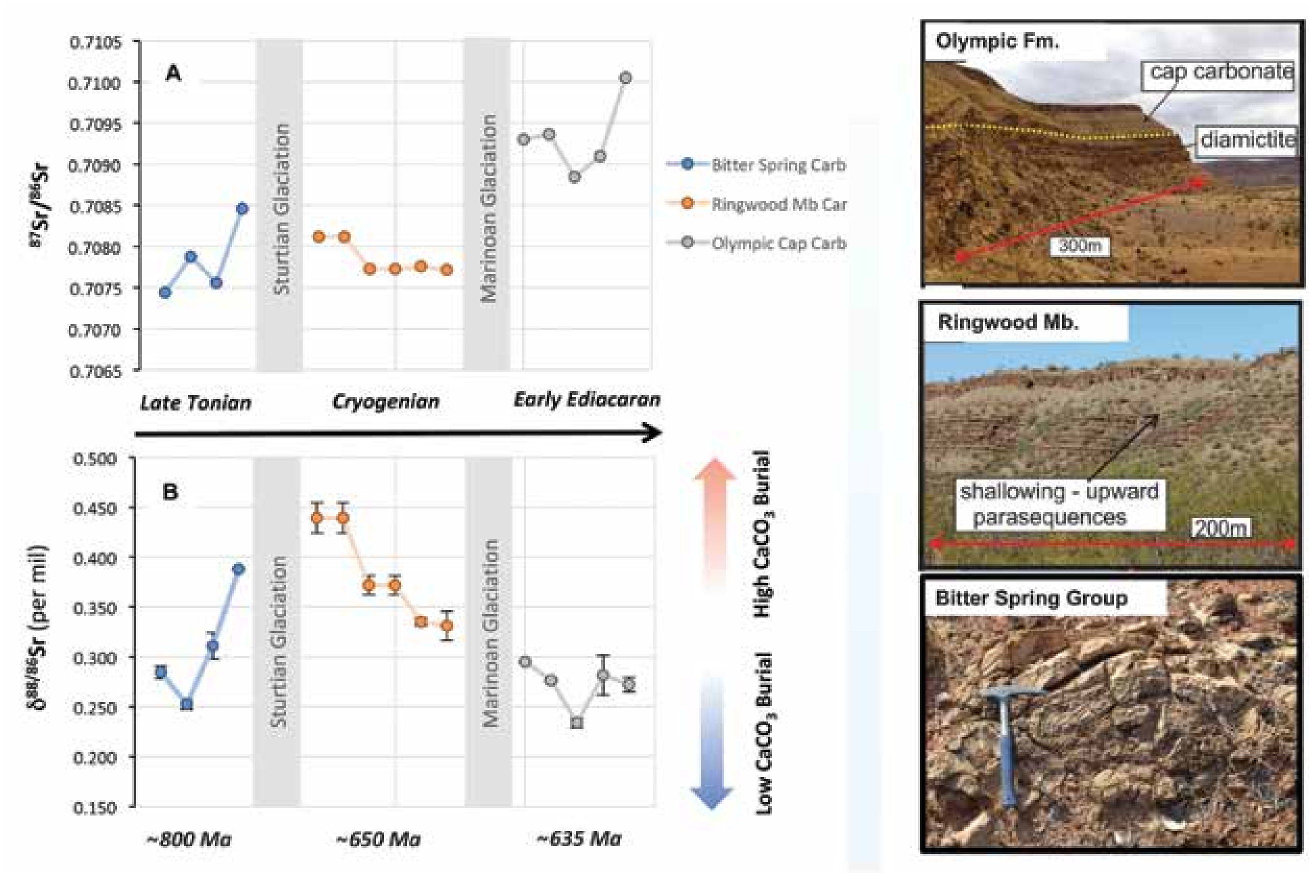

Figure 3: (A) Radiogenic $^{87}Sr/^{86}Sr$ and (B) stable $\delta^{88/86}Sr$ isotope variations in Neoproterozoic to Ediacaran sedimentary carbonates from the Amadeus Basin collected near Mount Capitor in the northeastern part of the Amadeus Basin, NT, Australia, with tentative interpretations in terms of carbonate burial fluxes, although the impact of possible palaeo-salinity changes must be also considered.

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In situ Rb–Sr dating and trace element analysis of glauconite-rich strata from the Arumbera Sandstone, Amadeus Basin

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The Rb-Sr dating technique is among the most widely used geochronological tool available in earth and planetary sciences. The method is based on the radioactive decay of 87Rb to 87Sr via a negative beta decay (the emission of an electron), with a half-life of 49.61 ± 0.16 Ga1. Traditionally rubidium-strontium dating has required the separation and acid digestion of mineral phases and/or bulk rocks, thus preventing high-resolution and micro-scale geochronology applications. Here we present results of the novel in-situ (laser-based) rubidium-strontium dating of selected mineral phases (i.e., glauconite and K-feldspar) in glauconite-rich strata of the Arumbera Sandstone from the northeast part of the Amadeus Basin in central Australia. The expected stratigraphic age of the Arumbera Sandstone ranges from latest Neoproterozoic (late Ediacaran, ~550 Ma) to early Cambrian (~520 Ma)2 based on trace fossil evidence, the local geological context and stratigraphic correlations. Detrital zircon U-Pb ages from the Arumbera Sandstone3 have a wide range, but most are 1,200–1,000 Ma, and even the youngest do not place tight constraints on depositional age.

This study employs a new in situ rubidium-strontium geochronology technique, coupled with simultaneous collection of trace-element concentration data by laser ablation tandem mass spectrometry (LA-ICP-MS/MS)4-5. Prior to analysis, the micro-scale mineralogy and petrography of the samples were characterized by backscatter electron (BSE) images and mineral maps (SEM/EDS) (Figure 1).

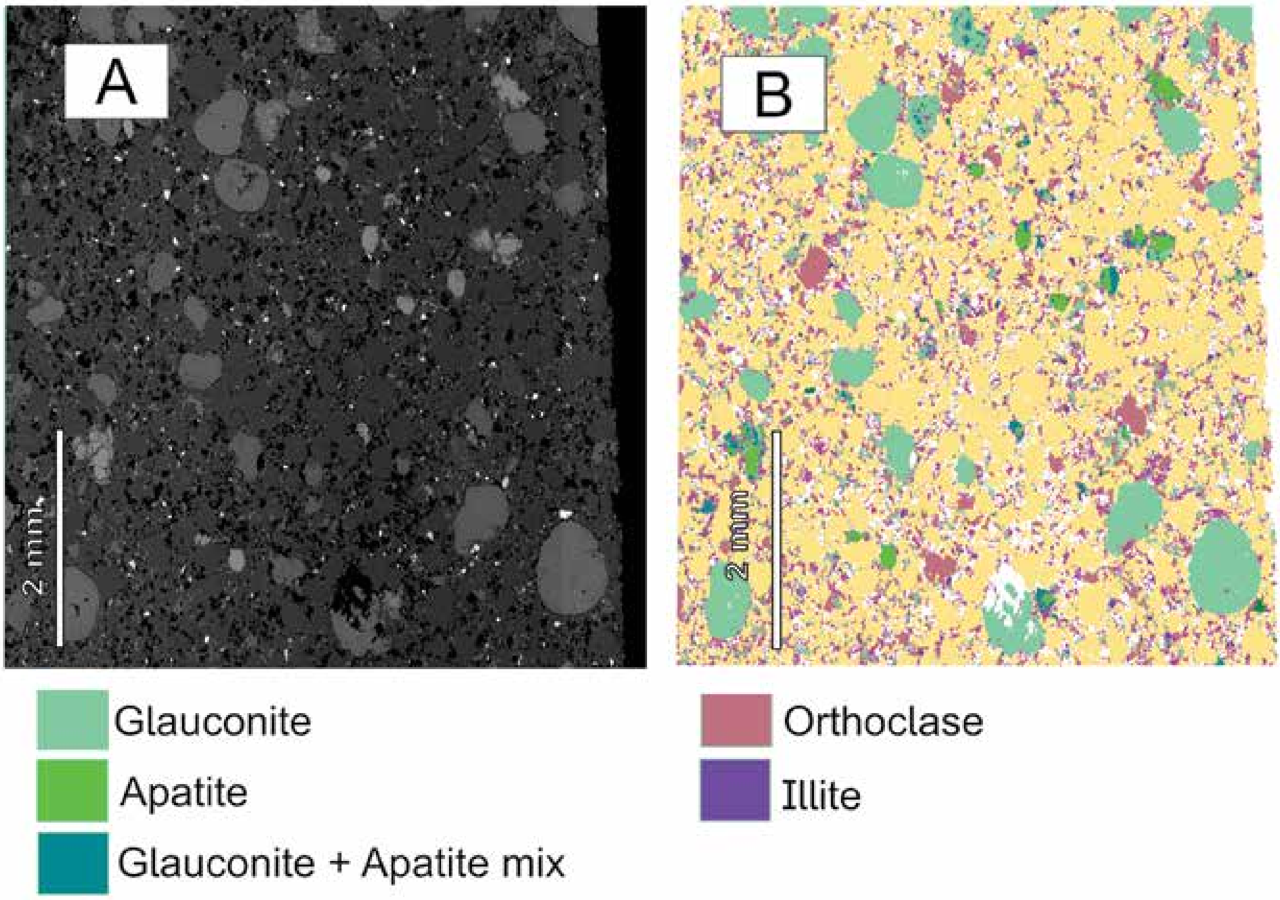

Figure 1: (A) Backscatter electron (BSE) image. (B) Mineral map (SEM/EDS) of glauconite-rich sample from Arumbera Sandstone.

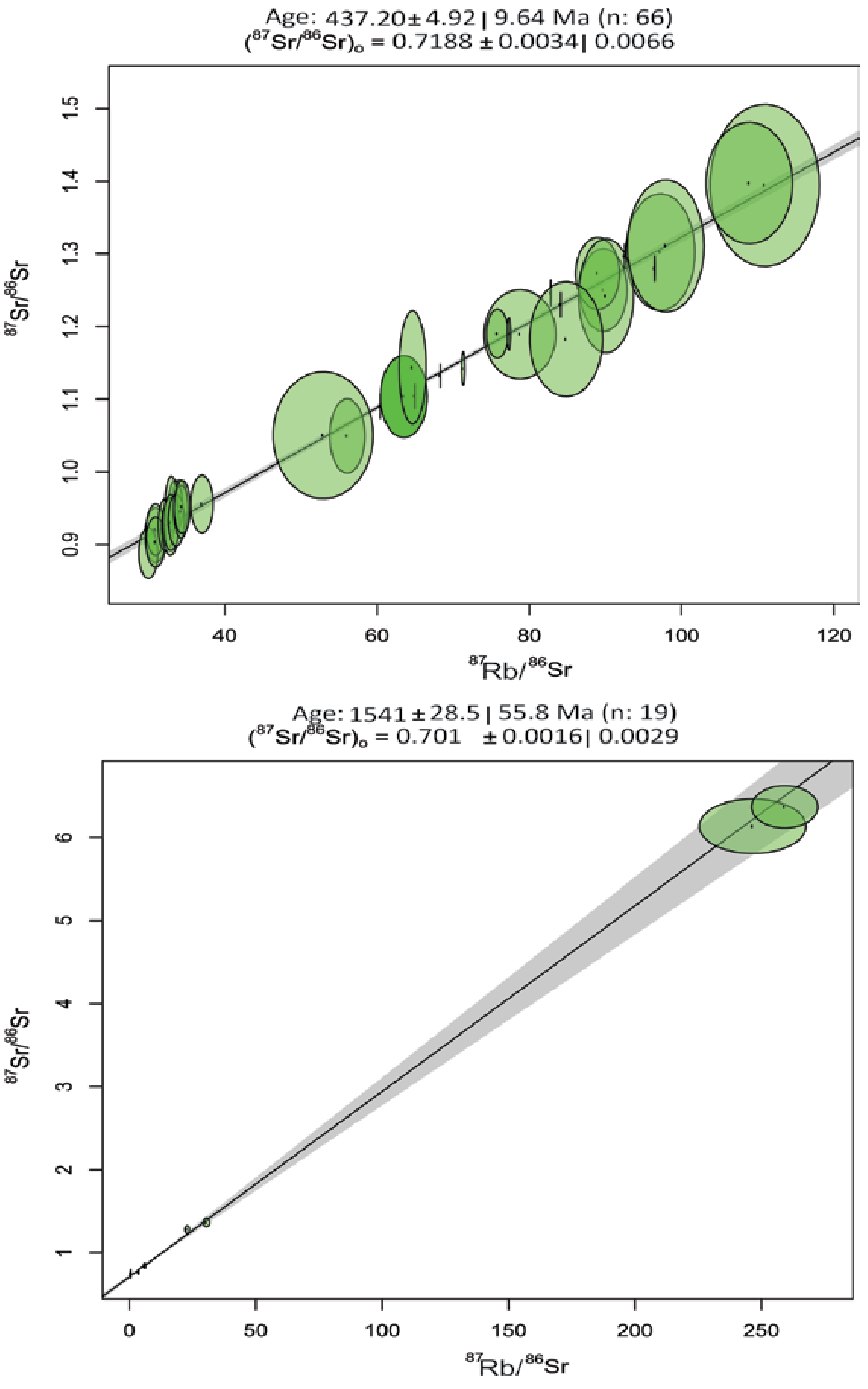

Figure 2: A - Isochron for the authigenic phases. B - Isochron for the detrital phases.

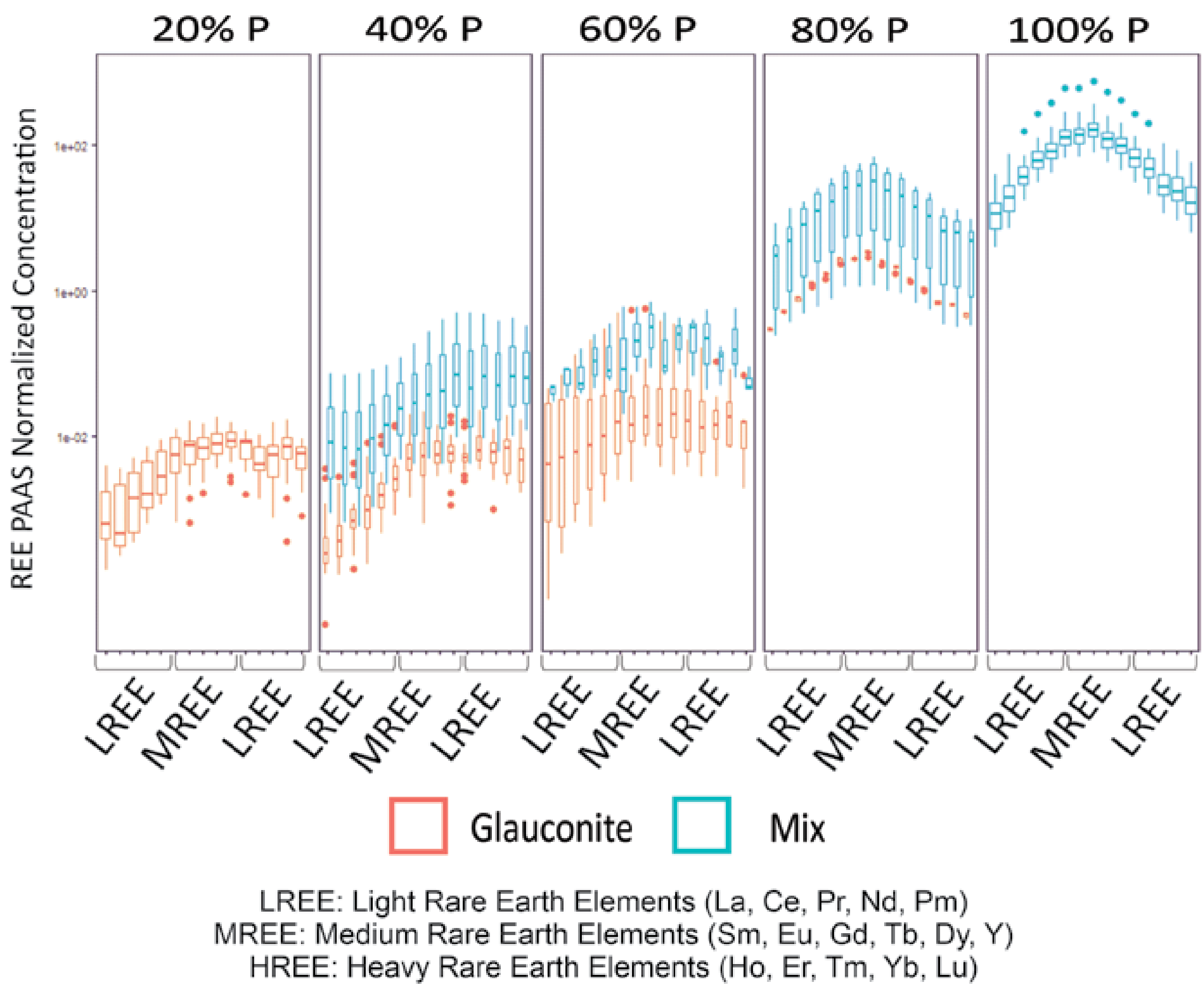

Figure 3: Rare earth element (REE) patterns normalized to PAAS. Bins corresponds to variable P content; and abbreviations LREE, MREE and HREE refer to Light, Middle and Heavy REE.

Mineral mapping reveals five main rubidium-strontium-rich mineral phases, including glauconite, apatite, 'mix' (glauconite+apatite), illite, and orthoclase (K-rich feldspar). These mineral phases were classified into two groups: (i) authigenic (comprises glauconite, apatite—plus 'mix', illite); and (ii) detrital mineral phases (orthoclase).

Isochrons were constructed using the IsoplotR package8, utilising the 87Rb decay constant reported by Villa et al., (2015)1 (Figure 2). Analysis of the authigenic phases returned an age of 437.2 ± 4.92 Ma (Figure 2.A). Although the age is younger than expected, it coincides with the early stages of the Alice Springs orogeny (450–300 Ma)2. The detrital phases returned an age of 1541 ± 28.5 Ma (Figure 2.B).

In addition, the Rare Earth Elements patterns revealed two different groupings. The apatite and mix (apatite-glauconite) mineral phases show an enrichment in middle REE (MREE in Figure 3), while the 'pure' glauconite shows a depletion in light REE (LREE), similar to documented REE patterns from marine pore waters reported by Smrzka et al. (2019)9 characteristic for an iron redox zone in marine settings. Thus, we argue that the observed REE patterns are 'primary' and record the palaeo-redox conditions during the deposition of the Arumbera Sandstones and associated formation of early diagenetic glauconites and apatites within a sediment-water interface in a late Ediacaran/early Cambrian oceans.

Overall, the results from this study illustrate the potential of novel in-situ Rb–Sr geochronology to date post-depositional events, which can be done quickly, efficiently, and with minimum sample preparation. Such data from both authigenic and detrital phases can yield not only age constraints on the deposition of sedimentary rocks and/or provenance of detrital components, but also on the timing and history of subsequent diagenetic and post-depositional events.

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The Lucas Outlier: a Western Australian update

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The Lucas Outlier was previously interpreted as an outlying component of the Canning Basin that crossed the Western Australian border into the Northern Territory (Hocking, 1994). Recent fieldwork and detrital geochronology (Wingate et al., 2021) now suggest a much older age for the lowest and dominant component of the Lucas Outlier than previously thought, suggesting a closer relationship with the underlying Murraba Basin, a component of the Centralian Superbasin.

The Lucas Outlier is oriented east–west, extends about 80 by 160 km, and spans the NT–WA border (Fig. 1). With limited outcrop on either side of the border, 75% of the aerial extent of the Lucas Outlier is in the NT, primarily in the southwest portion of THE GRANITES 1:250,000 map sheet and also in the northwest corner of the HIGHLAND ROCKS map sheet. The WA extent is confined to the southeast and northeast corners of the LUCAS and STANSMORE 1:250,000 map sheets, respectively.

The Lucas Outlier consists of the fluvial–lacustrine Lucas Formation (Blake et al., 1979) and the unconformably overlying Pedestal beds (Blake et al., 1976). The Lucas Formation type section is located in WA on the eastern edge of Lake Dennis, 7.2 km from the NT border and is named after Lake Lucas, whereas the Pedestal beds reference area is in the NT, named after the Pedestal Hills in THE GRANITES map sheet (Fig. 1). Recent work is restricted to the Lucas Formation in WA only.

Early work by the Bureau of Mineral Resources (BMR) in the 1960s and 70s provided the framework for the stratigraphy of the Tanami Region. An extensive shallow stratigraphic drilling program from 1971 to 1974 assisted in geological mapping of the Lucas Outlier and surrounding areas (Blake, 1974; Blake et al., 1976; 1979). The Lucas Formation has been inferred to unconformably overlie the Redcliff Pound Group (Fig. 2) (Blake et al., 1979), which has recently been redefined to include only the Murraba Formation and Erica Sandstone of the Murraba Basin (Haines and Allen, 2017). The upper boundary of the Lucas Formation is a low-angle unconformity with the overlying Pedestal beds (Blake et al., 1979), which are confirmed to be Paleozoic in age due to their position on top of the Cambrian Antrim Plateau Volcanics (Glass et al., 2013; Marshal et al., 2018). The Lucas Formation was previously correlated with the 286–273 Ma Noonkanbah Formation of the Canning Basin based on similar lithology, photo-pattern and structural expression (Casey and Wells, 1964) and later correlated with the Devonian Pertnjara Group (Blake et al., 1979) of the NT part of the Amadeus Basin (Wells et al., 1970; Jones, 1991). However, no definitive fossils have been identified in outcrop or drill core samples from the Lucas Formation and the only supporting evidence for a Paleozoic age has been an unidentifiable spore and several microscopic spheres of unknown affinity from core samples in BMR The Granites 2 and/or 3 in the NT (Blake, 1974; Blake et al., 1979).

