Shale geochemistry as an exploration tool in northern Australia: A comparison of the South Nicholson Basin and Lawn Hill Platform to the greater McArthur Basin

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Northern Australia contains extensive Proterozoic-aged sedimentary basins with potential energy, mineral, and groundwater resources concealed beneath the surface. The region is remote and largely underexplored with limited data and infrastructure, and therefore is considered to have high exploration risk. Exploration for hydrocarbons and basin-hosted base metals, although perceived to have very different exploration models, share a number of important similarities and key parameters. Foremost amongst these are shale geochemistry since the same reduced, organic-rich shales are both a hydrocarbon source rock and a depositional site for base metal mineralisation. Furthermore, anoxic and euxinic (anoxic with free hydrogen sulfide, H2S) water column and sediments are important for both the preservation of organic matter and as a H2S reservoir needed for precipitation of ore minerals after reaction with oxic metalliferous brines.

Here we present new organic and inorganic geochemical datasets for shales in the South Nicholson Basin, Lawn Hill Platform and greater McArthur Basin, including the organic-richness of shales and the inorganic geochemistry of redox-sensitive trace metals, to demonstrate changes in water-column chemistry and favourable base metals depositional sites. Parameters such as total organic carbon (TOC) content and redox-sensitive elemental concentrations are used to identify prospective packages with hydrocarbon and base metals mineral resource potential.

The results reveal that many units in the Lawn Hill Platform, South Nicholson Basin and greater McArthur Basin contain organic-rich rocks. A cut-off value of TOC ≥ 2 wt% is used to define several shale and carbonate sequences in the region that are favourable for both hydrocarbon generation and as base metals depositional sites. Inorganic geochemistry results demonstrate a range of paleoredox conditions, from predominantly anoxic, ferruginous conditions with deviations, to sub-oxic and euxinic conditions. Future work mapping the temporal and spatial distribution of this geochemistry, in combination with other mappable geological criteria, is required to create mineral and petroleum systems models that can define prospective fairways across the basins and increase our understanding of resource potential.

The precompetitive data generated in this study highlight the utility of shared geochemical datasets for resource exploration in the region. More broadly, this study improves our understanding of the energy and mineral potential across northern Australia, supporting resource decision-making and investment.

Introduction

Proterozoic-aged sedimentary basins in northern Australia have been identified as having high potential for a range of commodities, including mineral, petroleum and groundwater resources (e.g. Huston et al 2006, Jolly et al 2013, Revie 2017, Gorton and Troup 2018). Exploration for hydrocarbons and base metals are often related because reduced and organic-rich shales are both the source rocks for hydrocarbons and the depositional sites for base metals mineralisation (Magoon and Dow 1994, Embs 2009). For example, in the McArthur Basin, the mineral exploration well GR9 experienced a gas blow-out. Analysis of headspace gas demonstrated that the well was flowing gas condensate (hydrocarbon lengths >C7; Thomas 1981). This demonstrated a conventional gas play in the Barney Creek Formation, the host for the McArthur River (HYC) zinc-lead-silver deposit (Murray 1975). Furthermore, the black shale host rocks of the Century lead-zinc deposit in the Lawn Hill Platform contain TOC values up to 10 wt%; the identification of prolific oil staining and solid bitumen in the mine is also indicative of an active petroleum system (Waltho 1993, Broadbent et al 1998).

Petroleum exploration has largely focused on two regions: the Beetaloo Sub-basin in the greater McArthur Basin (Munson 2014, Revie 2017, Schenk et al 2019, Figure 1) and the northern Lawn Hill Platform in Queensland (Gorton and Troup 2018). Organic-rich shales of the Velkerri and Kyalla formations in the Beetaloo Sub-basin host conventional oil and gas plays, in addition to unconventional continuous shale-oil and gas prospects (Côté et al 2018). Recently, the United States Geological Survey quantitatively assessed these formations as having undiscovered, technically recoverable, mean resources of 429 MMbbls of continuous oil and 8 Tcf of continuous gas (Schenk et al 2019). On the Lawn Hill Platform, thick extensive organic-rich shale units of the River and Lawn supersequences have been estimated to contain 22.1 Tcf of gas condensate (hydrocarbon lengths >C7; Thomas 1981). Hydrocarbon shows and organic-rich sedimentary sequences indicate that other conventional and unconventional plays may also occur in overlying stratigraphic units within the Lawn Hill Platform and overlying Mesoproterozoic South Nicholson Basin (Gorton and Troup 2018, Jarrett et al 2019).

