Are spatial mineralogical variations in the Bessie Creek Sandstone, McArthur Basin, evidence for variable provenance, diagenesis or hydrothermal alteration?

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Introduction

The Mesoproterozoic Bessie Creek Sandstone of the Roper Group is a laterally extensive formation in the McArthur Basin (**Figure 1**). This formation is economically significant due to its potential as a hydrocarbon reservoir based on its sedimentological characteristics, stratigraphic position relative to source rocks, and the presence of oil shows in several wells (Munson 2014). An understanding of the distribution of mineralogical variations of the Bessie Creek Sandstone may assist in evaluating its reservoir potential in different parts of the McArthur Basin.

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Previous lithological descriptions of the Bessie Creek Sandstone have reported a supermature composition of >99% quartz with quartz overgrowth cement, rare chert and mica, minor interstitial clays and iron oxide minerals. Abbott *et al* (2001) described the lithological succession as monotonous, with a lack of paracycle development suggesting a uniformity of mineralogy. HyLogger™ data from wells intersecting the Bessie Creek Sandstone indicate a mineralogical variation that is inconsistent with this observation. Significant clay mineral differences are observed in the HyLogger data and may reflect variations in either diagenetic history, localised hydrothermal alteration, variable source material provenance, or a combination of these factors.

To test the apparent stratigraphic uniformity previously reported for the Bessie Creek Sandstone, 12 wells logged as intersecting the unit (**Figure 1**) were scanned using HyLogger 3-7. This instrument measures reflectance spectra