The Lucas Formation consists mainly of purple to grey, fine- to medium-grained, friable calcareous sandstone, medium- to coarse-grained non-calcareous sandstone (lithic to sublithic arenite), and thin-bedded to laminated siltstone and mudstone, with local thin limestone beds and sandy dolomite (Casey and Wells, 1964; Blake et al., 1979). Sample GSWA 237932, from the base of the Lucas Formation type section, provided 215 detrital zircon analyses, yielding a detailed age spectrum, a youngest zircon at 599 ± 4 Ma (1σ), and a conservative maximum depositional age of 974 ± 10 Ma (Wingate, et al., 2021). The age spectrum closely resembles those for samples from the upper Redcliff Pound Group and the Lewis Range Sandstone (Fig. 3), tentatively extending the Murraba Basin to include the Lucas Formation.

New paleocurrent data for the Lucas Formation, collected in the Canning Basin indicates a south- to southeast-directed paleoflow, which is also consistent with such data from the deltaic facies of the upper Murraba Basin. Additional palynology of available cores will be required to ascertain the significance of the previously unidentifiable spore of Blake (1974).

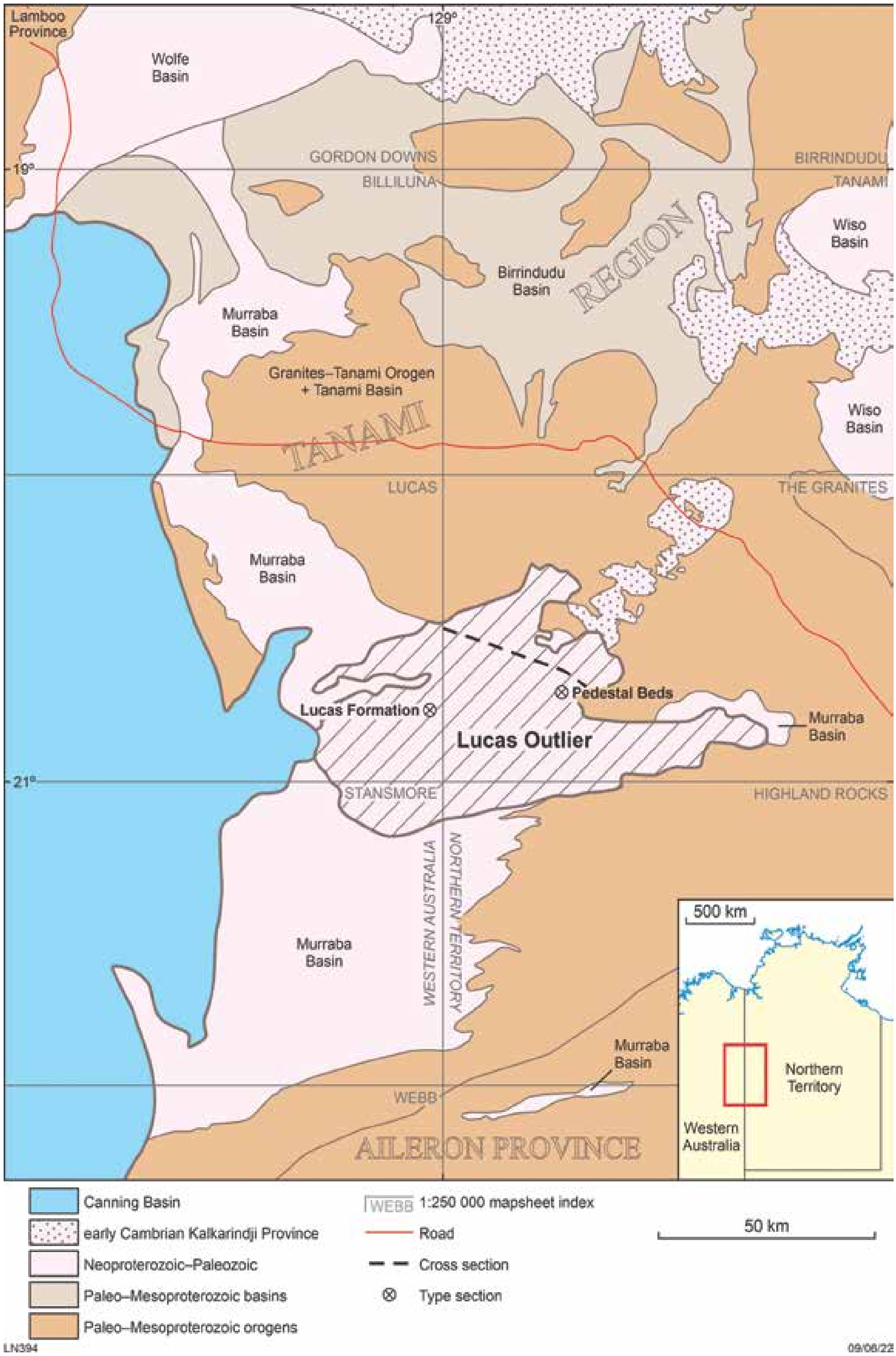

Figure 1: Regional map of the Lucas Outlier across the Northern Territory – Western Australia border, showing locations of type section for the Lucas Formation (WA: 20° 56'S, 128° 50'E) and the reference area for the Pedestal beds (NT: 20° 35'S, 129° 17'E)

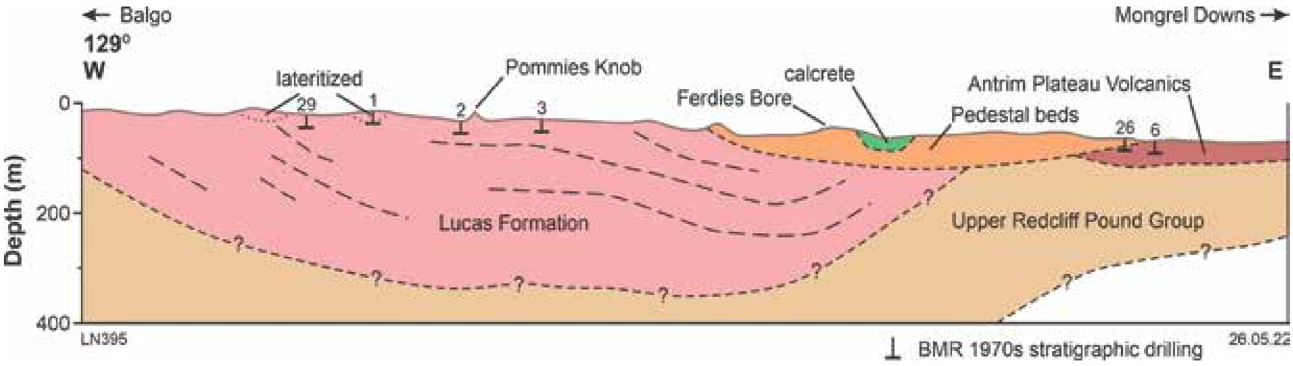

Figure 2: Cross section showing stratigraphic relationship of Redcliff Pound Group, Lucas Formation, Pedestal beds and Antrim Plateau Volcanics

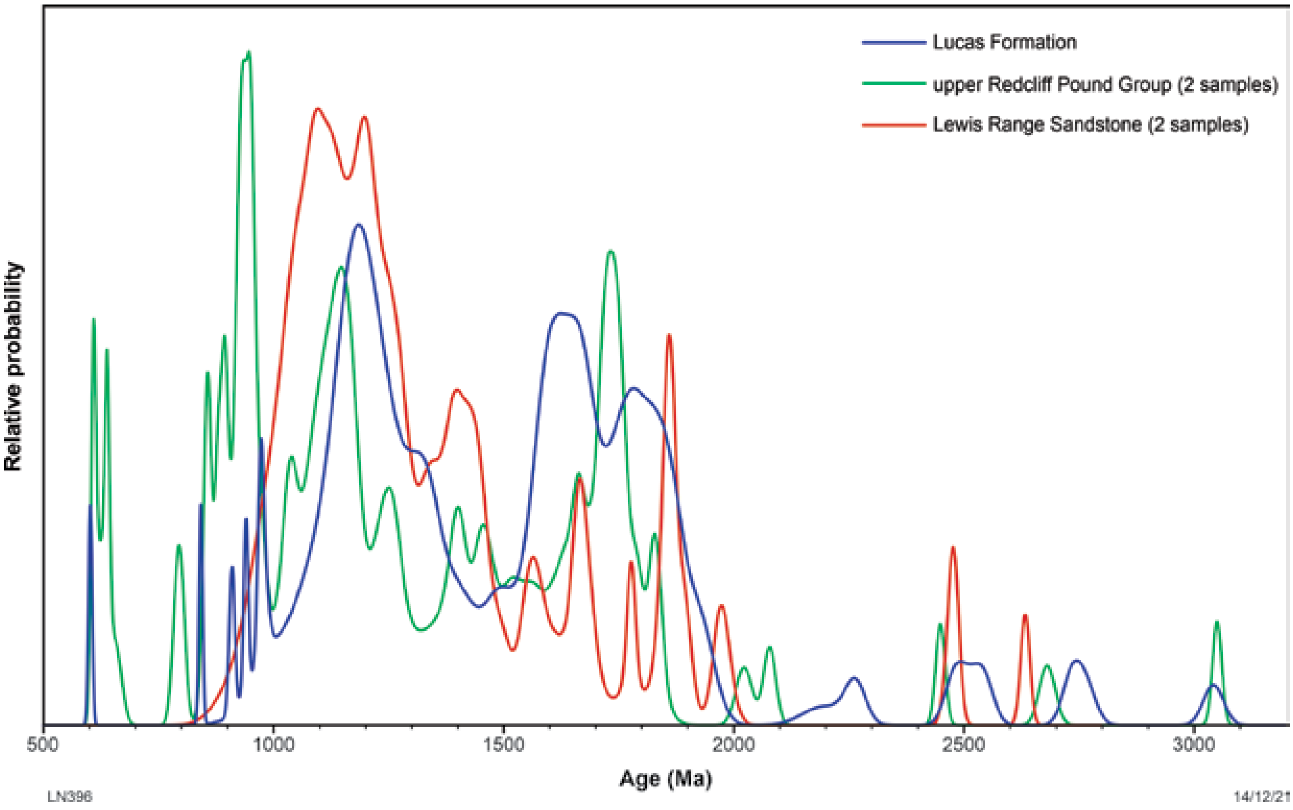

Figure 3: Detrital zircon age spectra for samples of the Lucas Formation (GSWA 237932), upper Redcliff Pound Group (GSWA 220004 and 220005, Wingate et al., 2022a,b) and Lewis Range Sandstone (GSWA 178851 and 178852; Wingate et al., 2008a,b)

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Combining the strength of Petroleum and Mineral System knowledge to advance exploration within the Critical Mineral space

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Both the petroleum and mineral industries have relied on proven methods when exploring for economic deposits. All methods have their origins in a deep understanding in geological principles, so it's no surprise that there are many analogous processes employed across both industries. A significant difference is "where" in the earth's crust the commodity of interest is accumulated and extracted. Economic recovery of any resource drives "how" explorers go about finding the commodity of interest and what tools they employ in their search.

This presentation focusses on the "how" of exploration; the similarities and differences between the two industries. Some suggestions are offered as to how we can cross-fertilise with ideas and applied methods of data acquisition.

The Systems Approach (Fig 1.), whether that is Mineral Systems or Petroleum Systems, is considered best practice and can be applied to the process of quantifying chance of success or conversely, risk.

In petroleum exploration, where the prospectivity of any accumulation is relatively deep in the Earth's crust (>2 km) and subsequently, expensive to find, understanding its size and chance of occurrence is at the forefront of the exploration process. Every activity in the process from thereon in is focussed on understanding the uncertainty around quantifying the resource. Typically, when exploring for a mineral deposit, a more pragmatic model-based, and data-driven approach is used in exploration programs.

The concept of abstraction is evoked here to explain why the industries behave and think in different ways in the exploration phase. The level of abstraction in the petroleum industry is higher due to the depth of target and its heavy reliance on geophysical modelled data like seismic. Whereas the converse is true in the search for minerals where more "touch, taste and see" information is possible. Mineral deposits are typically extracted from closer to the surface of the earth, therefore there are fewer levels of abstraction to consider. However, with the shift from near surface to deeper targets in the minerals industry, including exploration for base metals in sedimentary basins, mineral exploration has a new challenge on its hands and there is emerging opportunity for cross-pollination of ideas, data and knowledge across the sectors.

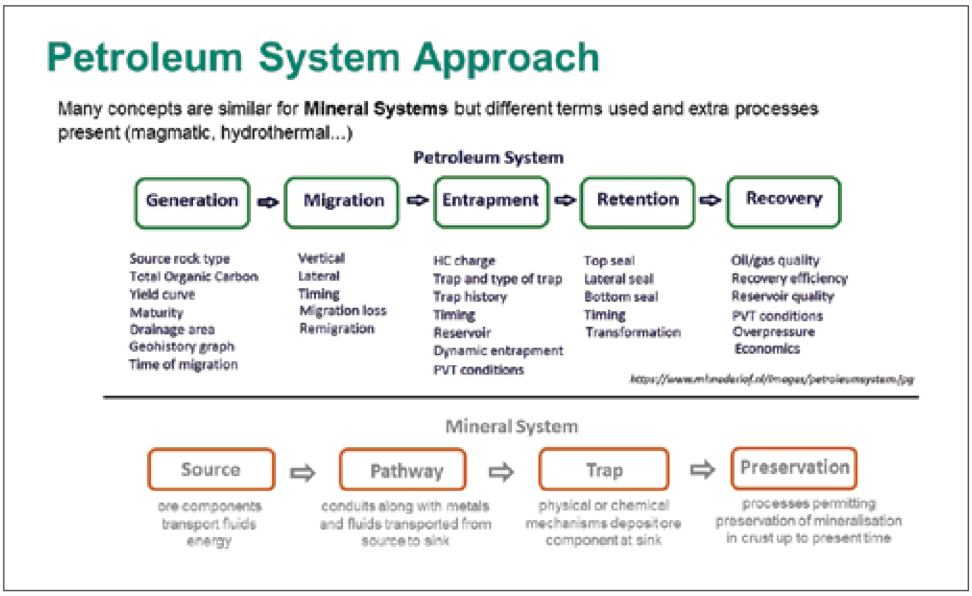

Figure 1: The Systems Approach

Nevertheless, each can learn from one another and provide insight from technologies typically used. Interest in mineral commodities, required for a sustainable clean energy future, such as copper in sedimentary basins, the global appetite for critical minerals and search for natural hydrogen, provide the opportunity for cross-over techniques common-place in the petroleum and minerals industries. These include but are not restricted to:

- A play-based approach, where each risk factor is investigated in a regional way and stacked on top of each other in a GIS platform, or map. The areas of greater exploration interest can then be delineated where each factor simultaneously occurs, and the risk of occurrence quantified
- Sequence stratigraphy approach: Mapping major sequence boundaries and deepening understanding of sedimentary depositional environments over geological time, can assist with identifying more prospective reservoir/seal couplets in which minerals may have been deposited and retained e.g., sedimentary copper and cobalt, critical minerals associated with oil shales
- Drilling technologies, such as coil tube drilling, can be adapted for mineral exploration so that drilling speed can increase without sacrificing the need for core acquisition e.g., Mineral Exploration CRC, Deep Exploration Technologies CRC
- Downhole data such as drill cuttings and petrophysical logs, acquired in the top-hole section of a petroleum well drilled in a sedimentary basin could be further investigated for their mineral potential; and its possible that with cross-industry collaboration more data could be acquired in future drilling programs
- Seismic data, designed for mid-depth investigation for petroleum targets, could be reprocessed or even acquired differently to image deeper lithospheric structures or shallower mineral targets
- Deep geophysical techniques commonly used to understand source and pathways for mineral deposition such as magneto-telluric, gravity and magnetic surveys could also be used more comprehensively in petroleum exploration, thereby improving understanding of structures, migration pathways and traps
- Use of spectral geology techniques provide high resolution mineral mapping of core and drill cuttings, which could provide considerable insight to the petroleum industry such as to inform top and fault seal competency or geomechanical behaviour of fracture stimulation targets
- Identification of salt diapirism (seal) and its association with iron-rich lithologies or alteration systems (source) may offer future targets for natural hydrogen, which will require the utilisation of both a minerals and petroleum exploration mind-set

The Geological Survey of SA, in conjunction with its research partners, is currently implementing multiple precompetitive projects testing new technologies and deep geophysical techniques, whilst also focussing on applying a sequence stratigraphic framework for the search for sedimentary copper in South Australia's basin areas and providing datasets to positively impact and de-risk future mineral exploration thereby supporting new discoveries.

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Base Metal Mineralisation of the Rover Field, Northern Territory

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The Warramunga Province of the Palaeoproterozoic North Australian Craton, in the central Northern Territory, represents a prospective terrane for mineral exploration. A well-known example is the Tennant Creek mineral field, which has a rich history of gold, copper, bismuth, silver, and selenium production. Some 80 km southwest of the Tennant Creek mineral field is the entirely undercover Rover field (Figure 1), which hosts base and precious metal deposits with established mineral resources (JORC). Despite this, the geological framework, nature and timing of mineral systems remains poorly understood.

This study determined that the Rover field is composed of three zones (northern, central and western), each hosting a different mineral system (Figure 2). The northern zone is dominated by coherent mafic and andesitic volcanic rocks that cause positive gravity anomalies. In this zone, the Bluebush basalt has an enriched mid-oceanic-ridge-basalt (E-MORB) composition, positive εNd(t) and Paleoproterozoic two-stage depleted mantle model ages (TDM2) that range between 2.22–2.12 Ga (whole-rock Sm–Nd; Farias et al 2022a). This basalt hosts 1758 ± 78 Ma minor orthomagmatic copper–nickel mineralisation (apatite U–Pb age; Farias et al 2022). The central zone is dominated by 1850–1840 Ma intermediate to felsic coherent volcanic and volcaniclastic rocks that were reworked from a homogeneous evolved Archean crust (negative εNd(t) with TDM2 ranging 2.58–2.50 Ga). The central zone hosts copper–gold deposits with similar characteristics to the deposits of the Tennant Creek mineral field and is characterised by mottled and striped east–west trending magnetic anomalies caused by magnetite-rich horizons (Farias et al 2022a).

The western zone, the focus of this contribution, is separated from the rest of the Rover field by a noticeable change in the basement gravity, magnetic and magnetotelluric signatures (Figure 2). The volcanic rocks of the western zone are derived from the same Archean crust than the central zone, but unlike the other zones, the western zone is dominated by fractionated volcaniclastic and siliciclastic rocks that host base metal mineralisation (Explorer 108 deposit and Curiosity prospect). The maximum depositional ages for different sections of the hosting sequence varies between ca 1850–1840 Ma (Huston et al 2020, Cross et al 2021, Cross et al 2022), and is interpreted to be part of the Ooradidgee Group, more specifically the Yungkulungu Formation (Huston et al 2020, Cross et al 2021, Farias et al 2022). This sequence is younger than the neighbouring ca. 1860 Ma Warramunga Formation that hosts the gold–copper deposits of the Tennant Creek mineral field (Fraser et al 2008, Maidment et al 2013).

We found that the base metal mineralisation in Rover field shares characteristics with volcanic-hosted massive sulfide (VHMS) deposits (Large 1992 for Australian deposits, and Ohmoto (1996) for generic descriptions). Volcanic hosted massive sulfide (VHMS) deposits, also known as volcanogenic massive sulfide (VMS) deposits, are mostly sub-aqueous, volcanic-related mineral systems that form in extensional and transtensional tectonic settings [(mid-ocean ridges, back-arc basins, intra-oceanic arc rifts, and continental arc rifts, Piercey et al (2010)]. These deposits are major sources of zinc, copper, lead, silver and gold, and significant sources of other critical metals. They typically occur as multiple lenses of polymetallic massive sulfides that form at or near the seafloor in submarine volcanic environments and form clusters at district scale (Galley et al 2007). Typically, VHMS deposits are formed during a hiatus in sedimentation in the sediment–water interface (for a purely syngenetic model), or in the early stages of diagenesis when the hanging wall rocks are being deposited (for an epigenetic model). The VHMS systems associated with post-Archean felsic or bimodal volcanism (like in Rover field) are hosted volcanic and volcaniclastic sequences enriched in high field strength elements (HFSE) and HREE. These compositions reflect mid to shallow-crustal melting depth (where garnet is not stable) and high temperature magmatism typical of rifting (Hollis et al 2015).

The fluids associated with mineralisation in Explorer 108 were oxidised, low-salinity with homogenisation temperatures of ~210°C. Sulfide δ34S data from Explorer 108 yielded narrow ranges of ~10‰, typical of Proterozoic volcanogenic massive sulfides (Huston 1999). Pervasive alteration of volcanic rocks that host base metal mineralisation suggests sulfur was sourced/leached from the volcanic rocks and not from seawater sulfate reduction. In situ apatite U–Pb geochronology indicates the base metal mineralisation and/or remobilisation occurred at ca 1.74–1.73 Ga. The large uncertainties on the apatite ages, precludes unambiguous resolution of epigenetic or syngenetic mineralisation. Some lines of evidence suggest a syngenetic origin (eg mineralisation associated with exhalative horizons, separating a footwall sequence from a different hanging wall volcanic sequence); others suggest an epigenetic origin (eg large alteration footprint on the hanging wall sequence and mineralisation locally remobilised after shearing). We favour a syngenetic origin with later (epigenetic) modification from structural reactivation and hydrothermal fluid flow revival. We argue that the western zone felsic volcanism and mineralisation took place in a sub-basin modulated by a dextral transtensional regime (Figure 3) after the ca 1.76 Ga juvenile magmatism of the norther zone. Base metal mineralisation in the Rover field western zone is comparable to the magnetite-rich, volcanic-hosted massive sulfide system of the Archaean Gossan Hill deposit in the Yilgarn Craton (Sharpe and Gemmell 2002).