A corridor of extensive Zn-Pb-Ag mineralisation spans across the region from the southern Mount Isa Province to the greater McArthur Basin (Figure 1). This region, known as the North Australian Zinc Belt, contains several world-class zinc-lead deposits (McArthur River, Hilton-George

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Fisher and Mount Isa) and a number of important smaller deposits (e.g., Cannington, Century, Myrtle, Teena and Lady Loretta; Sweet et al. 1993, McGoldrick and Large 1998, Large et al. 2005, Huston et al. 2006, McGoldrick et al. 2010), as well as uranium, iron, and copper-cobalt deposits. More recently, these basins have been recognised as having potential for critical, or new economy minerals, such as germanium (Shanks et al. 2017, Mudd et al. 2018).

Factors influencing unconventional petroleum system prospectivity have been summarised by Revie (2017); they broadly consist of geological considerations (thickness, extent and depth), TOC content, thermal maturity, mineralogy, and reservoir conditions. The work undertaken in this study has focused on generating new data for assessing TOC content (Figure 3), thermal maturity (e.g., Jarrett et al. 2019c) and mineralogy (Jarrett et al. 2019a). Revie (2017) undertook a petroleum resource assessment of the unconventional shale oil and gas potential of the Velkerri and Kyalla formations of the Wilton Package. A similar approach has been undertaken in this study, focusing on older units in the greater McArthur Basin, the Lawn Hill Platform and the South Nicholson Basin, by utilising new datasets generated during the Exploring for the Future (EFTF) program (Bradshaw et al. 2018, Palu et al. 2018, Jarrett et al. 2018a, b; 2019a, d; Bailey et al. 2019).

A mineral systems assessment approach to identify the fertility of regions of interest has been used for over 25 years (Wyborn et al. 1994, Schofield 2011, Dufier et al. 2016, Skirrow et al. 2019). Although the approaches and concepts have evolved through time, the four essential components of a mineral system remain similar and include: 1) metal, fluid and sulfur sources; 2) fluid flow trigger; 3) architecture and fluid pathways; and 4) ore depositional mechanisms. The results of this study are directly applicable to the fourth component of the mineral systems framework in sedimentary-hosted base metal mineral systems. In northern Australia, sediment-hosted zinc-lead mineralisation is found within fine-grained, reduced and organic-rich siliciclastic units and may contain varying concentrations of carbonate and pyrite (Large et al. 2005, Huston et al. 2006). The TOC content of sedimentary rocks is a defining characteristic of a fertile basin, thus TOC can be used to identify sedimentary units that would host and preserve base metal mineralisation. High TOC is associated with sediments that were deposited in anoxic and often euxinic conditions. Euxinia in particular, demonstrates free H2S in the water column and sediments, and will ultimately be favourable for reducing base metals from oxidised brines, in addition to the preservation potential of organic matter (Cooke et al. 2000, Emsbo 2009).

One of the challenges in exploring in northern Australian basins is the limited amount of shale data available due to the paucity of boreholes (Carr et al. 2016), low-resolution geochemical data coverage and often poor or incomplete legacy data quality, as well as disparate data storage locations. The McArthur Basin contains an extensive organic geochemistry dataset that has been compiled and maintained by the Northern Territory Geological Survey (Revie and Normington 2020). The South Nicholson Basin and Lawn Hill Platform region of the Isa Superbasin are relatively data poor in comparison, as demonstrated in a
baseline study undertaken prior to sampling and analyses (Jarrett et al 2018c). The baseline study results have shown significant data gaps and sometimes incomplete legacy data requiring reanalysis (Jarrett et al 2018c).

To address this data paucity, Geoscience Australia has undertaken a sampling program of legacy drill cores from the Northern Territory and Queensland to characterise the organic and inorganic geochemistry and mineralogy of Proterozoic-aged sedimentary rock units in the South Nicholson Basin, Lawn Hill Platform and greater McArthur Basin, in order to improve our understanding of basin-hosted resources. Herein we describe some of the results from this study using shale geochemistry as an exploration tool in a regional context. All data and derived reports are accessible on the EFTF portal (https://portal.ga.gov.au/persona/eftf), which provides a central location to access this research material to assist with informed decision-making.