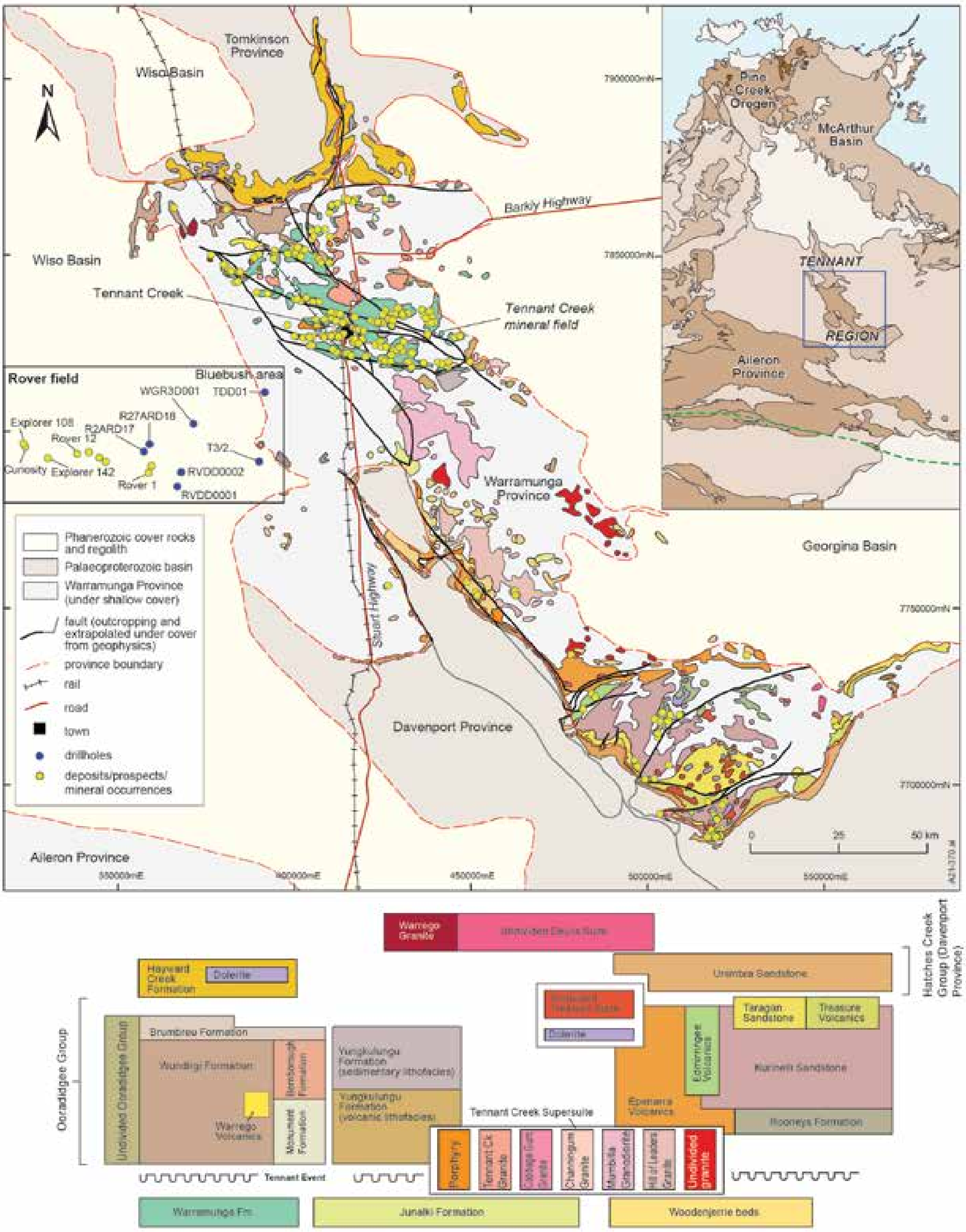

Figure 1: Generalised geology map of the Warramunga Province, modified after Donnellan (2013). Map shows location of the Rover field and drillholes in relation with the Tennant Creek mineral field.

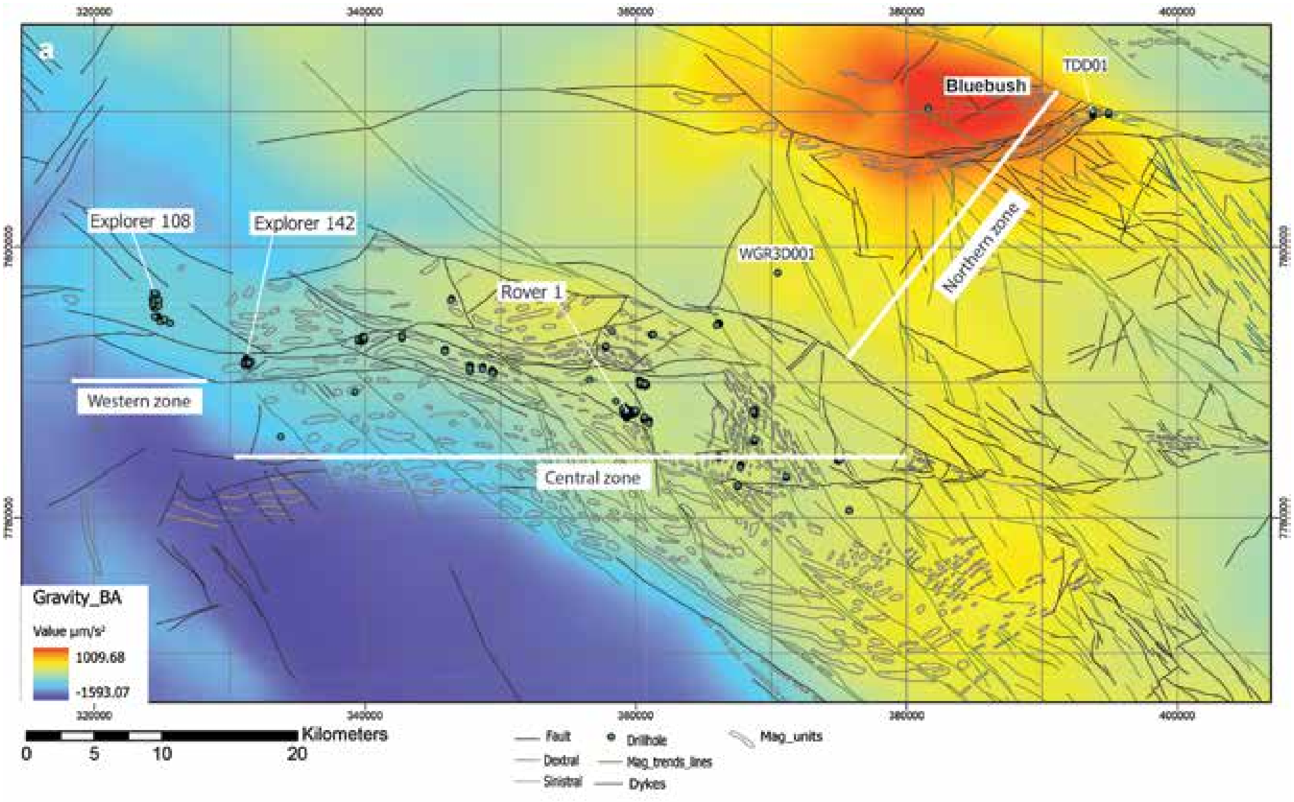

Figure 2: (a) Bouguer anomaly.

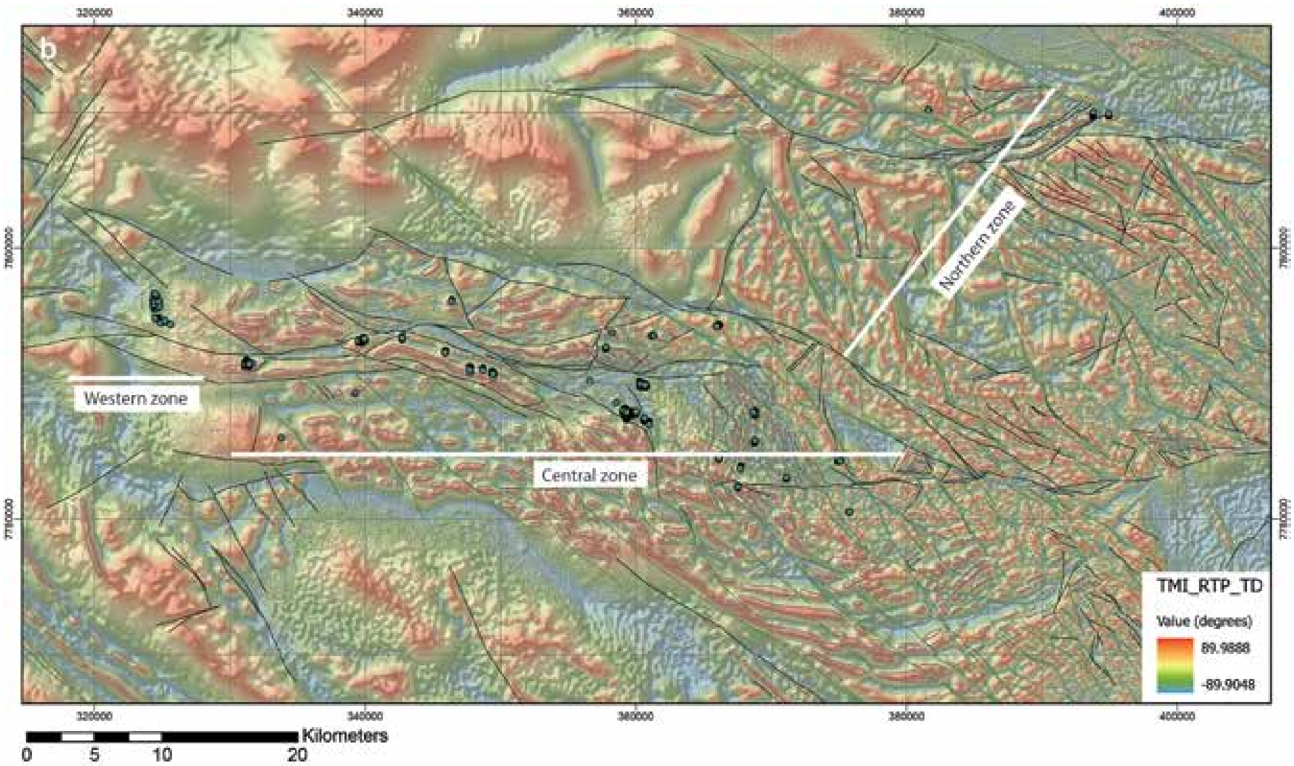

Figure 2: (b) Total magnetic intensity, reduced-to-pole tilt derivative image.

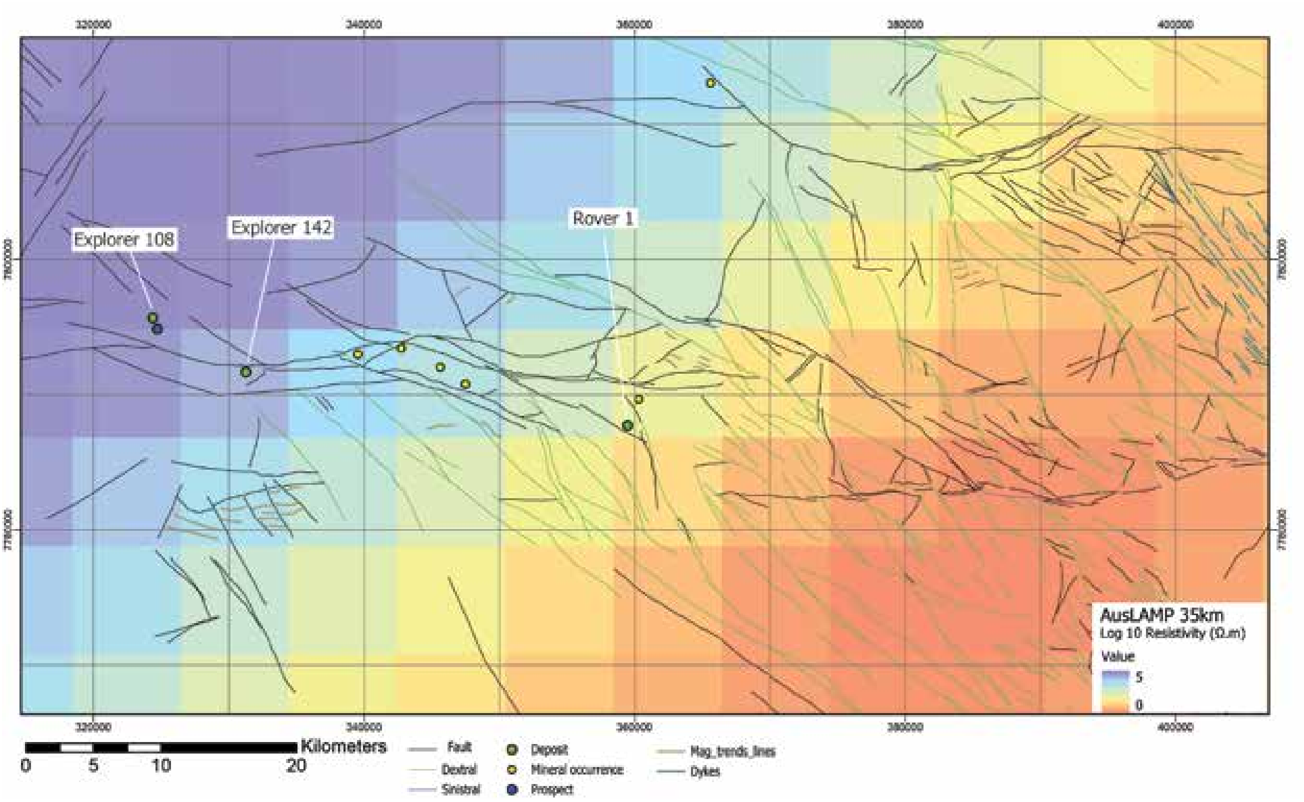

Figure 2: (c) Resistivity map of the Rover field with interpreted zones.

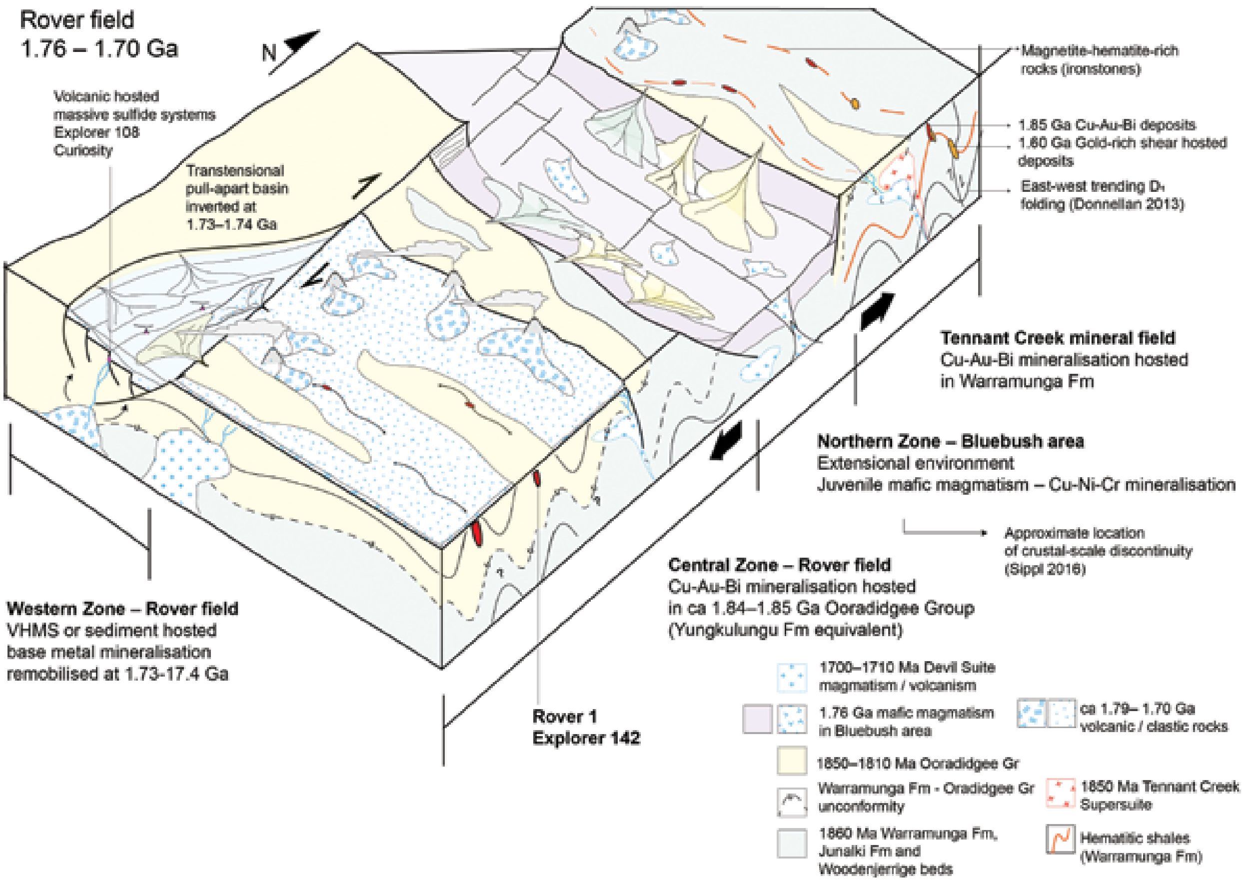

Figure 3: Schematic block diagram of the Rover field and Tennant Creek mineral field areas during the proposed extensional setting during the 1.70–1.76 Ga period.

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Natural Hydrogen and Helium Gas Exploration in the Amadeus Basin

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As the world transitions to a low carbon future and global helium consumption grows, the Amadeus Basin is emerging as a prime location for high helium and natural hydrogen gas exploration. With a regionally extensive evaporite seal, and significant hydrogen and helium identified in sub-evaporite gases, the Amadeus Basin has potential to be one of the world's premier provinces for naturally occurring hydrogen and helium production. Gas compositions from the Mt Kitty 1 well indicate >11% hydrogen and 9% helium (very high concentrations by global standards), with 6% helium also encountered in the Magee 1 well. These two exploration wells (Figure 1) are also the only Amadeus Basin wells that have penetrated the Heavitree Formation and basement beneath the Gillen Formation evaporites (Figure 2).

The main elements of the proven Tonian-aged helium/hydrogen play in terms of current understanding are summarised in following paragraphs and in the series of maps shown in Figure 3. Although a potential extension of the play into suitable shallower parts of the overlying basin stratigraphy is recognised, this would require unusual circumstances, so for the sake of brevity is not discussed in the current presentation.

Helium isotope studies interpret a crustal origin for the helium in the Mt Kitty 1 well, which suggests that the source of the helium is long term release of radiogenic 4He from uranium and thorium bearing minerals within the fractured granitic basement, as was intersected at the base of the well. Helium migration is thought to have occurred in two stages. Phase 1 is dependent on the mass ratio of solid to fluid, which governs the fluid's ability to provide a suitable sink for any noble gas. The preferential movement from solid to fluid phase will continue until equilibrium is achieved. Carrier gases (nitrogen and methane) are critical for Phase 2 migration from the granite source rock.

Several possible sources for the natural hydrogen encountered in Mt Kitty 1 have been considered. However, given the association of helium and hydrogen and the paucity of ultra-mafic minerals in basement rocks, water radiolysis is considered the most likely source of hydrogen at this stage. Potential fields interpretation, calibrated by wells and outcrop geology from the orogenic uplifts that surround the basin, indicate that the underlying basement terrane (Figure 3) likely comprises felsic amphibolite to granulite facies metamorphic rocks hosting widespread granitoid intrusions (Aitken & Betts, 2008; FrogTECH, 2015;

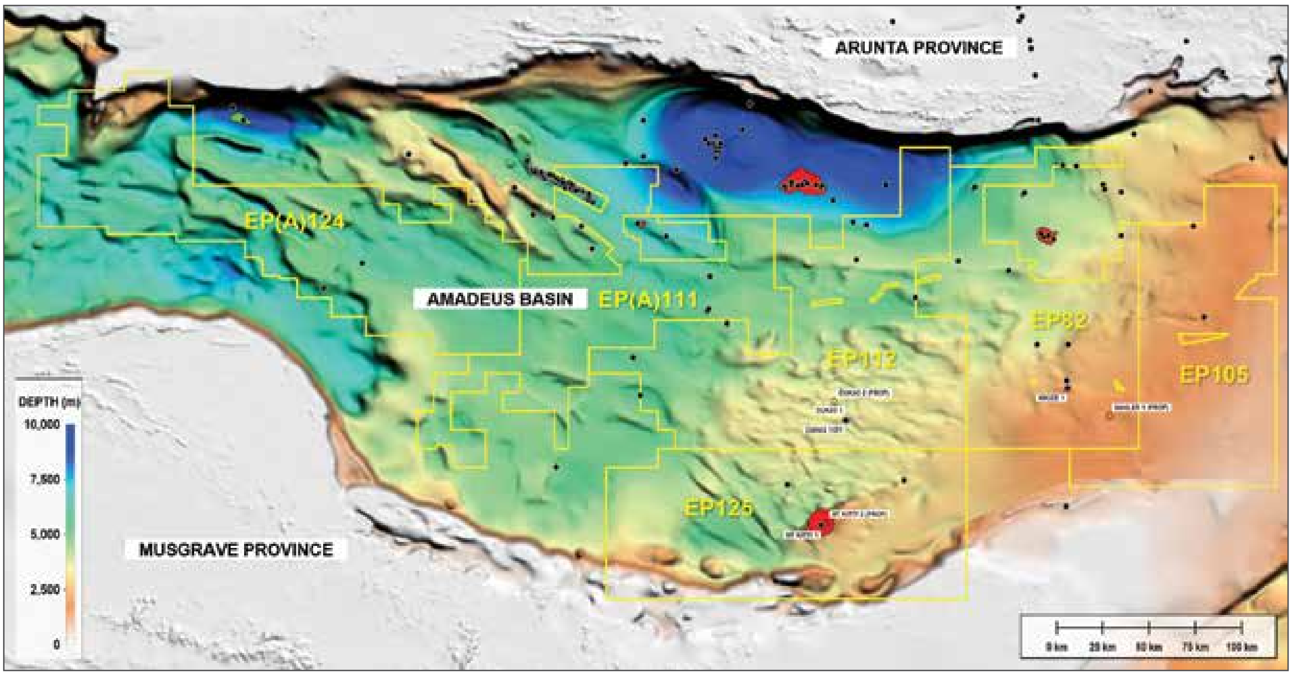

Figure 1: Location map of the Amadeus Basin showing Santos permits and borehole locations. Underlying image is FrogTECH Seebase depth to basement from potential fields interpretation. Current Santos exploration activities are focussed in the south-east of the basin.