Organic geochemistry

Shale geochemistry, including organic richness (TOC wt%) and hydrocarbon quality (Rock-Eval pyrolysis) was conducted on 1066 samples from wells in the South Nicholson Basin, the Lawn Hill Platform and brownfield areas of the greater McArthur Basin (Figure 1; See Jarrett et al 2018b for an updated methodology). TOC is used to screen potential petroleum source rocks where TOC ≥2 wt% is ‘good’ and TOC ≥5 wt% is ‘excellent’ (Peters and Casa 1994). Additionally, TOC is used to screen for potential base metal depositional sites where reduced stratigraphy can act as an effective chemical gradient along which metal may be deposited. Mass balance calculations suggest TOC of 1 wt% is the minimum amount of organic matter required; global sedimentary-hosted base metal deposits usually occur within shales that have TOC ≥3 wt% (Emsbo 2009). Therefore, to be consistent with both petroleum and mineral exploration, a TOC cut off of 2 wt% was applied as a minimum cut off for favourable shales.

The Lawn Hill Platform contains several shales and carbonates sequences with good organic richness (TOC >2 wt%), including the Walford Dolostone, Riversleigh Siltstone, Mount Les Siltstone, Lawn Hill Formation, Termite Range Formation, and the Doomadgee Formation (Figure 2). For example, new geochemistry generated from the Mount Les Siltstone in Northern Territory drillhole ND2 demonstrate ‘good’ organic-richness extending the petroleum potential of the River Supersquence (Bradshaw et al 2000) from the resource-rich northwest Queensland into the Northern Territory. New regional seismic data, obtained as part of EFTF, have established that these thick Paleoproterozoic superequences extend through the South Nicholson region into the Carrara Sub-basin (Carr et al 2019, Henson et al 2018).

Samples from the greater McArthur Basin shales are also organically rich (TOC ≥2 wt%) with good to excellent petroleum potential (Revie and Normington 2020). Shales from the Redbank Package (including the Wologorang Formation and McDermott Formation), in addition to shales and carbonates from the Favenc package (including the Balbirini Dolostone and Dungaminnie Formations), have TOC ≥2 wt% (Figure 2). Several formations in the Glyde Package of similar age to those of the Lawn Hill Platform also contain good organic richness, including the Barney Creek Formation, Caranbirini Member of the Lynott Formation, Kunja Siltstone, Lynott Formation (unspecified), Fraynes Formation, Saint Vidgeon Formation, Toogangie Formation, Vaughton Siltstone, and the Yalco Formation (Figure 3). Finally, Mesoproterozoic-aged shales in the Wilton Package with favourable TOC include the Velkerri, Kyalla and Cocoran formations (Figure 3).

In the South Nicholson Basin, only three wells intersect shales of the Mesoproterozoic Mulhera Formation, one of which (drillhole NTGS 00/1) does not penetrate the entire succession. The Mulhera Formation has a maximum TOC of 4.05 wt%, demonstrating ‘good’ organic richness (Figure 3). Although geochemical data is not available for these units, field mapping in the South Nicholson Basin identified ‘saprolite facies’ interpreted as weathered pyritic shale (Rawlings et al 2008). This formation has recently been reinterpreted as the Paleoproterozoic Crow Formation (Kositcin and Carson 2019; see Carson et al 2020 - this volume). The identification of pyritic shale units within the Paleoproterozoic significantly increases the resource potential of the South Nicholson region by adding an additional target interval for future exploration.

Work is currently being undertaken to spatially plot the extent of TOC values across each basin as a mappable geological proxy for petroleum source rocks and base metal depositional sites. This will allow for the identification of prospective fairways within the basin where explorers can focus resources (Hood et al 2000). Additional mappable criteria, including base metal sources and regions of geochemical alteration, are being generated as part of the EFTF program (See Champion et al this volume) that could be used as inputs to map base metal potential over northern Australia (eg Skirrow et al 2019).