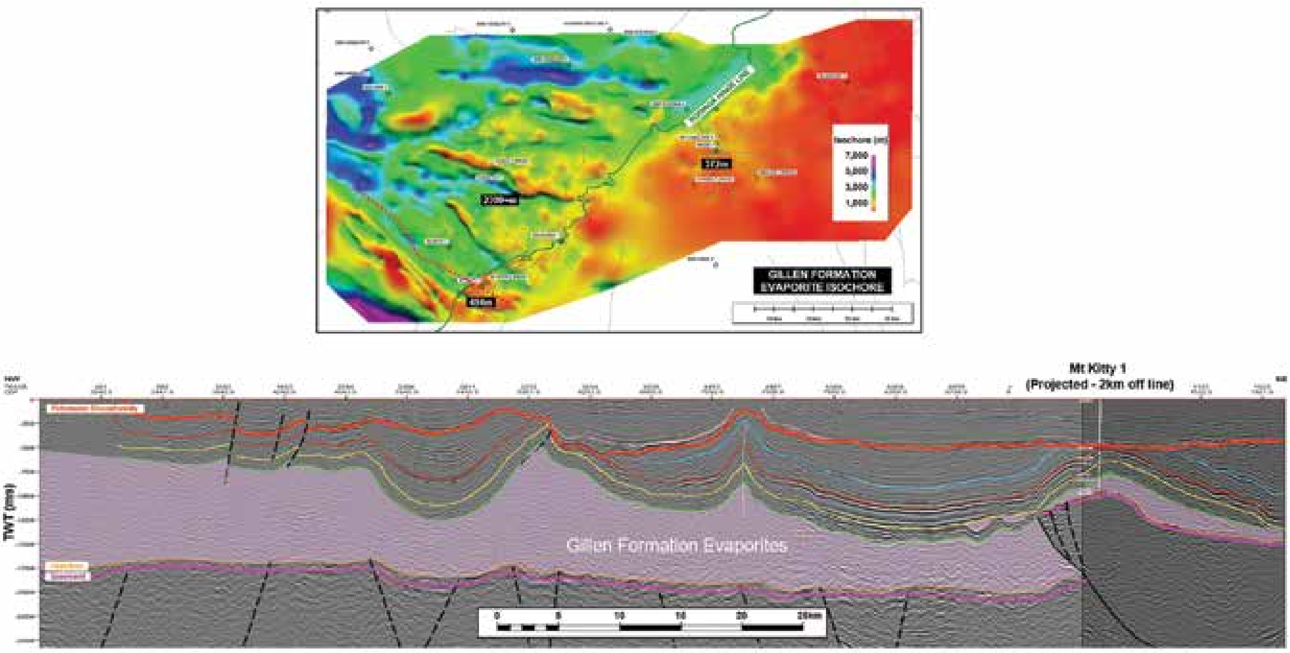

Figure 2: Interpreted seismic line showing influence of thrust tectonics and halokinesis on stratal configurations in proven south-east area of play. Evaporites represent the seal, while both crystalline basement (magenta horizon) and Heavitree Fm (orange horizon closely shadowing basement) provide reservoir targets. Line location indicated by dotted red line on isochore map of Bitter Springs evaporites.

Schmid et al., 2016; Geognostics, 2021). Recent U–P SHRIMP zircon geochronological results by Northern Territory Geological Survey (Kositcin et al., 2022), derived from igneous and meta-igneous rock samples of crystalline basement from Mt Kitty 1 and Magee 1, reveal a bimodal age clustering of circa 1600Ma and 1170Ma. Both ages are typical of basement rocks that outcrop in the Musgrave Province south of the basin (Figures 1 and 3), with the older relating to the Musgravian gneiss protolith and the younger derived from widespread Pitjantjatjara Supersuite granitoids that intrude the gneisses (Edgoose et al., 2004; Aitken & Betts, 2008). Further afield, the regional geology indicates that the Amadeus basement terranes probably represent a north-east extension of the Albany-Fraser Orogen (AFO) and Coompana Province, situated to the south-west of the Musgrave Province. These terranes show a similar Palaeo- to Mesoproterozoic age range and tectonic significance, interpreted to represent an ancient mobile belt suturing the North, West, and South Australian cratons.

A less likely radioactive source for the gasses may be from an arenaceous clastic interval overlying basement. An obvious candidate would be the Heavitree Formation, which could contain widespread feldspar detritus in itself sourced from basement. Alternatively, a similar role could be played by an unnamed, non-magnetic sedimentary interval (Figure 3) that has been identified in various potential fields studies of the Amadeus Basin to occur between seismically mapped crystalline basement and magnetic basement derived from potential fields interpretation (FrogTECH, 2015; Schmid et al., 2016; Geognostics, 2021).

In terms of reservoir storage and gas migration pathways, all proposed candidate reservoirs would benefit from the presence of pervasive fracture networks, implying a vital component of tectonic structuration. Fractures have been shown to be present in both wells that have intersected these reservoirs in the basin thus far i.e., Mt Kitty 1 and Magee 1 (Figures 1 and 2). As suggested by the regional basement compositional variations interpreted from potential fields data (Figure 3), some variation in the felsic crystalline basement lithologies is also seen in the wells. While Mt Kitty 1 penetrated a granitoid, Magee 1 drilled into mixed metamorphic rock types, including both felsic gneiss and biotite schist. Theoretically, these lithologies may be expected to develop different kinds of fracture systems under stress, being better developed in the more brittle lithologies like granite, and less so in the gneisses and schists. Like the granites, the perceived brittleness of the Heavitree Formation (quartz arenite at Magee 1) may also promote favourable fracture development.

There are multiple tectonic events that may be responsible for fracture generation. Some pre-date basin development, having been involved in the tectonic processes that produced the basement fold and thrust belt (Figure 3), while others occurred synchronously with basin filling, most importantly including the Petermann (Circa 520-660Ma) and Alice Springs (Circa 300-450Ma) orogenies. All tectonic events potentially have relevance regarding basement fracture systems, while only the younger events are likely to have contributed to extensive fracturing of the unnamed non-magnetic unit and Heavitree Formation. The distribution and trends of this younger deformation

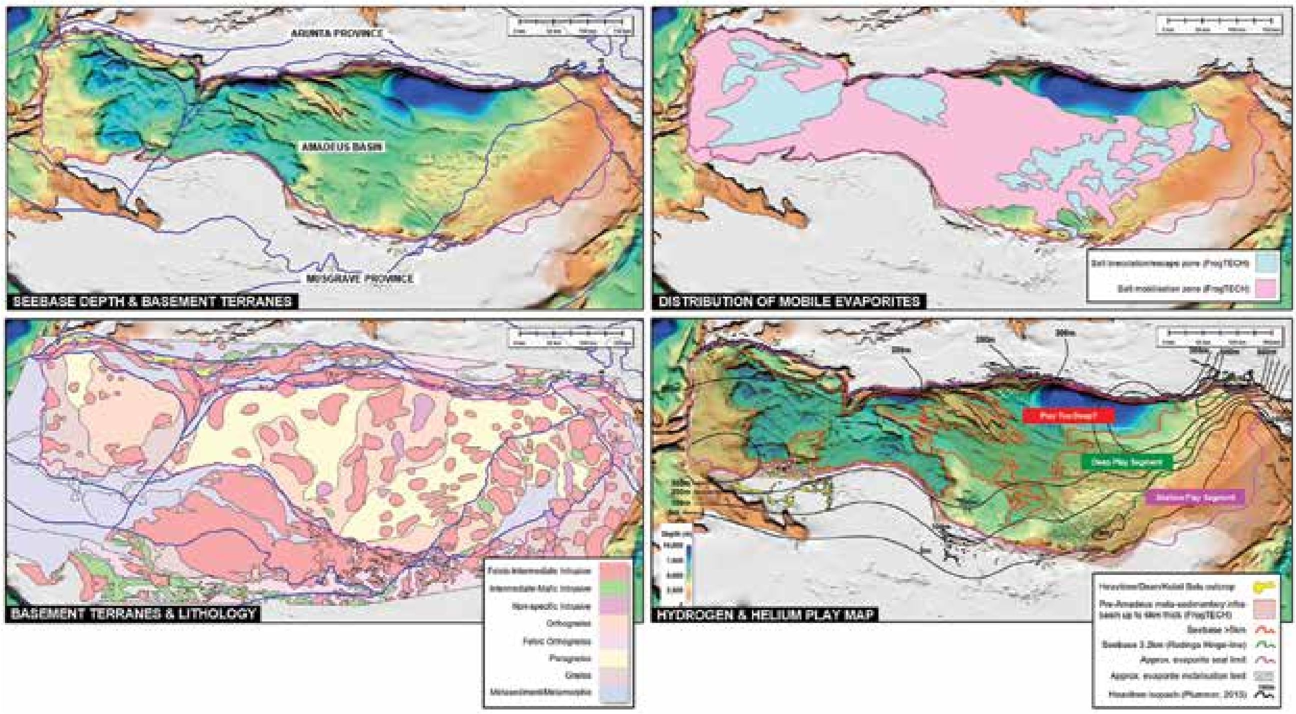

Figure 3: Regional summary maps of the Amadeus Basin, including: (Top Left), Simulated Depth to Economic Basement (SEEBASE); (Bottom Left), Basement Lithology; (Top Right) Gross distribution of mobile and brecciated evaporites; (Bottom Right), Hydrogen and Helium play map as currently understood. Maps produced from integration of wells, seismic mapping, outcrop geology and potential fields modelling (e.g., FrogTECH, 2015). Basement terranes outlined in blue and basin evaporite seal extent in magenta.

(including fracturing) would likely have been influenced by reactivation of rheological weaknesses pre-existing in basement, associated with the older tectonic events. However, it is important to note that much of structuration affecting the Amadeus basin-fill strata was imparted by thin-skinned mechanisms related to detachments located largely within the Gillen evaporites i.e., above the level of all proposed candidate reservoirs. Except where hard linked into basement, these detached systems are not expected to have direct bearing on reservoir fracture systems. This same argument also applies to the generation of structural traps, where trap formative mechanisms would need to post-date top reservoir emplacement and be thick-skinned. Traditionally, reverse faulted and/or thrusted structures of this nature (e.g., Mt Kitty; Figures 1 and 2) have been proposed as most likely trap types. However, broad distributed basement flexures and erosional geomorphic features on top basement presumably could also be viable, the geometry of which are both probably controlled to some extent by inherited basement structural fabric.

The Gillen Formation evaporites play an important role in trapping and preserving significant helium and hydrogen gas concentrations. The 2D seismic acquired by Santos in the southern Amadeus Basin highlights the thickness and lateral extent of the Gillen Formation evaporites (Figures 2 and 3). The evaporites pinch out along the south-eastern basin margin but thicken dramatically to the north-west into the interpreted depocenter (Figures 2 and 3). This transition takes place abruptly across a prominent north-east trending monoclinal basement flexure that appears to influence deposition (Figures 1, 2 and 3). The feature corresponds approximately with the north-west edge of the intrusion-rich Rodinga orthogneiss basement terrane (FrogTECH, 2015; Figure 3), which may represent a major north-east-trending basement shear zone as occurs in the Coompana Province. In the region to north-west of the Rodinga flexure, evaporite thickness is highly variable due to salt flowage during the Petermann and Alice Springs orogenies (Figures 2 and 3). This can vary from apparent salt welds, where the Gillen Formation evaporites may be only 10's of metres thick, to more than 2300m as encountered in the Dukas 1ST1 well (Figure 2).

Future exploration and appraisal wells planned for the southern Amadeus Basin (Figure 1) will target the Heavitree Formation and fractured granite basement reservoirs at both basin margin and deep basin locations. A follow up to the Dukas 1ST1 well is planned to test the target reservoirs in a deep basin location. Wells are also planned to appraise the Mt Kitty accumulation and to test target reservoirs up dip of the Magee accumulation near the basin margin.

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The Camooweal seismic survey extends the known Carrara Sub-basin sedimentary packages

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The Camooweal deep-crustal seismic reflection survey (GSQ Open Data Portal SS095590) was acquired in 2019 by the Geological Survey of Queensland (GSQ) as part of the Queensland Government's Strategic Resources Exploration Program (SREP). The survey is centred on the northwest Queensland town of Camooweal, with the total length of acquisition spread over three lines: 19Q-C1 (65.8 km), 19Q-C2 (173.6 km) and 19Q-C3 (60.9 km) (Figure 1). These seismic lines link to Geoscience Australia's Exploring for the Future (EFTF) program South Nicholson (L210) and Barkly (L212) seismic surveys as well as to the 1994 Mount Isa seismic line (94 MTI-01). The Camooweal seismic survey was acquired via vibroseis using a nodal geophone system (Edwards, 2020).

The Camooweal survey increases data coverage over the southern Isa Superbasin, the South Nicholson and the Georgina basins, tying these underexplored regions with the more well explored and highly prospective McArthur Basin and northern Lawn Hill Platform. The Camooweal survey images the southern part of the Carrara Sub-basin, a newly discovered Proterozoic depocentre in northwestern Queensland and the Northern Territory (Carr et al., 2019; Figure 1). The units underlying the northern Georgina Basin imaged on the Camooweal survey include strata that are interpreted as age equivalents to the Paleo- to Mesoproterozoic Isa Superbasin and the Mesoproterozoic South Nicholson Group (Carr et al., 2020, Carson et al., 2022). This study presents a new interpretation of the southeastern extent of the Carrara Sub-basin sedimentary packages, made possible using the Camooweal survey.

In the absence of well control or surface outcropping of imaged units in the Camooweal survey area, stratigraphy is constrained by the contiguous EFTF surveys, L210 and L212 (Figure 1) where the stratigraphy is analogous and constrained in some parts by new stratigraphic drilling (https://portal.ga.gov.au/bhcr/minerals/648482). The interpretation focused on the top 3-4 seconds of data (Figure 2), where a thin veneer of Georgina Basin sediments is observed unconformably overlaying the Proterozoic interval. The interpretation of reflectors representing the Calvert and Leichardt Superbasin equivalents are speculative, and based on previous interpretations made without well or outcrop control (Carr et al 2019). The Carrara Sub-basin sedimentary packages, defined on Figure 2, interpreted on the Barkly line 19GA_B1 and South Nicholson line 17GA-SN2 are laterally continuous through the Camooweal Survey (Southby et al., 2021; Carr et al., 2020). The continuation of these sedimentary packages implies that the Carrara Sub-basin extends further south than the currently recognised basin boundary (Figure 1). The boundary could extend even further south as the horizons continue laterally to the edge of 19Q-C2 (Figure 2).

The interpreted horizons are associated with units previously recognised prospective for hydrocarbons and mineral deposits, as well as with water resources within the Georgina Basin (Rollet et al., 2021). They potentially form an extension of the known north Queensland Proterozoic shale play fairway identified on the northern Lawn Hill Platform (Gorton and Troup 2018). These units are deformed by deep crustal structures similar to one observed beneath the world class Century base metal deposit. (Carr et al., 2019)

Recommendations for future work include reprocessing of the Camooweal seismic survey data at the basin scale to enhance the visualisation of the sedimentary section. More regional work also needs to be undertaken to understand the full extent of the Carrara Sub-basin and related depocentres. Further stratigraphic drilling along the Camooweal seismic lines would complement the recent drilling program completed on the western margin of the Carrara Sub-basin and in the East Tenant region to provide additional stratigraphic and age control within the basin, (e.g. Carson et al., 2022.)

Acknowledgements

Geoscience Australia would like to acknowledge our collaborators GSQ. This abstract was improved by Nadege Rollet and Chris Nicholson (both of Geoscience Australia) both are thanked for their constructive reviews. This paper is published with the permission of the CEO, Geoscience Australia. eCat 146096.

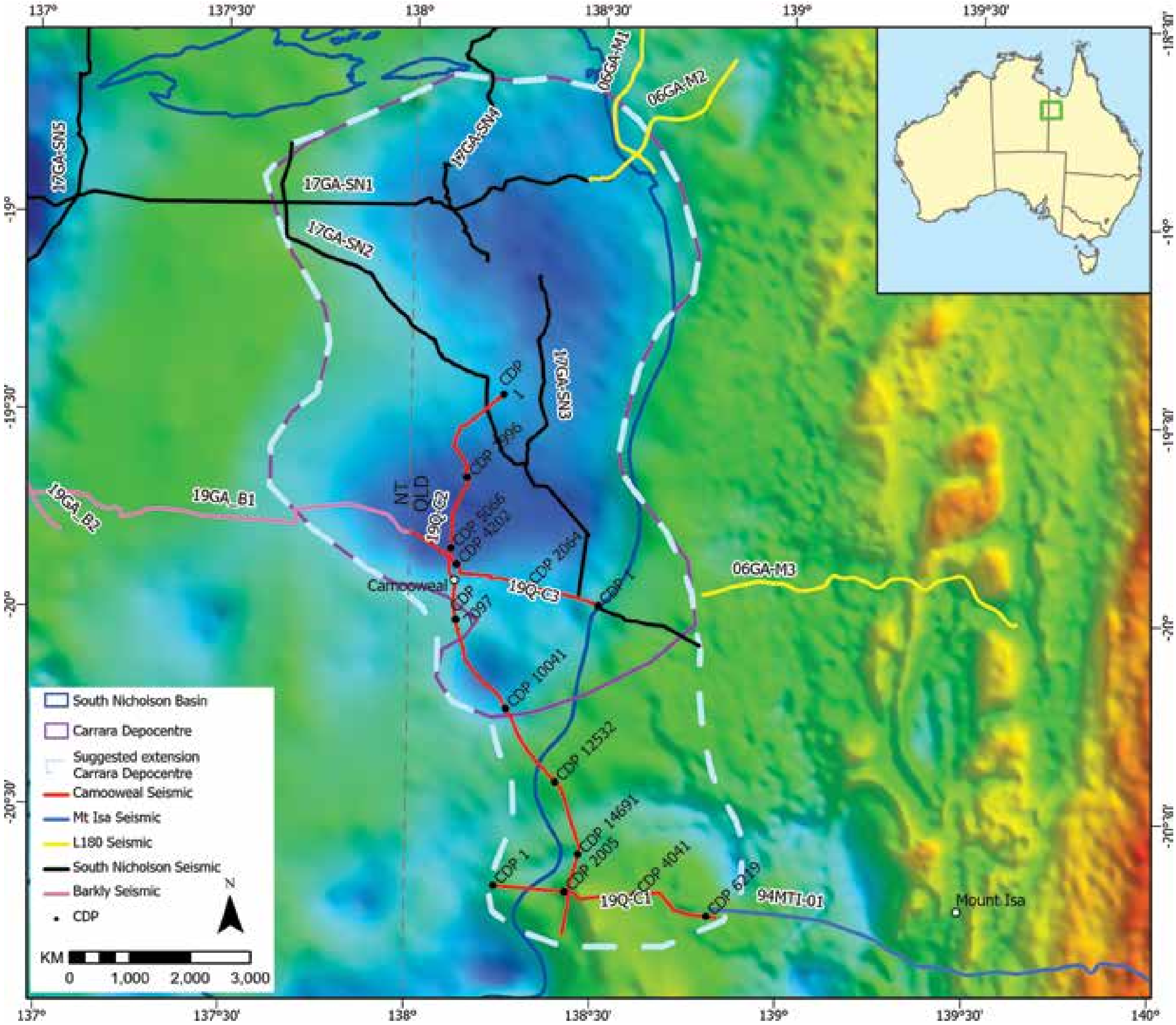

Figure 1: Location map of the Camooweal seismic survey in northwest Queensland near the Northern Territory border overlaid on a Bouguer gravity anomaly image. The original outline for the Carrara Depocentre is shown in purple and the suggested extended outline based on the Camooweal seismic survey interpretation is shown in dashed light grey. Figure 2 seismic surveys are in red.

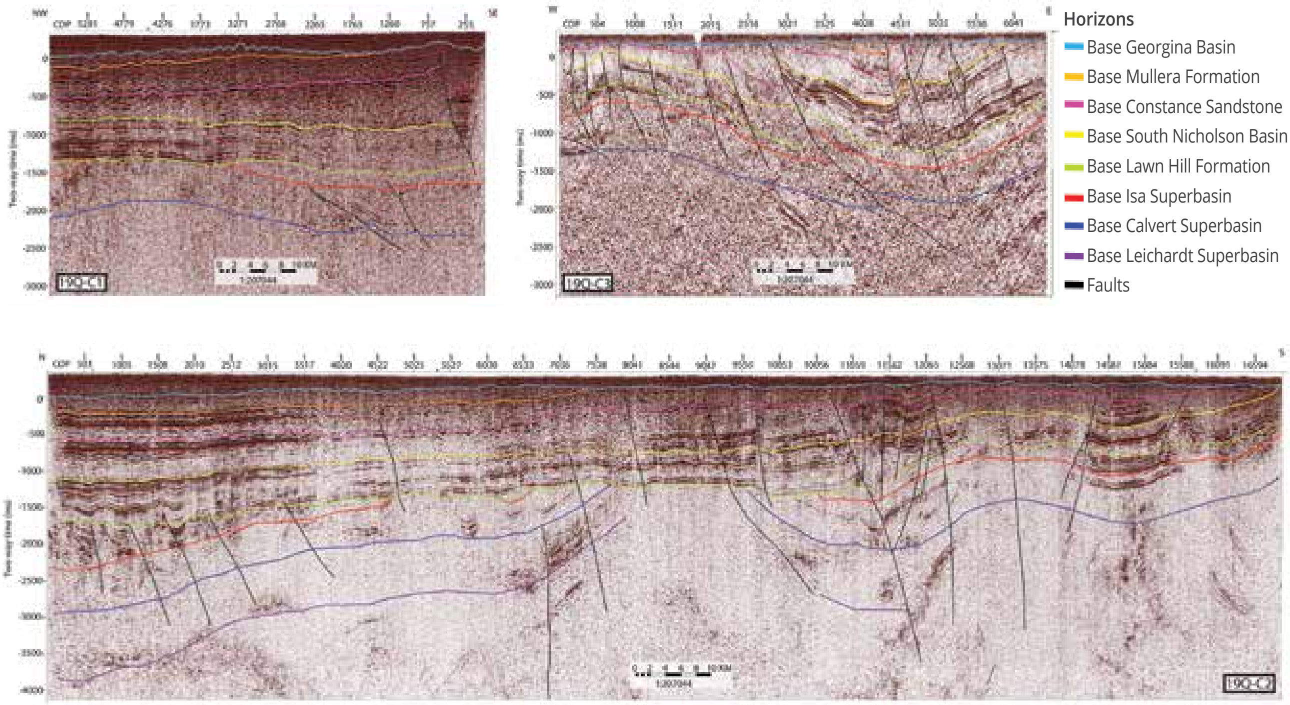

Figure 2: Interpreted Camooweal seismic lines cropped at 3¬–4 seconds (two-way time) showing inferred prolongation of Carrara Sub-basin stratigraphy from the Leichardt, Calvert, Isa Superbasins and overlying South Nicholson and Georgina basins. Seismic vertical exaggeration is 1:5.

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Exploring for the Future - Officer Musgrave project update

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Introduction

The Officer-Musgrave project investigates the groundwater and energy resource potential of the Officer Basin and neighbouring Musgrave Province near the junction of South Australia, Western Australia and the Northern Territory (Figure 1).

Groundwater investigations focus on the Musgrave Province and overlying Officer Basin to identify potential palaeovalley groundwater resources, to support geological framework data acquisition and geochemistry. Groundwater systems in remote regions, such as the Officer-Musgrave region, are poorly understood due to sparse geoscientific data and few detailed scientific inestigations having been undertaken. Characterising the distribution and quality of groundwater resources, will lead to a better understanding of the groundwater resources for community supply and economic development opportunities.

The energy resource component of the project focuses on the analysis of existing legacy datasets, including seismic and well data, in the Officer Basin and acquisition of key new precompetitive data. These activities will improve understanding of regional resource potential, with the aim of stimulating industry exploration investment in the medium-term, ultimately leading to new discoveries and wealth creation. This work builds directly on work completed in the first phase of the Exploring for the Future program, which enhanced our understanding of Centralian Superbasin stratigraphy (Khider et al., 2021; Bradshaw et al., 2021).

Data acquisition, reprocessing and analysis

To date, the Officer-Musgrave Project has prioritised the analysis and reprocessing of existing samples and datasets to further define and understand regional stratigraphy and geological processes, focussing on groundwater and energy systems. New and reprocessed AEM also forms part of this project (Carr et al., 2022) to provide new data and insight to further the geological knowledge of the region.

Palaeovalley Groundwater Characterisation

In this study of Palaeovalley Groundwater Characterisation, publicly available industry airborne electromagnetic (AEM) data have been reprocessed and inverted to produce conductivity models and a suite of derived datasets, using Geoscience Australia's Layered-Earth-Inversion algorithm (Brodie, 2016). This new data release includes conductivity sections, grids, and other derived products shows an example comparing the reprocessed and original industry data (Figure 2). Reprocessed AEM data is available at http://pid.geoscience.gov.au/dataset/ga/146089.

The second component of this study is the acquisition and processing of a new AEM survey of ~23,000 line km at five kilometre line spacing. Data from this survey will be modelled, in late 2022, to derive the base of palaeovalleys in the study area.

Officer Basin Energy Systems

Officer Basin South Australia 2021 Seismic Reprocessing Data Package

In 2021, Geoscience Australia commissioned reprocessing of selected legacy 2D seismic data in the South Australian part of the Officer Basin. This seismic data package (Leven, 2021 and Geoscience Australia, 2021) contains reprocessed data from five surveys acquired between 1966 and 1987. Data is available from: https://dx.doi.org/10.26186/145905 and http://pid.geoscience.gov.au/dataset/ga/74944.

Petrophysical and geomechanical testing study of the Officer Basin

As part of the Officer-Musgrave Project a regional stratigraphic study, with a focus on the Officer Basin in South Australia and Western Australia, was conducted (Bailey, 2021). This new data provides digital photography, X-ray Computerised Tomography (XCT) scanning, unconfined compressive strength (UCS) and tensile strength, laboratory ultrasonic testing, and gas porosity and permeability experiments for 41 samples from five legacy stratigraphic and petroleum exploration wells within the Officer Basin. This study is available at: http://dx.doi.org/10.11636/Record.2021.028

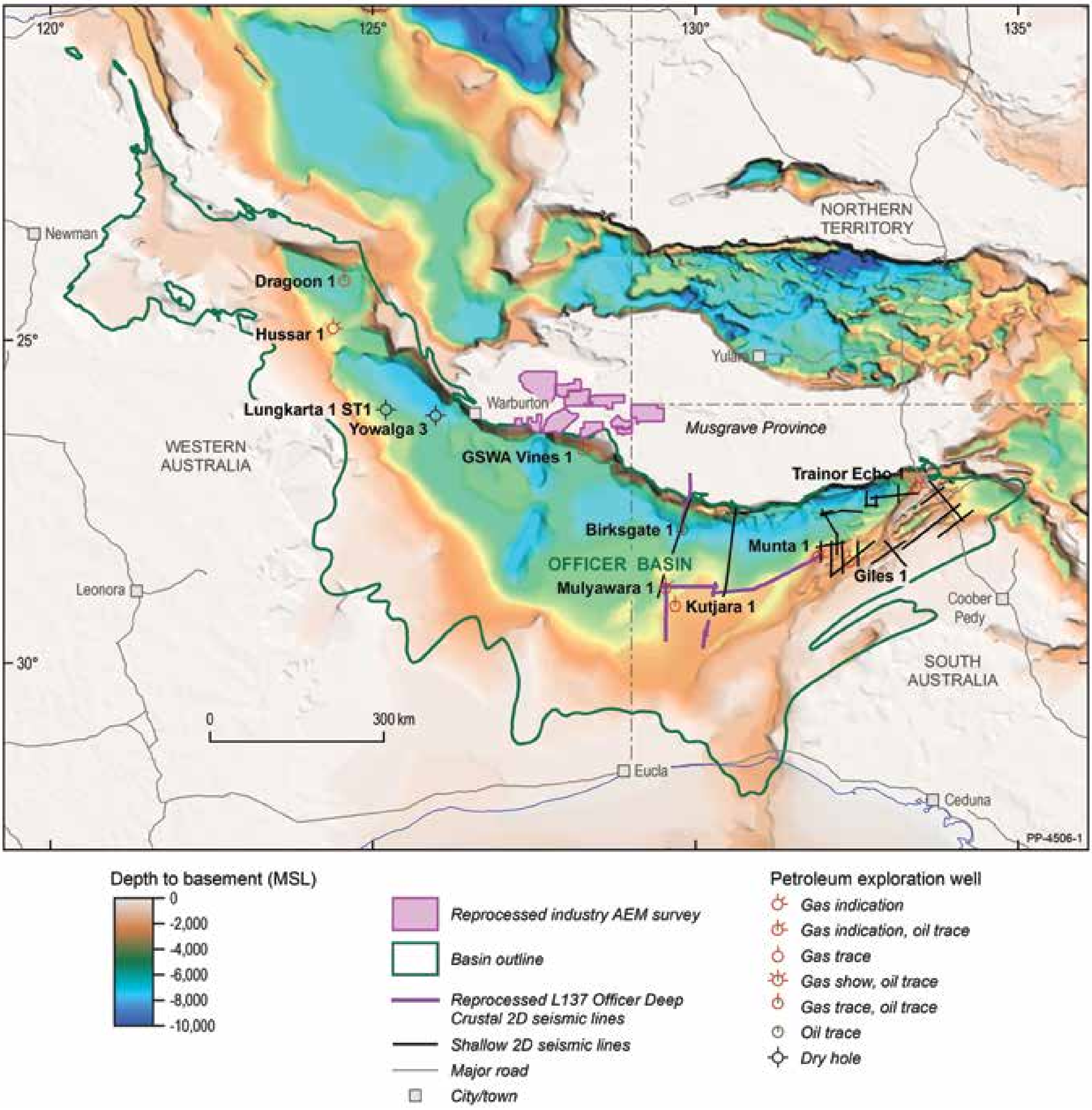

Figure 1: Map showing the Officer-Musgrave Region in Western Australia and South Australia (Raymond et al,, 2009; 2018), superimposed on OZ Seebase 2021 (Geognostics 2021).

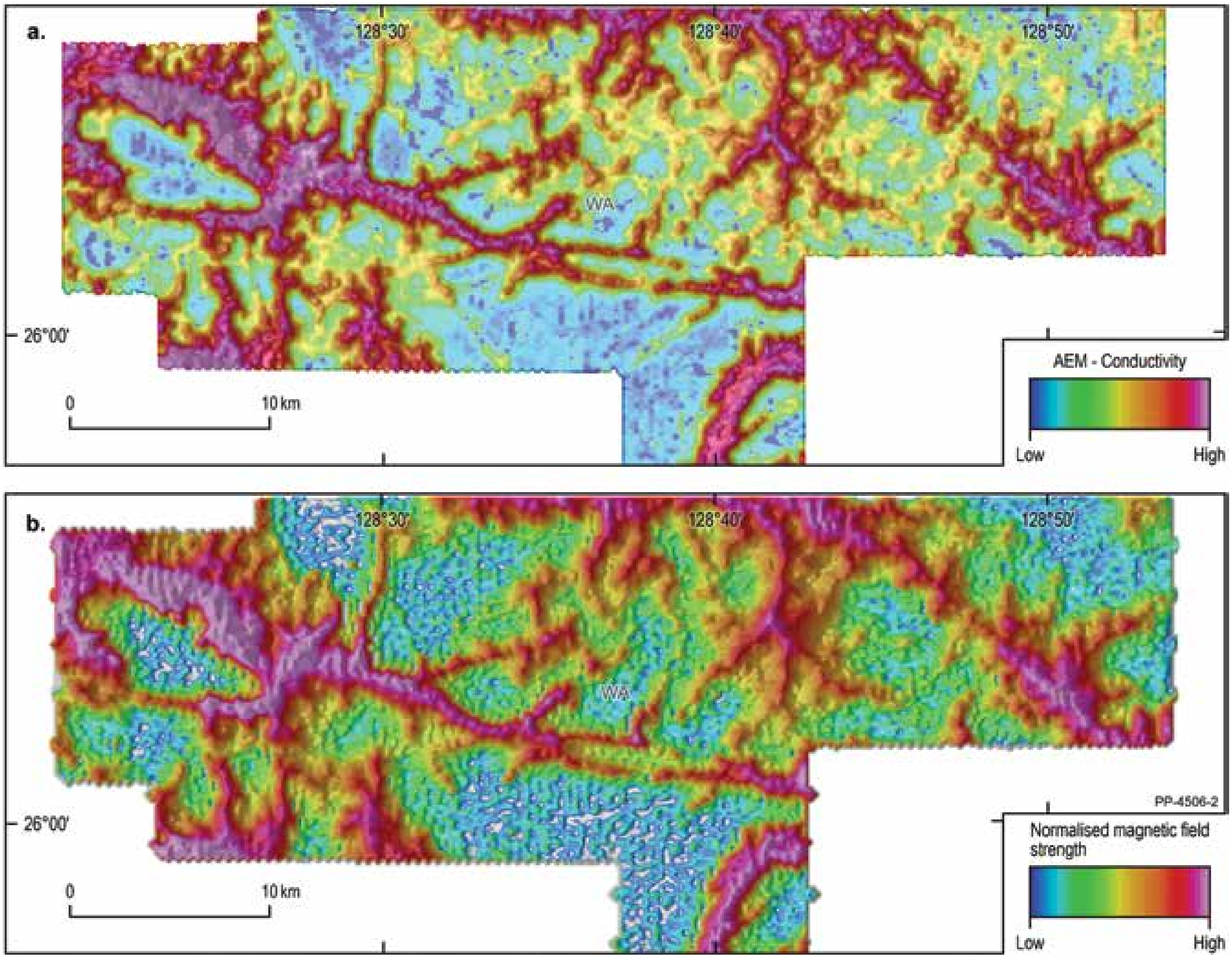

Figure 2: Gridded reprocessed AEM data example showing comparison of (a) GA-LEI Layer 6 (24 to 31 m depth) inverted conductivity and (b) original z-channel 4 EM generated from publicly available survey data (normalised magnetic field strength). The reprocessed grid highlights subtle breaks in conductive features, such as at ~128°25', 128°40', and 128°49.

Building on the petrophysical and geomechanical data above, further well logging data analysis and interpretation has been conducted using both conventional and machine learning approaches (Wang et al., 2022). This work updates the knowledge of rock properties to aid in the evaluation of the resource potential of the Officer Basin (Wang et al., 2022).

Defining a chemostratigraphic framework for the Officer Basin

To gain additional stratigraphic understanding of the Officer Basin a new chemostratigraphic framework was developed, utilising elemental data obtained using Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) testing, by Chemostrat Australia on 1245 cuttings and 241 core samples from ten Officer Basin wells. Five chemostratigraphic mega-sequences (MS1 to MS5) were defined, predominantly in the Neoproterozoic and Cambrian successions of the Officer Basin. This work has updated the stratigraphic columns of the Neoproterozoic–Cambrian successions after Khider et al. (2021), Haines et al. (2008), Bradshaw et al. (2021) and Hashimoto et al. (2018), and integrates the new chemostratigraphic mega-sequences and sequences of the ten Officer Basin wells (Munday et al., 2021). The report is available at: http://dx.doi.org/10.11636/Record.2022.007

Results

As part of the Officer-Musgrave Project, a wide array of new analyses and data are now publicly available. Further analysis is underway, including well log digitisation, fluid inclusion analysis and a petrographic report on Officer Basin wells. This work is expected further improve the hydrogeological and geological knowledge of this region for the future.

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Possible Late Mesoproterozoic or earliest Neoproterozoic glacial deposits, Beetaloo Sub-basin, Northern Territory

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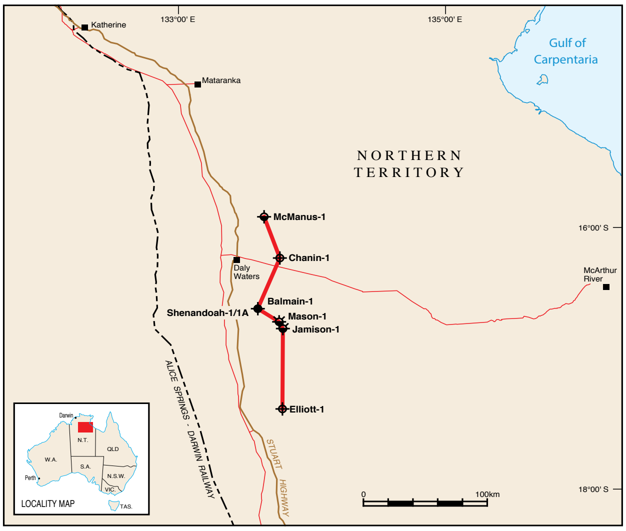

Figure 1. Locality map with north to south well log correlation.

In the Beetaloo Sub-basin (Figure 1), the Kyalla Formation is unconformably overlain by a late Mesoproterozoic to early Neoproterozoic sandstone to mudstone succession comprising three formations/units: the lower Jamison sandstone, the upper Jamison sandstone, and the Hayfield mudstone (Munson, 2016; pers. comm. 2022). Gorter and Grey (2013) subdivided the Jamison sandstone into two mappable units separated by an unconformity (Figure 2). The Jamison sandstone and overlying Hayfield mudstone represent a marked change in provenance and were deposited after the Musgrave Orogeny in a basin dominated by silciclastic sedimentation that may have formed a shallow, long-wavelength foreland basin to areas uplifted during the Musgrave Orogeny.

As there are no direct palaeontological or radiogenic age dating for the deposition of the upper Kyalla Formation to top Hayfield mudstone (Figure 3), zircon dating has been used to constrain the maximum age of deposition from the reworking of tectonically uplifted former basin fills (Yang et al., 2019; 2020a; 2020b). The names and ages may change but the rocks remain the same. The maximum depositional ages for these three units (i.e. the upper and lower Jamison sandstone and the Hayfield mudstone) are constrained by detrital zircon U–Pb isotopic ages, suggesting that the lower Jamison sandstone was deposited after 1,092 ± 16 Ma, and the upper Jamison sandstone and Hayfield mudstone were deposited after 959 ± 18 Ma (Yang et al., 2018; 2019; 2020).

The boundary between the Neoproterozoic and the Mesoproterozoic is generally taken as 1 billion years ago (Shields et al., 2021). The zircon dating of the 'lower Jamison sandstone' of Munson (2016) suggests a maximum age and could be younger, possibly as young as early Neoproterozoic (Tonian, 1000 to 720 Ma based on radiometric chronometry).

Lanigan et al. (1994) concluded that the Jamison sandstone–Hayfield mudstone succession is likely to be considerably younger than the Roper Group and possibly Neoproterozoic. Yang et al. (2020) interpreted a possible early Neoproterozoic age for the Jamison sandstone and subsequent strata in the Beetaloo Sub-basin (Figure 4).

Lithological evidence (Figure 5) suggests the possibility of a glacial imprint in the Mesoproterozoic–Neoproterozoic depositional environment of the Beetaloo Sub-basin (Gorter and Grey, 2013). Cores from Jamison-1 are interpreted as a basal diamictite in the lower Jamison sandstone directly overlying the erosional top of the Kyalla Formation. Zircon chronology indicates that the Kyalla Formation was deposited after 1313±47 Ma, based on zircons from Elliott-1 (Yang et al., 2017) and the basal Jamison sandstone strata have a similar peak age to the zircons in the Kyalla Formation, suggesting that the basal Jamison sandstone sediments were in-part derived from reworking of older, nearby siliciclastics, including the Kyalla Formation (~1300 Ma).

In Jamison-1 a weathered zone occurs at the top of the lower Jamison sandstone and is overlain unconformably by a transgressive clastic system of the upper Jamison sandstone, which passes upward into the Hayward mudstone where syneresis cracks suggest a depositional environment in flux between saline and freshwater/ brackish conditions. As the biota reported by Grey (2015) suggests a dominantly marine depositional environment, the syneresis cracks are interpreted as freshwater runoff into the depocentre, possibly with a seasonal component.

At McManus-1 there is a log correlatable zone of thin, low gamma ray units, which contain a possible shale dropstone at 451 m in the lower Hayfield mudstone. This interpreted dropstone has penetrated varve-like strata and was likely rafted in from ice on a lake or fluvial system. The Jamison sandstone-Hayfield mudstone transition is interpreted as a deglaciation sequence. Along similar lines, the upper Kyalla

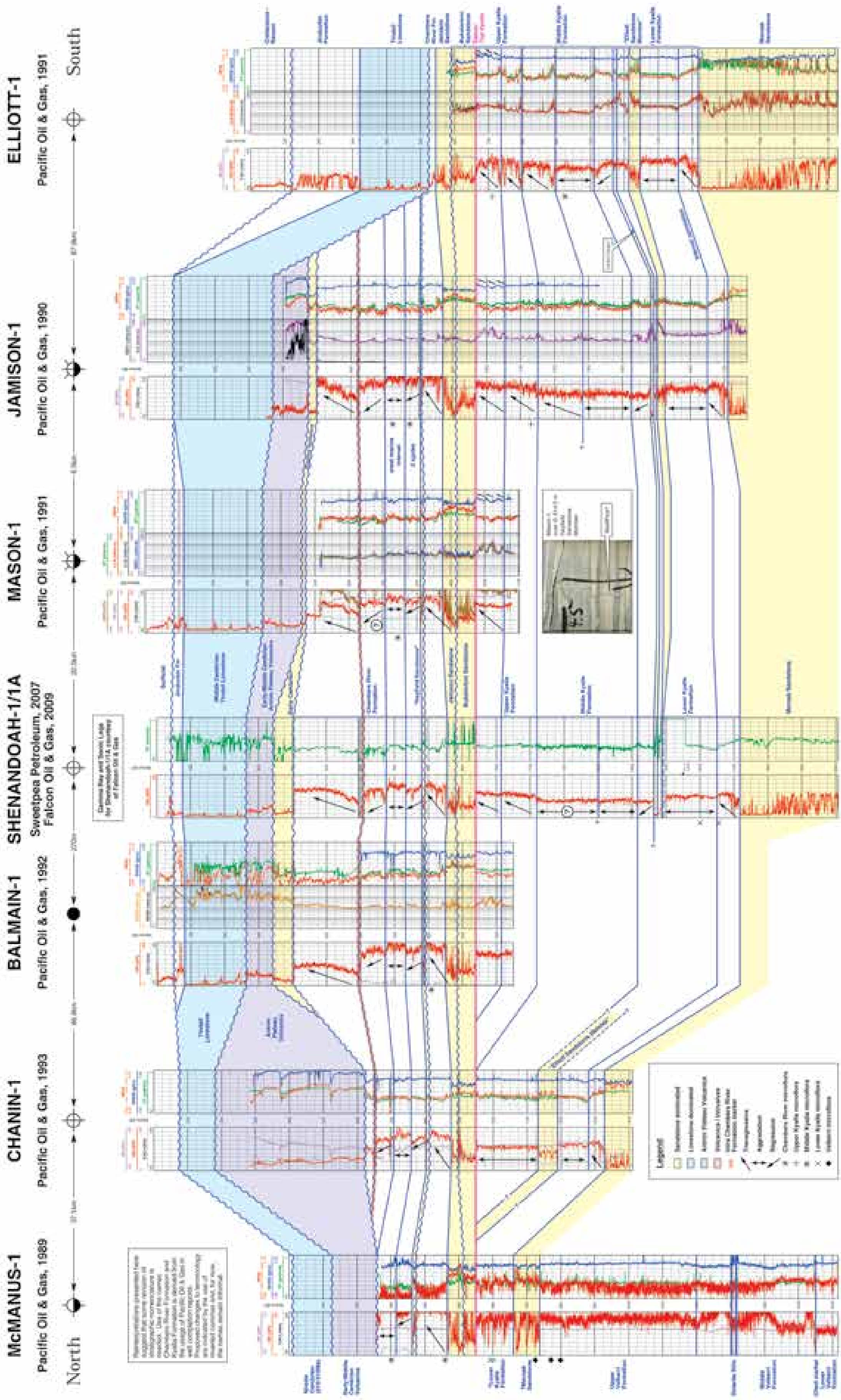

Figure 2. North to south well log correlation datummed on the base of the Bukalorkmi Sandstone of Gorter and Grey (2012; 2013). Stratigraphic revision of the nomenclature of Gorte and Grey (2012; 2013) as determined by the Northern Territory Geological Survey (NTGS).