Inorganic geochemistry

Understanding the key controls on TOC are important to predicting the location of petroleum and mineral systems, and reducing the exploration search space. Variations in the redox state will affect the amounts of H2S in the sediment, the preservation potential of organic matter and the availability of a hydrogen sulfide reservoir required for a base metal depositional site. Cooke et al (2000) describe paleoredox as a first-order control on base metal mineralisation since an euxinic water column, by definition, is anoxic with free hydrogen sulfide, H2S (Berner et al 1985). Excess H2S will readily react with oxidised metal-bearing fluids precipitating sulfide-bearing minerals (Emsbo 2009). Additional sources of electrons include the oxidation of organic matter facilitated by biological or thermochemical sulfate reduction (BSR or TSR) that does not require water column euxinia (Dick et al 2014).

To understand variations in paleoredox in organic-rich shale, inorganic geochemistry was undertaken at Geoscience Australia’s inorganic geochemistry laboratory on 1954 samples from the McArthur Basin, Lawn Hill Platform and South Nicholson Basin (Champion et al 2020a, b; Carson...
Figure 2. Stratigraphic column of Proterozoic basins in northern Australia with box and whisker plots showing the distribution of total organic carbon (TOC wt%) for formations with TOC ≥2 wt%.
Figure 3. Inorganic geochemistry of shale samples comparing the greater McArthur Basin (composed of the Birrindudu Basin and McArthur Basin proper, in this study) with the Lawn Hill Platform and South Nicholson Basin. All data used in this study is from Geoscience Australia’s OZROCKS database. (a–b) Total Fe/Al vs Mo/TOC. (c–d) Pr* vs Ce*, where Pr* = PrSN / 0.5(CeSN + NdSN) and Ce* = CeSN / [0.5(LaSN + PrSN)]. Normalization was to the Post Archean Australian Shale (PAAS) (Nance and Taylor 1976). (e–f) Mo (ppm) vs V/Mo. (g–h) U enrichment factor (UEF) vs Mo enrichment factor (MoeF) where the trace metal (TM) enrichment for samples was calculated as TMef = (TM_sample/Al_sample)/(TM_PAAS/Al_PAAS).
The paleoredox state was determined using redox-sensitive trace elements, including ratios of total iron (Fe), molybdenum (Mo), uranium (U), vanadium (V) and cerium anomaly (Ce*) (eg Algeo and Lyons 2006, Scott et al 2008, Wilde et al 1996). Trace metals suggest a range of redox states from sub-oxic to eutinic, with pervasive sub-oxic deep water to anoxic waters occurring through the Proterozoic. Definitive eutinic conditions based on trace metal and ratios are only evident in some samples (ie Barney Creek, Fraynes, Wollogorang and Velkerri formations), but this redox state appears episodic. These results are consistent with other studies in the region (Planavsky et al 2011 Cox et al 2016, Spinks et al 2017, Farkas et al 2018, Jarrett et al 2019b). Water column, or pore water euxinia represents more favourable deposition sites for sediment-hosted base metals, especially where these occur in conjunction with favourable architecture and metal sources.

Conclusions

Exploration for both hydrocarbons and base metals can use shale geochemistry to define favourable conditions and reduce the exploration search space. In order to improve our understanding of basin-hosted resources, Geoscience Australia has undertaken a sampling program of legacy drill core from the Northern Territory and Queensland to characterise the geochemistry of Proterozoic-aged sedimentary units in the South Nicholson Basin, Lawn Hill Platform and greater McArthur Basin.

The results of this study demonstrate that multiple formations in the Lawn Hill Platform, greater McArthur Basin and South Nicholson Basin contain ‘good’ organic richness with ≥2 wt% TOC. Inorganic geochemistry demonstrates a range of paleoredox from predominantly anoxic, ferruginous conditions with deviations to eutinic conditions favourable for base metal prospectivity and important for organic matter preservation. The temporal and spatial distribution of this geochemistry can be combined with additional geological and geochemical information to predictively map resource potential and advise on areas of higher favourability.

Future work will consist of mapping out these geochemical changes in organic and inorganic geochemistry across the region to provide a spatial representative of the ore-depositional potential in the region. Additionally, combining this new data and geochemical interpretations across multiple scales from the regional system to the deposit scale (Spinks et al 2019) will also be a useful tool for understanding the extent and composition of shales across the region.

This study highlights the utility of shale geochemistry as an exploration tool for understanding both hydrocarbons and base metal prospectivity in the region. Significant findings demonstrate the continuity of prospective supersequences from the resource-rich northwest Queensland into the Northern Territory. The results assist to increase our understanding of the greater McArthur Basin and the South Nicholson Basin with precompetitive data for resource exploration.

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