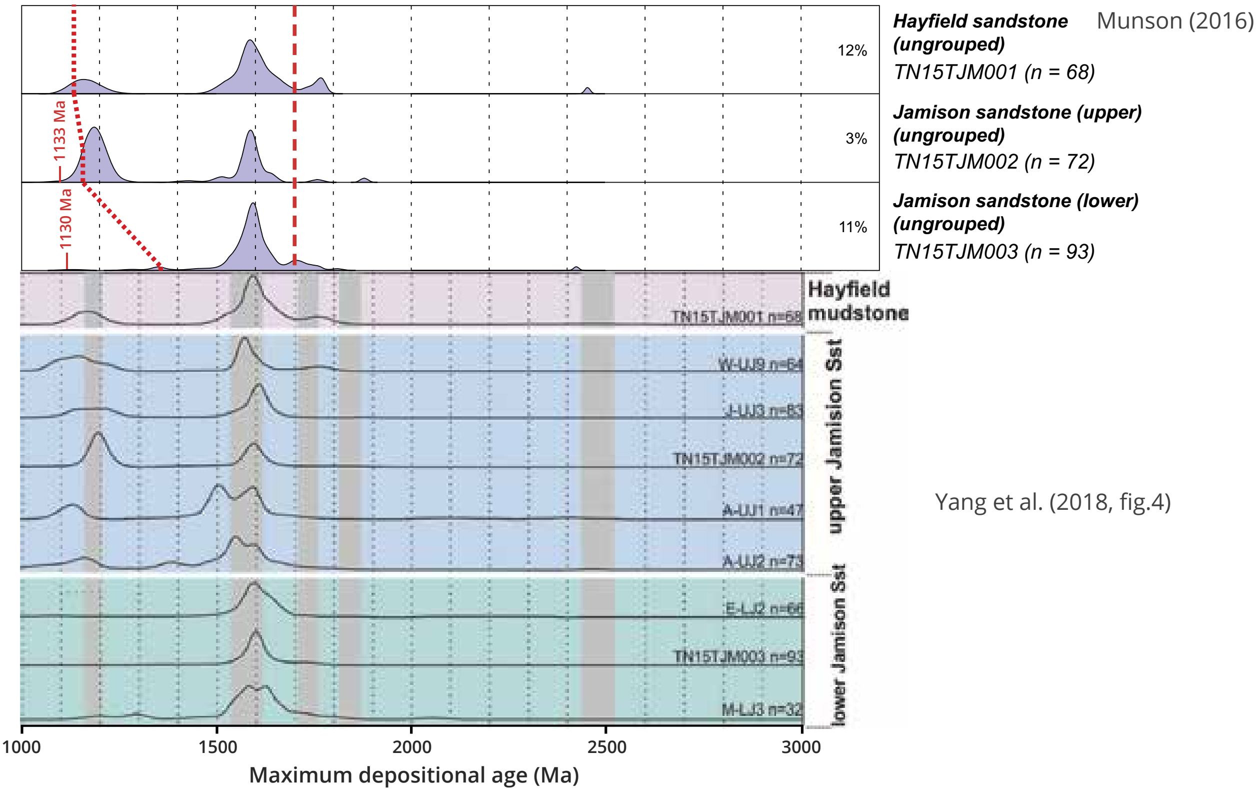

Figure 3. Comparative relative probability diagram of detrital zircon data arranged in stratigraphic order for the lower and upper Jamison Sandstone and the overlying Hayfield siliciclastics. Extracted from Munson (2016, fig. 116) and Yang et al. (2018, fig. 2).

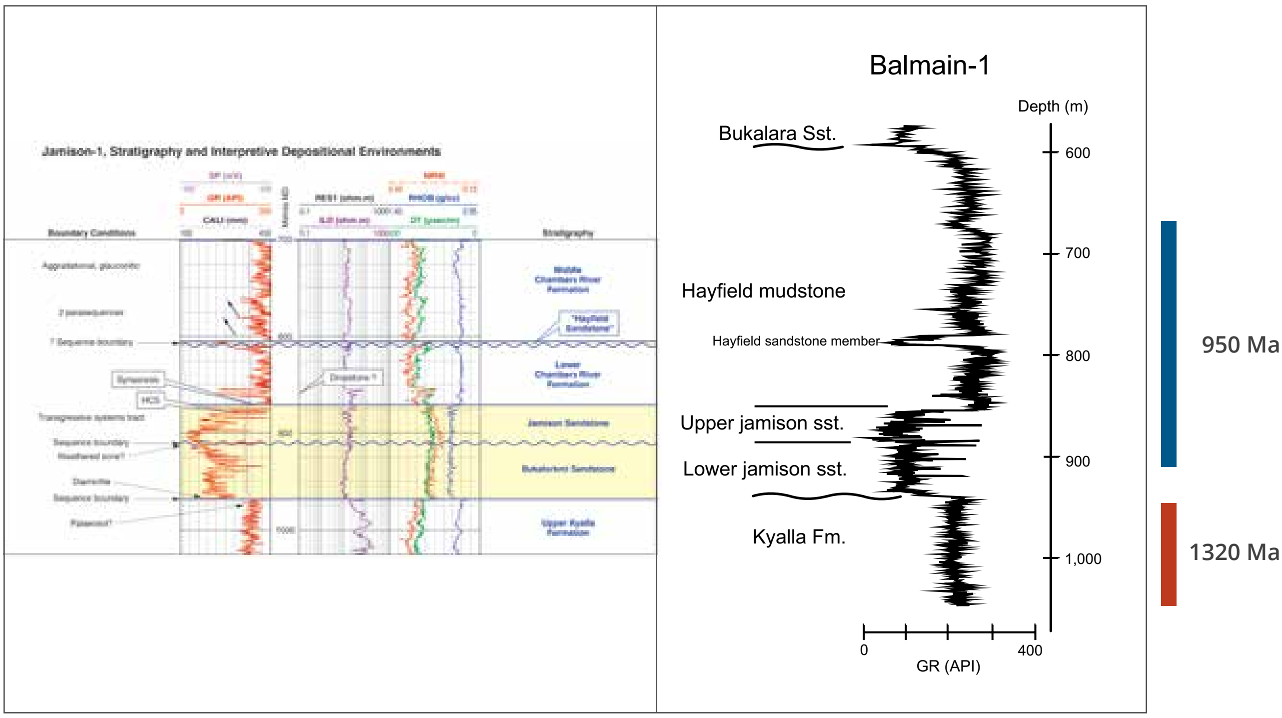

Figure 4. Stratigraphic nomenclature for Jamison-1 from Gorter and Jackson (unpublished Eni Australia Report, August 2010) and Gorter & Grey (2012: 2013) compared to that of Yang et al., 2020a, their fig. 5) for Balmain-1. The coloured vertical bars from Yang et al. (2020a, their Table 1) are concordant zircon ages. This suggests that the possible diamictites at the base of the lower Jamison are earliest Neoproterozoic in age.

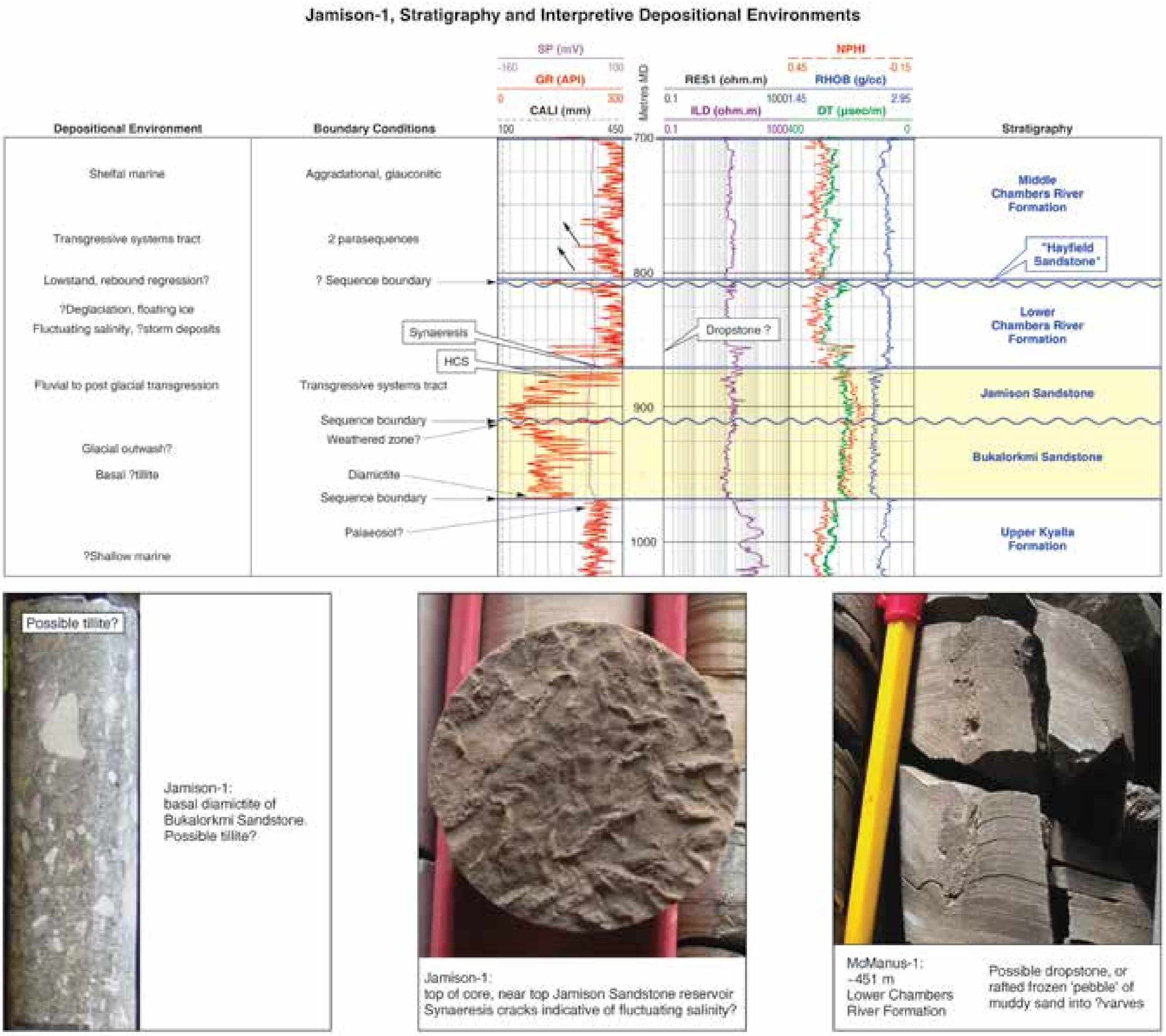

Figure 5. Top: Stratigraphy and interpretive depositional environments in Jamison-1 (Gorter & Grey, 2013). Left bottom: Basal diamictite of the lower Jamison Formation, possible a tillite, in Jamison-1. Middle bottom: Near top Jamison Formation in Jamison01 with synaeresis indicative of fluctuating salinity. Possible dropstone or rafted frozen pebble of muddy sands into ?varves in McManus-1 at ~451 m, and the correlated by logs to the correlative position in the lower Chambers rive (Hayfield) unit in Jamison-1.

Formation in Jamison-1 contains a ~5 m thick zone of small, diagenetic carbonate nodules that at least superficially resemble glendonites (Figure 6), generally considered to form in frigid, organic rich sediments.

There are no body and few trace fossils seen in the cores inspected from the post-Kyalla Formation section. However, in Mason-1 (Figure 7) there is a possible Skolithos vertical burrow at about 814.5 m in what is interpreted to be the "Hayfield Sandstone Member of the Chambers River Formation" of Gorter and Grey (2013). Also present is a possible horizontal burrow that may be attributed to Planolites. The same microflora occurs above this depth in Mason-1 and below the Hayfield Sandstone Member in nearby wells based on log correlation (Gorter & Grey, 2013). The oldest Skolithos (i.e. S. declinatus) are found in Russia and are Vendian/Ediacaran in age (Fedonkin, 1985).

Some palaeogeographic reconstructions place northern Australia near the north pole during the Stenian (late Mesoproterozoic), although there is still much uncertainty in this conclusion. Several palaeogeographic reconstructions indicate that northern Australia, including the Beetaloo Sub-basin, straddled the north pole during the latest Mesoproterozoic to early Neoproterozoic (Betts et al. (2007, Fig. 3); Evans & Mitchell (2011, Fig. 1B); Buchan et al. (2001); Geboy et al. (2013); Hartley et al. (2020). If correct, the polar position supports a probable frigid climate during the deposition of the late Mesoproterozoic/ early Neoproterozoic sequence in the Beetaloo Sub-basin.

Positioning the Beetaloo Sub-basin in sub-polar climes is consistent with the sparse depositional environment information from cores and logs that supports cold melt water and possibly glacial depositional features. There is

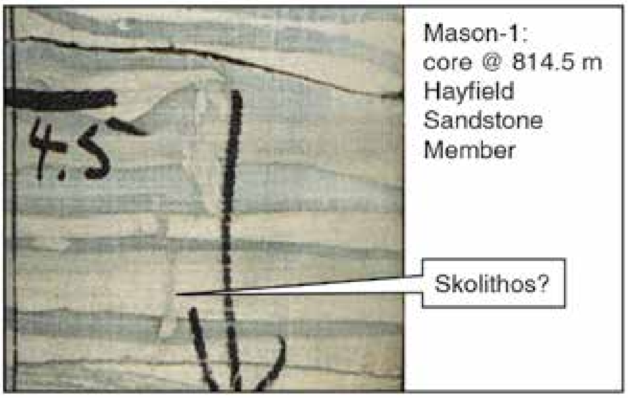

Figure 6. Possible Skolithos trace in interbedded shallow marine strata of the Hayfield Sandstone Member in Mason-1 at 814.5 m. Note also possible horizontal Planolites-like trace (white oval in grey siltstone). Arrow points towards the base of the core. Planolites is unlined and having an infill different than the host rock (Pemberton and Frey, 1982).

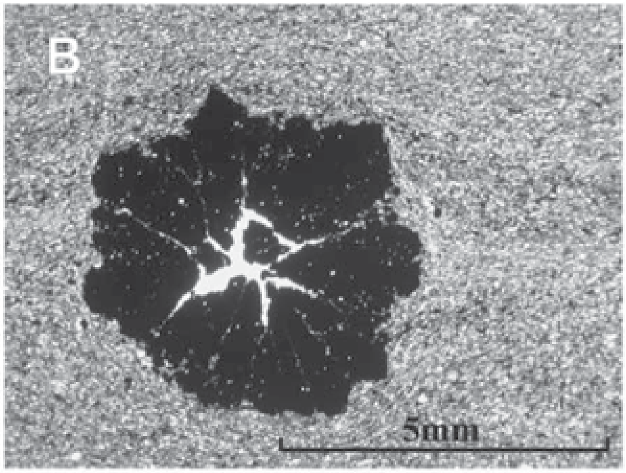

Figure 7. Left : Small pyritized glendonite from the Liffey Group Tasmania in thin section (Rogala, 2010). Right: Possible glendonite crystals from core from 1130.87 m in Jamison-1, upper Kyalla Formation (crossed-polars photomicrograph). Scales in mm.

evidence of mid- to late Mesoproterozoic glaciation recorded from southeastern Brazil, coincident with the Stenian (1200 to 1000 Ma) and older Ectasian (1400 to 1200 ma) but located closer to the palaeoequator (e.g. Azmy et al., 2008; Misi et al., 2014; Geboy et al., 2013).

The first record of Late Mesoproterozoic (S tenian) ice was reported from the 1000 Ma Scottish Diabaig Formation, where dropstones are recorded from ice rafting in a lake thought to have frozen over in the winter (Hartley et al., 2020). Temperatures at the poles dropped below freezing in winter, allowing for temporary sea ice formation and snowfall, but there were likely no permanent ice sheets (Liu et al., 2019). Subsequently Azmy et al. (2008); Geboy et al. (2013) and Misi et al. (2014) demonstrated at least four glacially influenced units in the Vazante Group in south-central Brazil.

Yang et al. (2020, Table 1) interpreted a likely Neoproterozoic depositional age for the Jamison sandstone and overlying strata in the Beetaloo Sub-basin. Detrital zircon U–Pb age and hafnium isotope data collected from these three formations suggest provenance from the eroding Musgrave Province in central Australia. The Jamison sandstone and overlying Hayfield mudstone reflect a marked change in provenance representing a siliciclastic basin that formed a shallow, foreland to areas uplifted during the Musgrave Orogeny.

This well-based evidence highlights that the depositional environment for the Jamison sandstone and Hayfield mudstone has some glacial influence and may in fact be evidence of an extended period of glaciation during the late Mesoproterozoic to early Neoproterozoic in the Beetaloo Sub-basin. Recognition of this event will hopefully encourage further study and the development of future models for sediment distribution during this period.

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Oodjuongari - A possible impact crater in the Beetaloo Sub-basin

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The Oodjuongari Structure (-16.636, 134.205), seen on aeromagnetic data as a circular feature (Figures 2, 3a and 5), and traversed by four 2D seismic reflection profiles (Figures 6 and 7), is interpreted as a possible impact crater concealed by superficial Cainozoic strata. There is no surface expression of the structure which is located within the Beetaloo Sub-basin and overlying Georgina Basin (Figure 1), although small streams appear to deviate around the feature (Figure 3b). The structure appears to be circular on the aeromagnetic data and has a maximum diameter of 5 km. It has similar size and aeromagnetic signature to the Foelsche impact structure located 275 km to the east (Haines & Rawlings, 2002). In both cases the pronounced circular aeromagnetic feature appears to be related to a circular disruption of flat-lying mafic volcanics, which are the Mid-Cambrian Antrim Plateau Volcanics at Oodjuongari. If the Oodjuongari Structure is an impact structure, the 5 km diameter would be consistent with a complex crater with a central uplift. Seismic profiles indicate that beneath the surficial sediments the section within the circular outline is heavily faulted and there appears to be a depression of seismic horizons within the outline that are not present on the relatively flat lying and undisturbed horizons outside the structure (Figure 4). From the regional geology and seismic correlation to nearby petroleum exploration wells (Chanin-1, Amungee NW-1, Burdo-1, and Ronald-1), the maximum age of the possible impact is considered as post-Middle Cambrian based on the interpretation of deformed Cambrian limestone within the possible impact structure. However, faulting (or thickening) in the Antrim section could indicate an impact age in the pre-Mid-Cambrian, whereas Figure 6 would indicate pre-Cambrian.

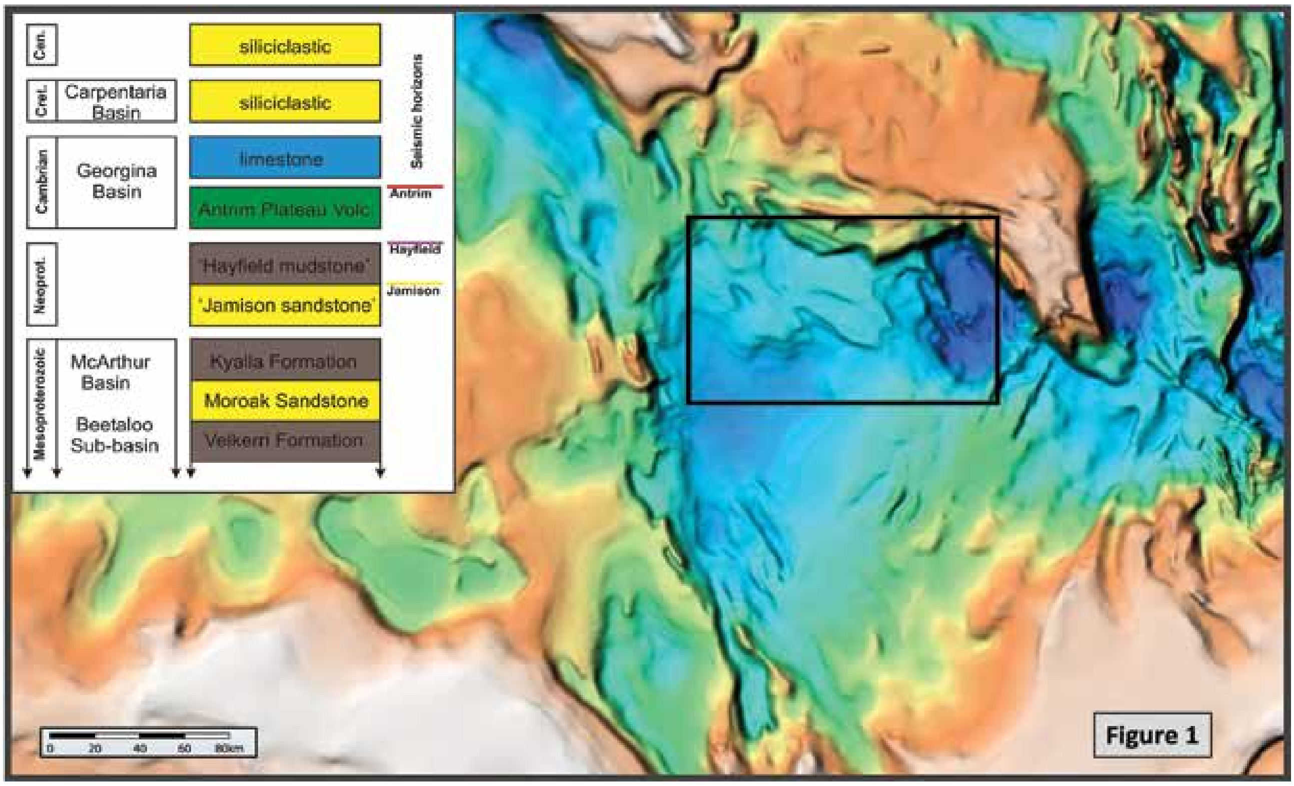


Figure 1: SEEBASETM map showing study area and simplified Beetaloo stratigraphic column.

An impact structure may have local implications for hydrocarbon migration. Oil and gas found in the mid-Cambrian Antrim Plateau Volcanics, source unknown, is evidence that at least some generation in the Beetaloo Sub-basin is late, possibly latest Cambrian, and/or oil has migrated from breached older Mesoproterozoic shale reservoirs (e.g. Kyalla and Velkerri units). An impact may have produced fractures and enhanced permeabilities in the Mesoproterozoic and possibly Neoproterozoic sandstone reservoirs, and fractures within the organic rich shales of the Kyalla and Velkerri formations leading to better unconventional prospectivity.

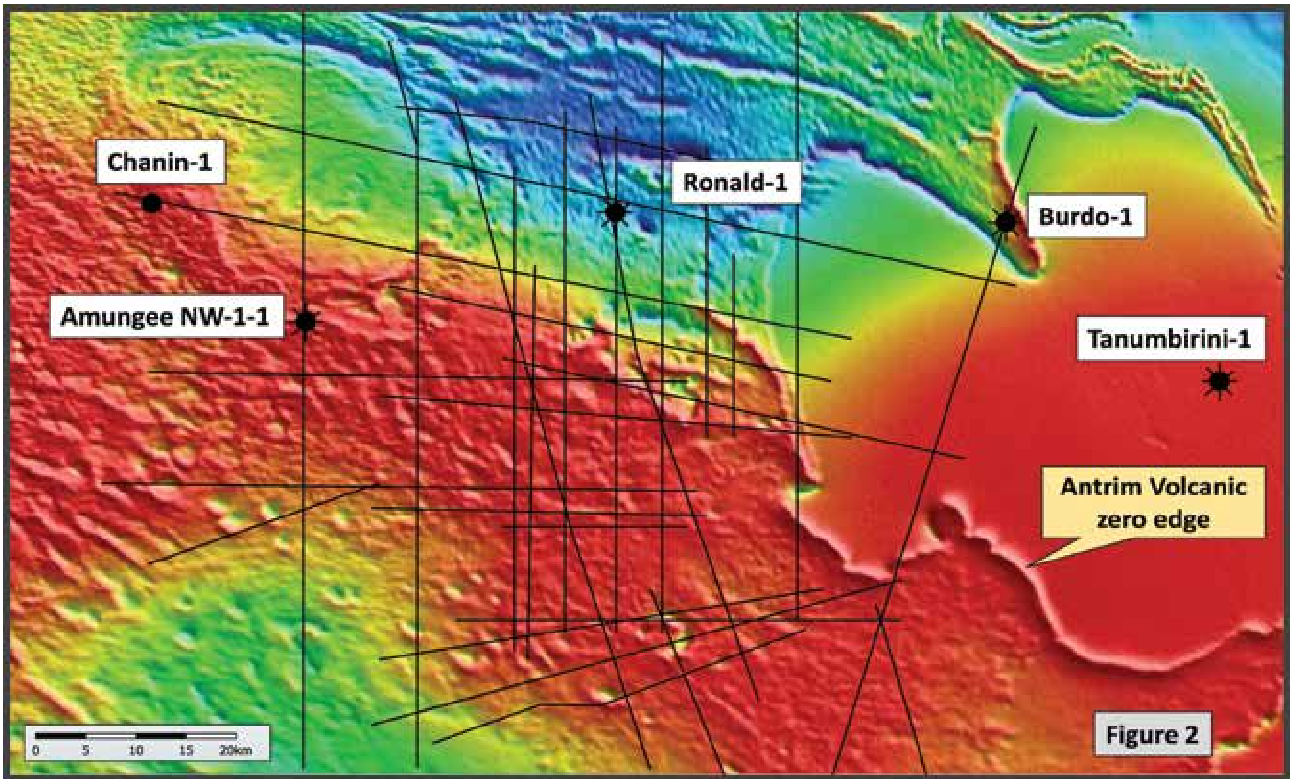
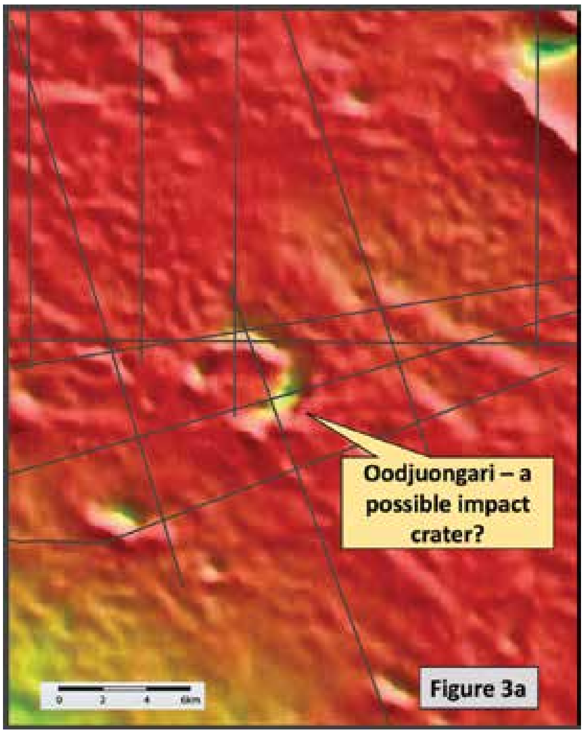


Figure 2: Total Magnetic Intensity (TMI) with Pre-Stack Depth Migrated (PDSM) seismic and wells.



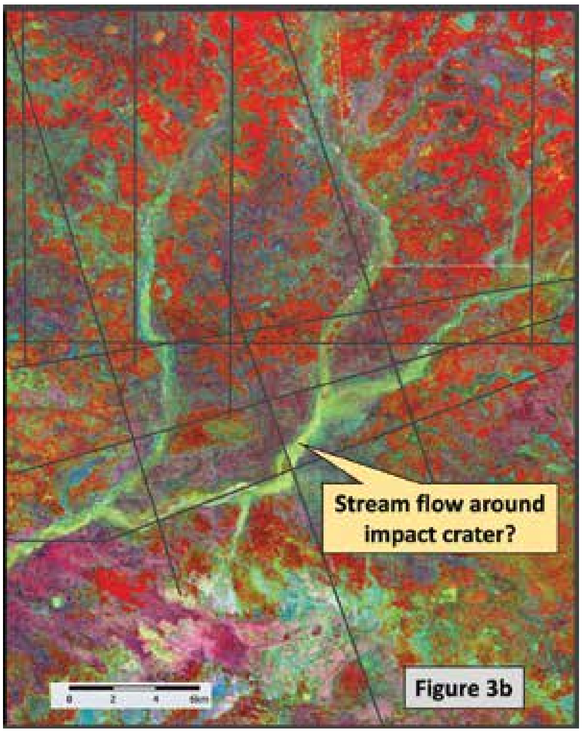


Figure 3a, b: TMI and Landsat showing stream offset around possible crater.

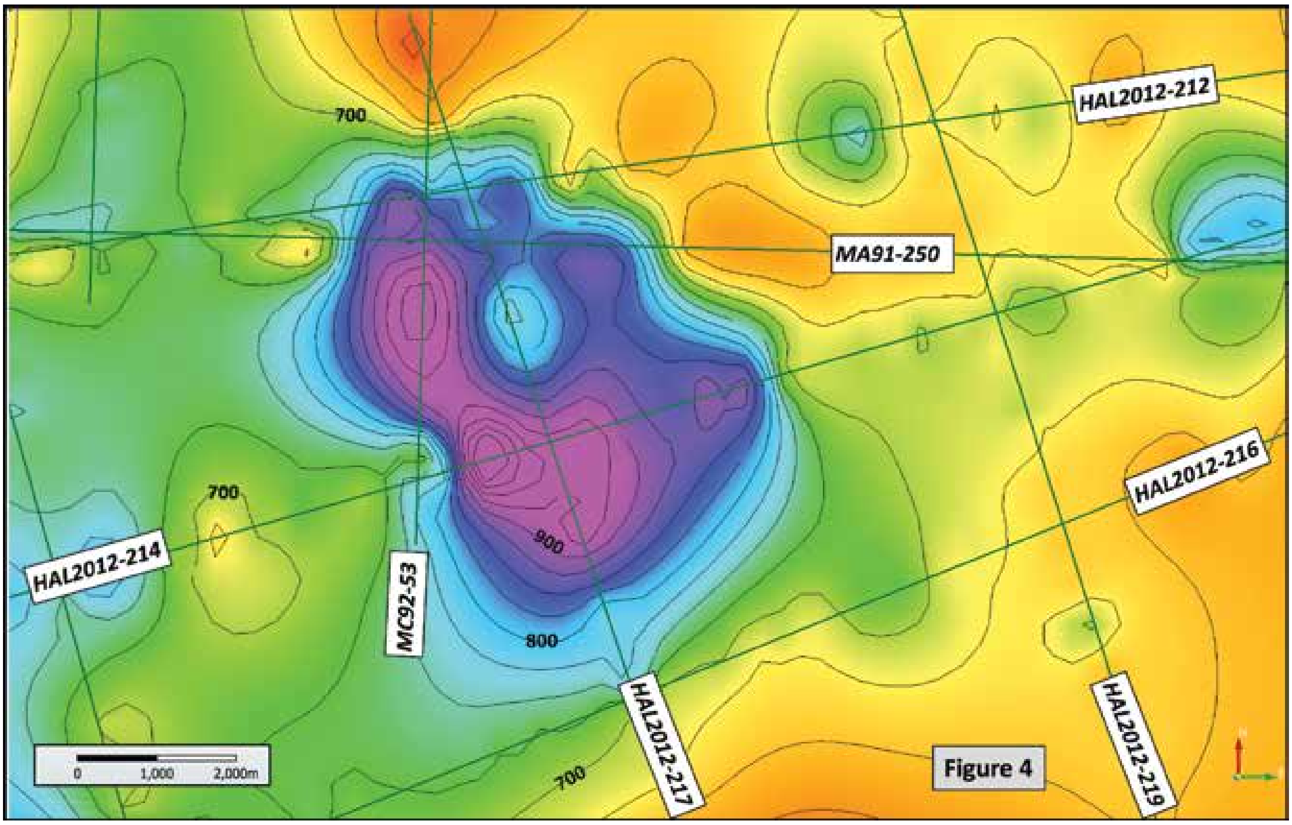


Figure 4: Top Jamison sandstone subsea depth map based on PSDM seismic. Depth of the crater ~ 250 m. Fault pattern not shown, 3D seismic required.

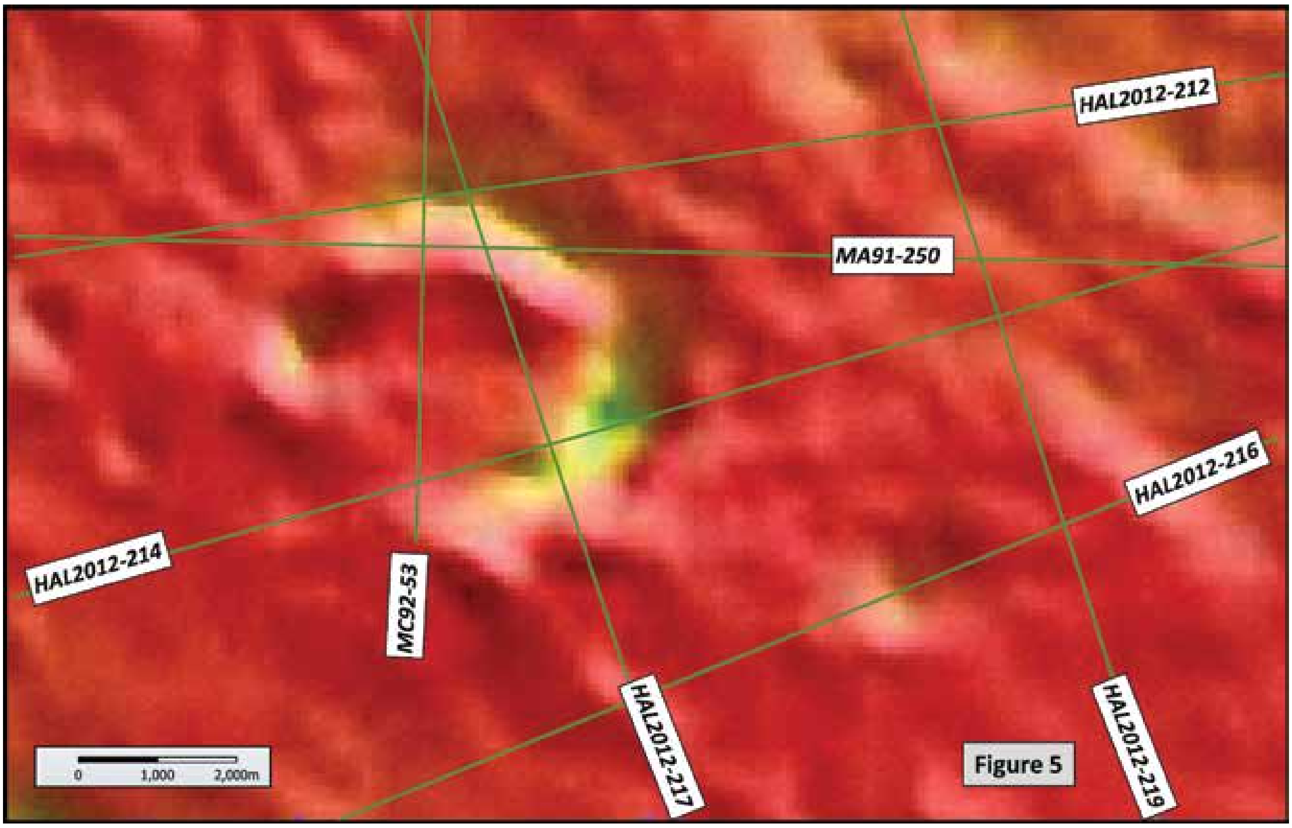


Figure 5: Detailed TMI image showing coincident anomaly with underlying Jamison structure.

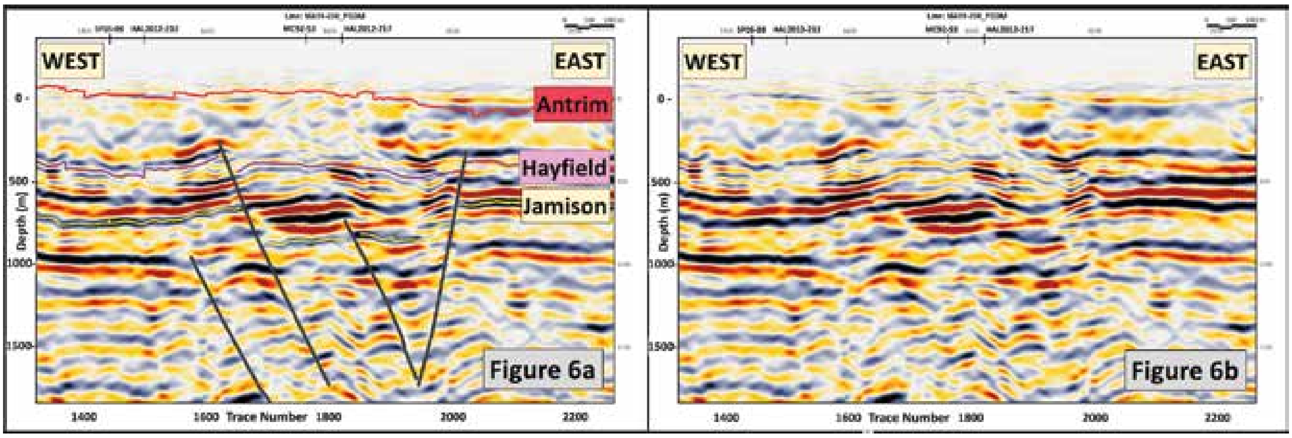


Figure 6a, b: PSDM line MA91-250 interpreted (left) and not interpreted (right). Line location in Figure 4. Line inter-sections at top. PSDM processing to 2000 m. Note smooth Antrim volcanic section and thickened Hayfield. Black is an increase in acoustic impedance.

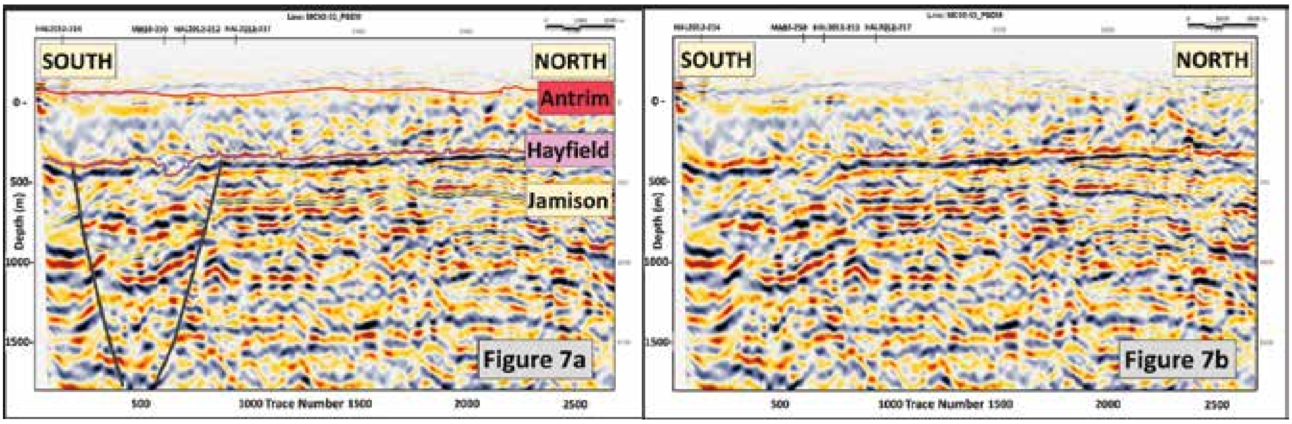


Figure 7a, b: PSDM line MC92-53 interpreted (left) and not interpreted (right). PSDM processing to 2000m with black indicating an increase in acoustic impedance. Note smooth Antrim Volcanic section and undisturbed Hayfield section either side of the fault bounded low.

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Coleen Harris from NT government provided help obtaining the seismic data.

All Landsat, TMI and SEEBASETM images from NT government STRIKE database.

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Amadeus Basin's H2 Geo-Storage capacity

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In recent years, there has been increased interest in Hydrogen's production and use, not only for ammonia production but also as an energy carrier (IEA, 2017). It could be produced from carbon-abated fossil fuels, as well as renewable and clean energy sources (USDOE, 2021). Like fossil fuel, hydrogen can be transported and stored in fluid form (IEA, 2017).

Geoscience Australia estimates that about 11% of Australia could be highly suitable for renewable hydrogen production, based on the quality of wind, solar and hydro resources (Finkel, 2018). In 2018, the Council of Australian Governments agreed that hydrogen is emerging as a significant economic prospect for Australia. The use of hydrogen as fuel and energy carrier will help decarbonise and provide electricity systems' resilience. Hydrogen production is essential in maintaining Australia's status as an energy export superpower (Finkel, 2018). It will help achieve the challenging climate changes targets set by the COP26, as hydrogen is considered the optimal solution for carbon-free, long-term seasonal storage of energy (IEA, 2020).

If the production of hydrogen increases according to the prediction, it will be necessary to manage places where it could be stored. Underground gas storage is a well-established industry practice that can provide a large-scale storage solution for increasing electricity production by renewable source. Man-build salt caverns are already being used to store pure hydrogen gas in the U.S and England (Lord, 2009). The advantages are that the cavern can be built according to the volume and pressure request and they are practically impermeable (Lord et al., 2011), as the salt composition reduces possible gas contamination and gas leakage (Prinzhofer et al., 2018).

With the overall aim of assessing the geological and geomechanically viability for the salt cavern construction for pure hydrogen storage in Australia, the distribution of geological salt deposits within the terrestrial basins was screened. The Amadeus Basin was chosen as a case study with its two relatively well-studied geological units, the Chandler Formation, and the Bitter Springs Group. To encounter a specific site for the salt cavern construction, a geological model of the Amadeus Basin was build using geophysical data from the oil industry (GEMIS, 2020). After data collection, wireline log study of correlatability, character, and extension of the salt deposits, we deducted that the basin contains an appropriate unit for the salt cavern construction, the Chandler Formation, which is placed in the northeast part of the basin (Figure 1).

Assuming that the salt caverns will be built using a simplified design that required a minimum salt formation thickness of 65 m, the maximum cavern height was calculated using the isopach maps. The preliminary results suggest a potential to build caverns sized to a maximum of 300 meters high (Lankof and Tarkowski, 2020). However, the ground stress regime has to be considered for the cavern design and also the fracturing gradient of the rock (Mortazavi and Nasab, 2017). Although an exhaustive search of geomechanical data was carried out in the wells, no favourable data was found to calculate the geomechanical parameters. It is necessary to obtain the geomechanical data to carry out the final design of the salt caverns. In addition, it is essential to highlight that the geostatic load determines the cavern's internal gas pressure, especially knowing that the salt unit's depth varies between 700 and 2280 m.

In conclusion, adding to having these units suitable for the construction of salt caves, the zone has high renewable resource potential. The renewable energy resource can be used to produce both "green hydrogen" As well as "blue hydrogen" with the methane gas found in the area.

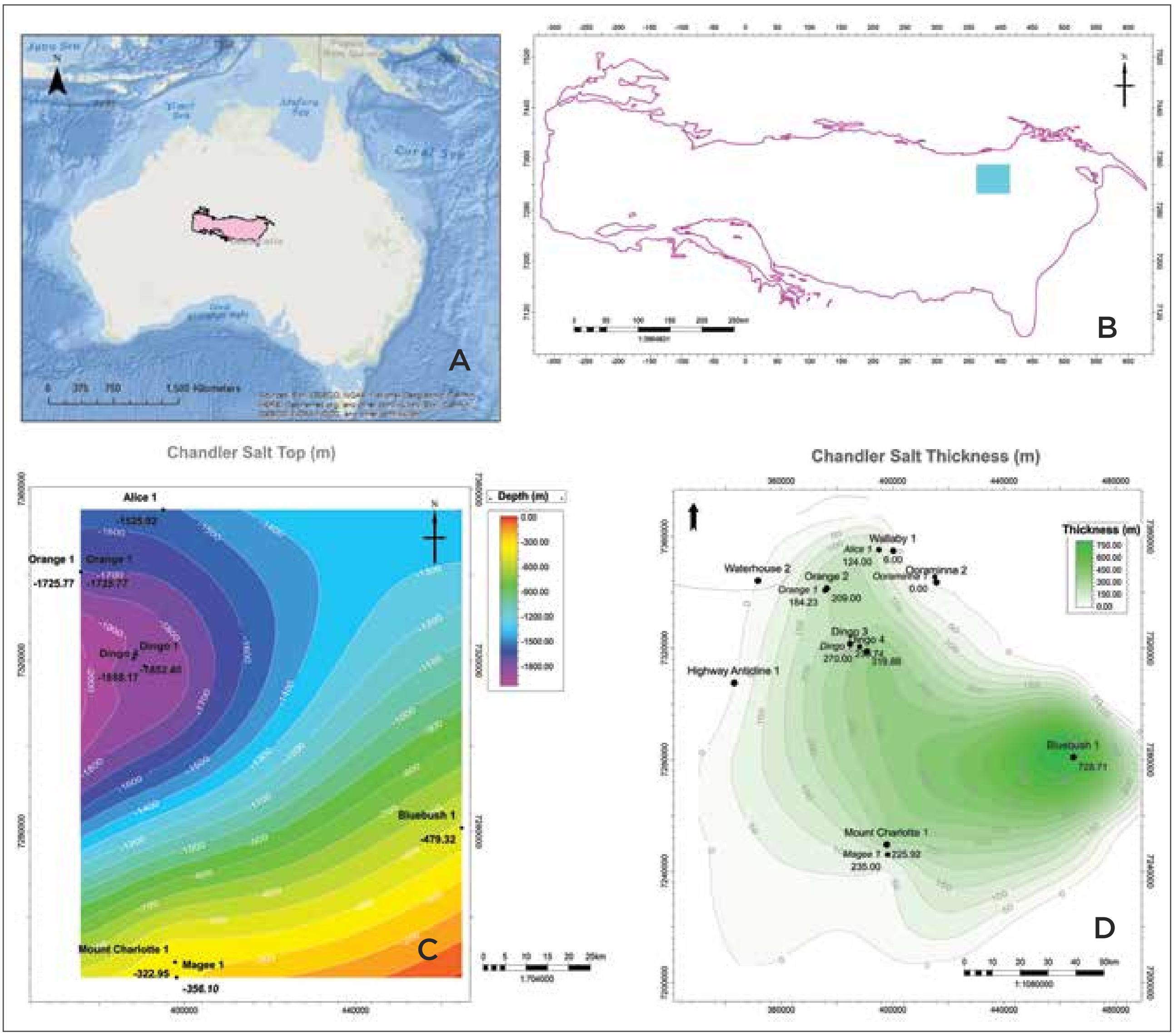

Figure 1: (A) Map showing the location of the Amadeus Basin, Australia.
(B) Map of the Amadeus Basin showing the location of the Dingo Area.
(C) Top Chandler Formation depth map in the Dingo study area.
(D) Chandler Formation isopach within the study area.

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The hidden Proterozoic successions of the Barkly region

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The Barkly 2D Deep Crustal Reflection Seismic Survey (L212) was acquired in 2019 by Geoscience Australia as a major objective of the Australian Governments' multi-year $225m Exploring for the Future (EFTF) program in partnership with, and co-funded by, the Northern Territory Geological Survey under the Resourcing the Territory initiative. The Barkly Seismic Survey extends from the newly discovered Carrara Sub-basin (Figure 1) in the South Nicholson Basin region (e.g. Carr et al., 2019) to the south-eastern margins of the Beetaloo Sub-basin. The Barkly Seismic Survey, comprising five lines (a total of 813 line kms), ties into the 2017 EFTF 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 (Figure 1). The Barkly Seismic Survey images interpreted Paleoproterozoic to Mesoproterozoic

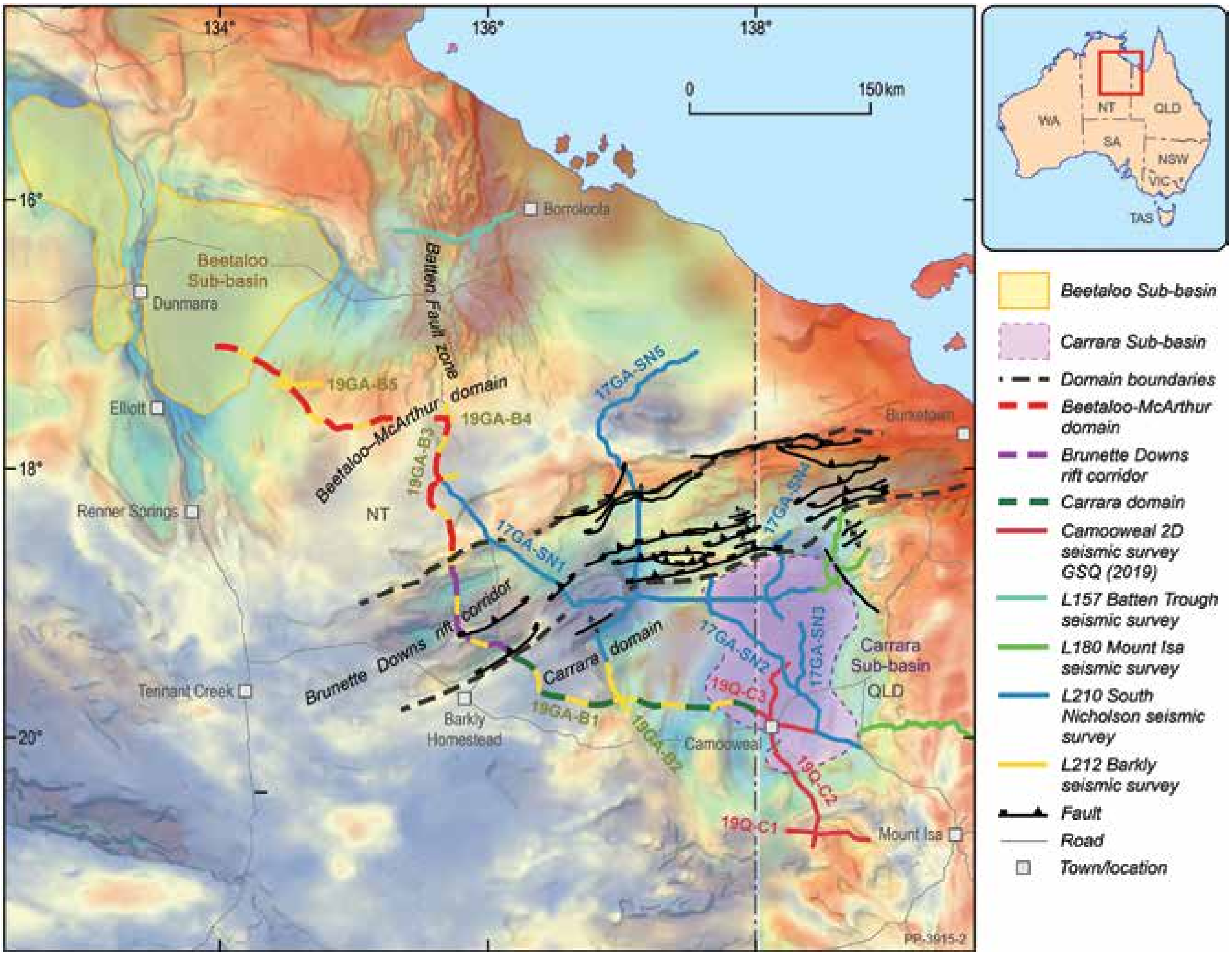

Figure 1: Location map of northeastern Northern Territory and the Mount Isa region of northwestern Queensland showing the location of the Barkly seismic survey (L212). The coloured dashed segments of the Barkly seismic survey lines indicate that component of the seismic line residing within one of the three informal domains as described in the text. The South Nicholson seismic survey (L210), acquired in 2017, also shown for reference. 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.

successions extending from the Carrara Sub-basin to the highly prospective Beetaloo Sub-basin of the McArthur Basin. These successions are concealed by a persistent cover of up to 600 m of Paleozoic Georgina Basin sediments. Interpretation of the Barkly Seismic Survey established three informal geological domains (Figure 1), each defined by structural elements and/or basin characteristics (Southby et al, 2022). These informal domains, from southeast to northwest, are:

- **Carrara domain:** includes the south-western margin of the Carrara Sub-basin and a region where the Georgina Basin unconformably overlies metamorphic basement (Figure 2). The Carrara Sub-basin is as much as 10 000 m deep (Carr et al 2019, 2020), and comprises four superbasin sequences, the Paleoproterozoic 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) (Figure 2). Within the Isa Superbasin, there is evidence of significant stratal thickening to the west where it juxtaposes a major east dipping fault (location 'C' in Figure 2, highlighted by the green dashed outlines), suggesting crustal extension during Isa Superbasin deposition, probably during the 'River' extension event at ca. 1640 Ma (e.g. Carr et al., 2019). The River extension event is widely reported for the Isa Superbasin sequences on the Lawn Hill Platform to the north-west. Structural remnants of the Roper Superbasin are labelled as A and B in Figure 2.
- **Brunette Downs rift corridor (BDrc)** (Figure 3): the Barkly Seismic Survey identified a pair of south-easterly deepening half-grabens bounded by steeply dipping bounding faults and containing the same sedimentary successions present in the Carrara domain. The Leichhardt Superbasin successions show stratal thickening to the northwest, away from the half-graben bounding faults, whereas the Calvert Superbasin and, in particular, the Isa Superbasin, show significant south-east directed stratal thickening *into* the bounding faults. These features show remarkable similarity in orientation, geometry and structural evolution to half-grabens identified along strike, to the north-east, in the South Nicholson and Lawn Hill Platform regions, indicating a continuous rift corridor extending over 400 km (Carson et al., 2020, Southby et al., 2022). The tectonic significance of the **BDrc** in the evolution of northern Australia remains to be assessed.
- **Beetaloo-McArthur domain:** (Figure 1 and 4) the seismic data reveal mostly flat-lying Proterozoic successions, between the **BDrc** and the south-eastern margin of the Beetaloo Sub-basin. These successions are interpreted to be lateral extensions of the late Paleoproterozoic successions of the Redbank, Glyde and Favenc packages (Williams, 2019). These successions are truncated to the south against a fault-bounded horst of Proterozoic basement, interpreted to be a concealed component of Murphy Province basement, which separates the **Beetaloo-McArthur domain** from the **BDrc**.

The seismic data collected during the EFTF program has established the widespread presence of highly prospective Proterozoic successions across the Barkly Tablelands region. The Barkly Seismic Survey has revealed continuous stratigraphic connections from the highly prospective Beetaloo Sub-basin across the Barkly Tablelands into the recently discovered Carrara Sub-basin. Together with the South Nicholson Seismic Survey, the Barkly Seismic Survey demonstrates direct stratigraphic continuity between the concealed Proterozoic successions across the Barkly Tablelands, the Carrara Sub-basin and the highly prospective successions of the Lawn Hill Platform. These findings will enable greatly improved regional energy and mineral resource evaluations, and stimulate greenfield exploration across this part of northern Australia.

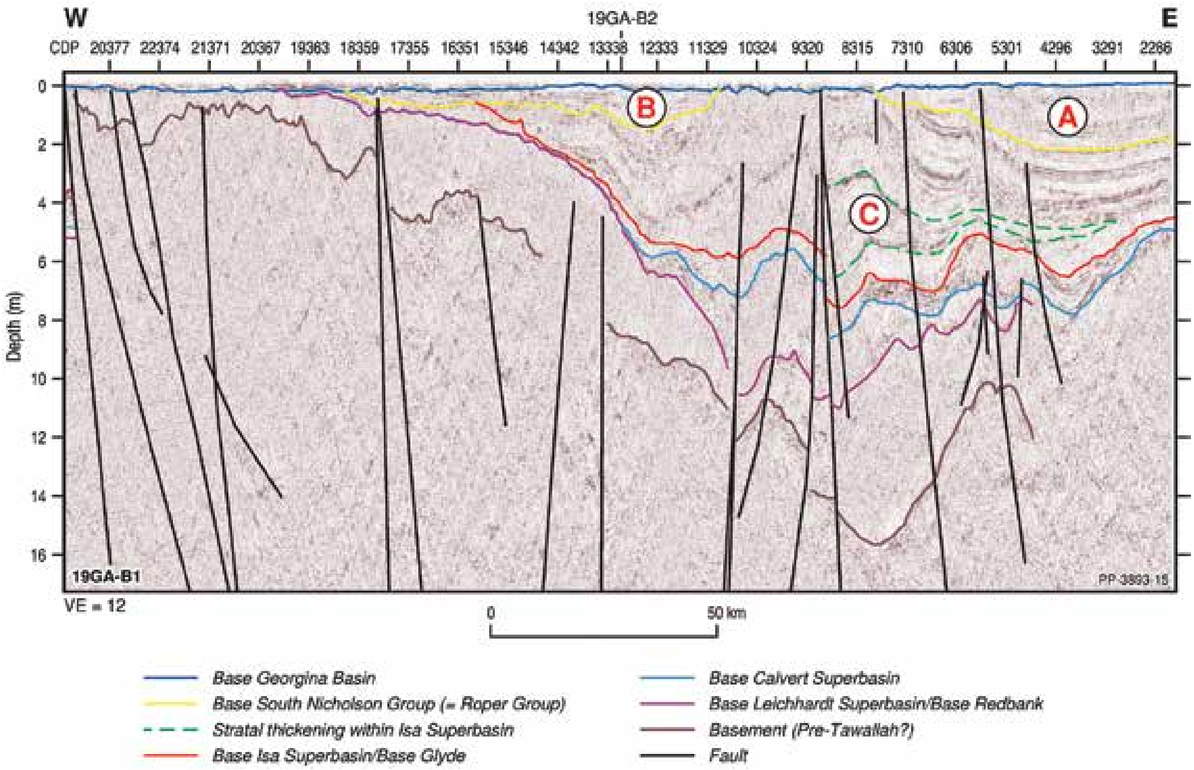

Figure 2: Seismic profile of the Carrara domain incorporating the south western part of the Carrara Sub-basin to a shoulder of metamorphic basement. Labels 'A' and 'B' denote the structural remnants of the South Nicholson Group and 'C' denotes an area of syn-depositional River extension.

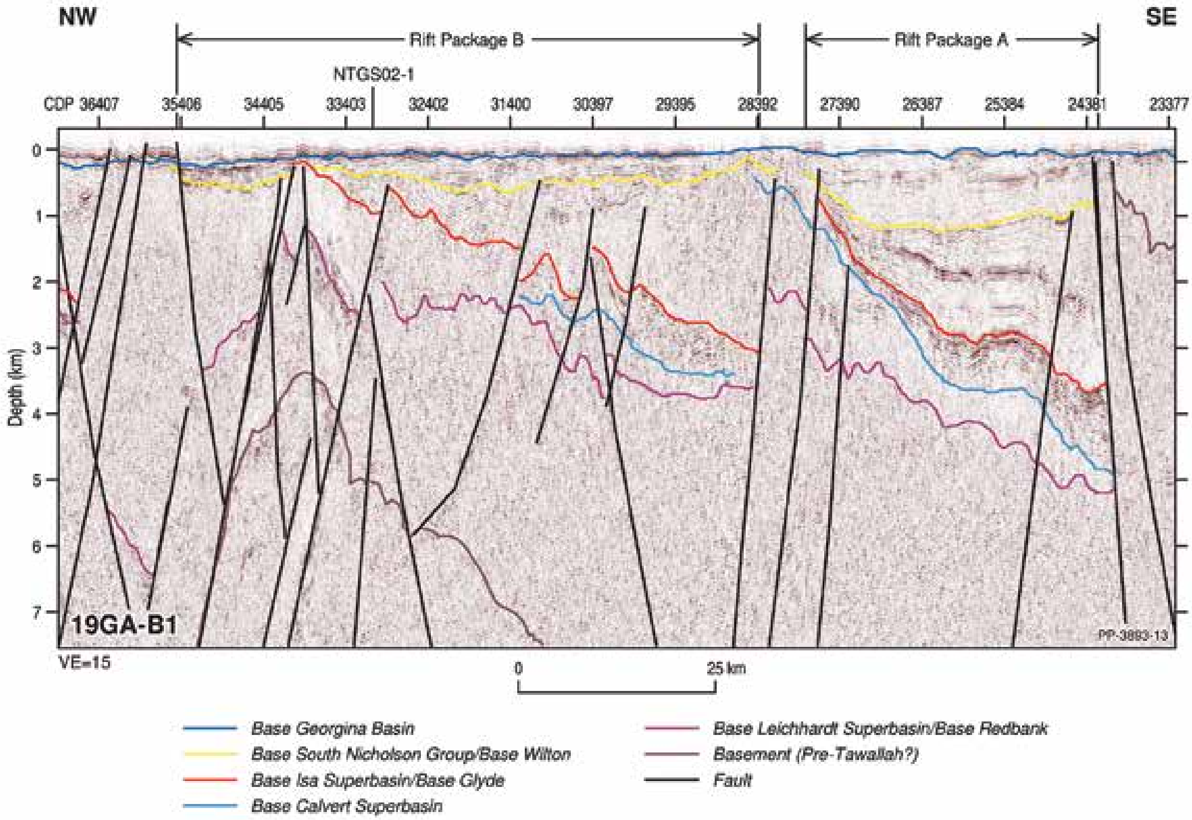

Figure 3: Interpreted seismic profile of the Beetaloo-McArthur domain

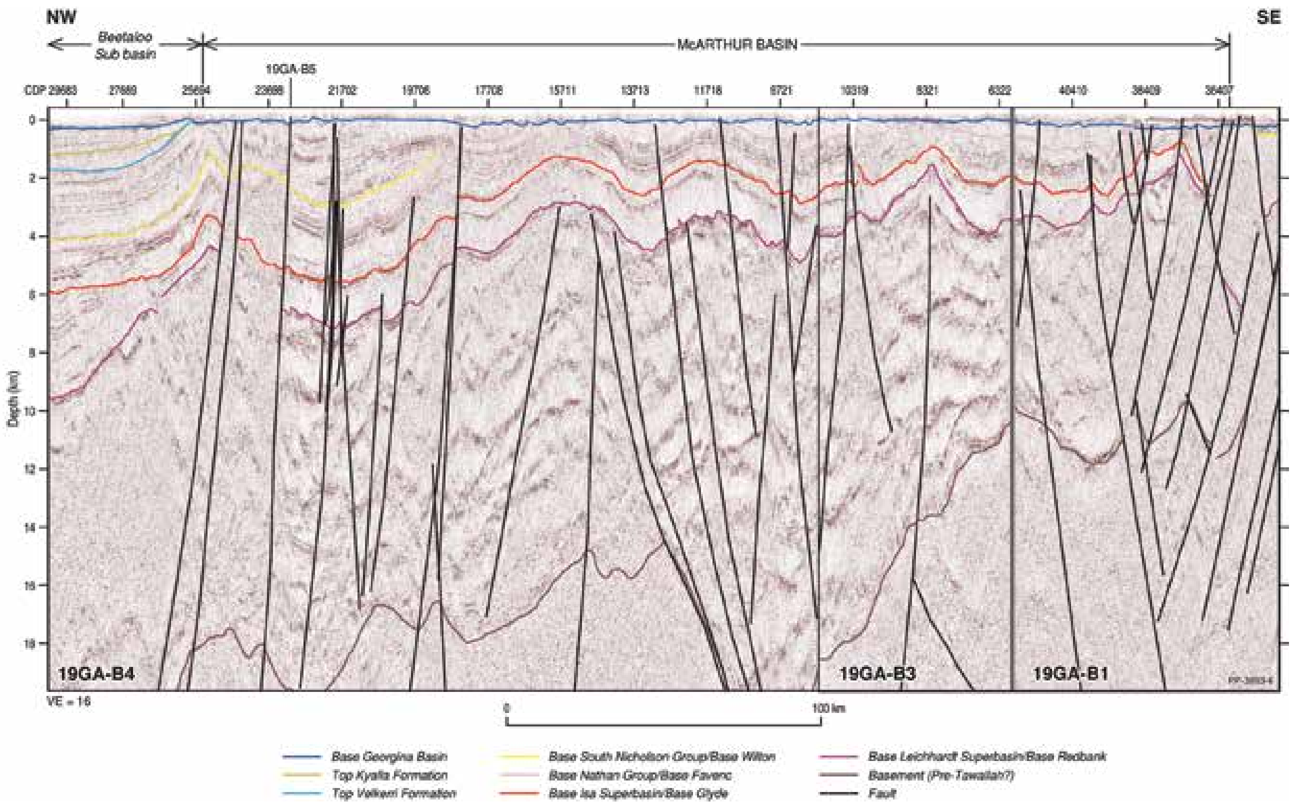

Figure 4: Interpreted seismic profile of the Beetaloo-McArthur domain.

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Notes

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