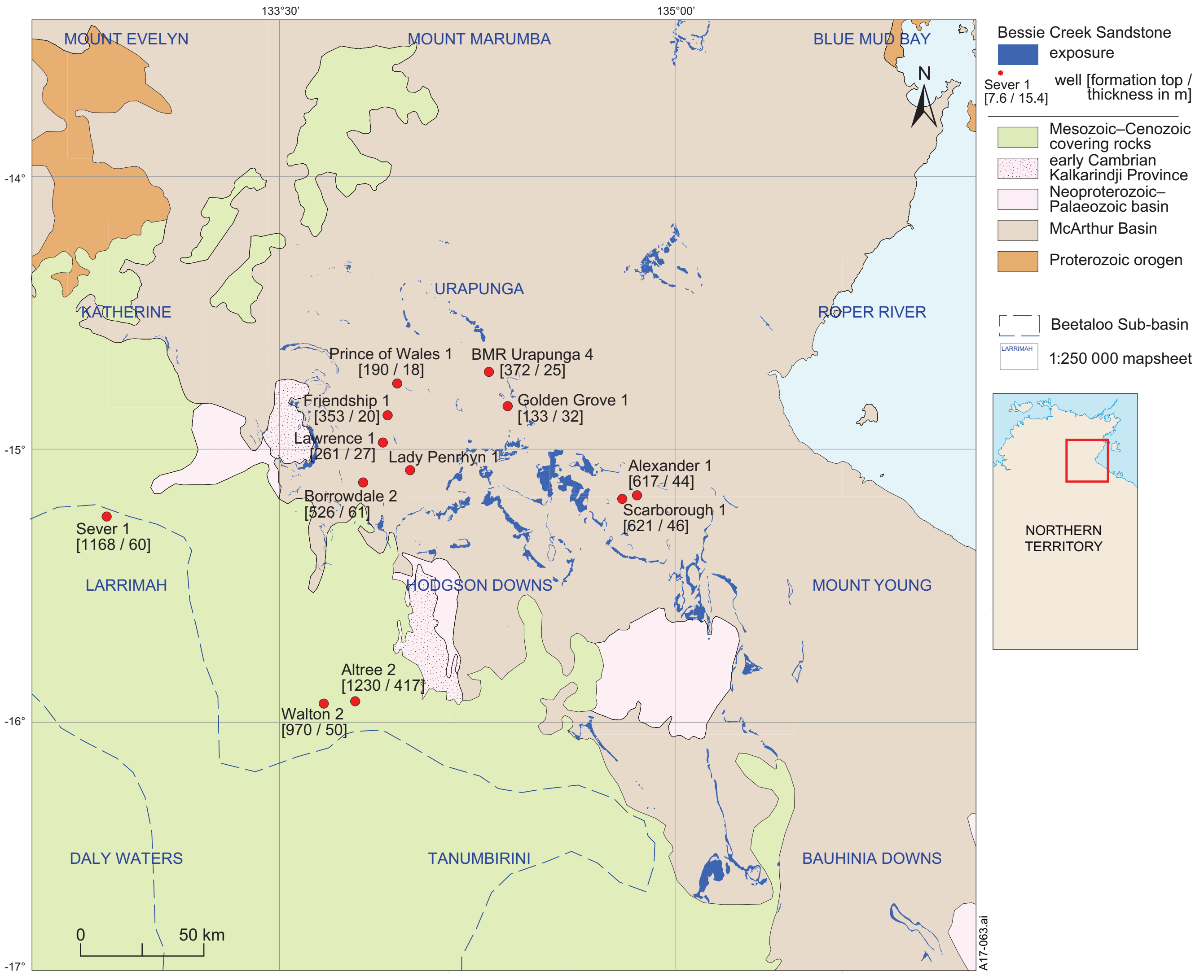

Figure 1. Location map showing extent of mapped Bessie Creek Sandstone and HyLogged wells that intersect the Bessie Creek Sandstone. Each well is marked with the depth to the formation top and the logged thickness (rounded to nearest metre) of the stratigraphic succession. Modified from Munson (2016).

and collects co-registered digital imagery from the drill core intercepts. Measured reflectance spectral data is from the visible-near-infrared (VNIR) to shortwave-infrared (SWIR) wavelengths (380–2500 nm) and thermal infrared (TIR) wavelengths (6000–14 500 nm). Spectra are spaced at 8 mm along the cored material.

The reflectance spectra were modelled using The Spectral Geologist (TSG) software to produce an interpreted mineral composition using The Spectral Assistant (TSA) algorithm and by referencing the inbuilt spectral mineral library. The TSA mineral results may be different in the SWIR and TIR wavelength ranges due to the physical properties of the minerals in the rock sample. Anhydrous silicate minerals such as quartz and feldspars have diagnostic features in the TIR wavelength range but none in the SWIR. For example, a quartz-rich rock with minor clay will match only to the clays in the SWIR but will match to the quartz in the TIR.

X-ray diffraction (XRD) analysis was used to validate the HyLogger mineral results. Eleven samples from five drillholes were sent to Mineral Resources Tasmania for XRD analysis, three of which were further analysed by X-ray fluorescence (XRF) to confirm the XRD-determined mineralogy. One sample was prepared as a thin section to study the presence and distribution of hydrocarbons (Bottrill and Woolley 2016).

The resultant data for all drillholes are available to view and download from the Australian Geoscience Information Network (AusGIN) portal (http://portal.geoscience.gov.au/gmap.html: Boreholes | National Virtual Core Library submenu). Five of the wells are also available as HyLogger Data Packages (Smith 2014a, b, c; Smith 2015a, b). These reports contain additional interpretations and information for the individual wells.

Results

Both TIR spectra reflectance spectroscopy and XRD analyses confirmed quartz as the dominant mineral for all measured samples (**Table 1**). **Figure 2** shows the variations in mineralogy for the Bessie Creek Sandstone intercepts in both the SWIR and TIR. However, there are mineral variations, both within a drillhole profile and between drillholes, as shown by the SWIR spectra. The variations in the SWIR mineral matches can be broadly grouped as:

a) kaolin group minerals (which can be subdivided into kaolinite-rich zones, or dickite-rich zones)
b) white mica minerals (which may be diagenetic white micas or illites; or a combination)
c) chlorite minerals
d) ‘aspectral’ response or no mineral match: a response that does not match to any reference mineral sample in the spectral library. Several factors may cause a SWIR aspectral response: It may be due to the absence of the mineral in the library, noisy spectra from melanocratic core, or from finely disseminated magnetite or sulfides.

The easternmost wells (BMR Urapunga 4, Golden Grove 1, Scarborough 1 and Alexander 1) can be grouped both spatially and by the dominance of dickite in the SWIR spectra. Dickite is also dominant in Walton 2, drilled further west within the Beetaloo Sub-basin. Dickite is generally considered as being a relatively high temperature and low pressure kaolin polymorph, typically associated with hydrothermal alteration or diagenesis following a relatively great depth of burial (Beaufort *et al* 1998).

Further west, Sever 1 and Borrowdale 2 have similar divisions of white mica (>50% of the profile), with small chlorite zones (near stratigraphic boundaries) and SWIR aspectral zones (**Figure 2**). In Sever 1, the top section of the hole is dominantly aspectral; white mica is dominant at depth. In Borrowdale 2, the pattern is reversed with the top part of the well dominantly white mica, and aspectral at depth.

Lawrence 1 is dominantly chlorite (SWIR) for the upper part of the Bessie Creek Sandstone (260–280 m). The upper contact of the Bessie Creek Formation in Lawrence 1 is the Derim Derim Dolerite, a Mesoproterozoic sill that intrudes Roper Group metasedimentary rocks (Munson 2016).

In Friendship 1, the upper part of the Bessie Creek Sandstone (352–370 m) produces an aspectral SWIR response corresponding to documented hydrocarbon shows (Ledlie and Torkington 1988). Within this zone, the SWIR response displayed reflectance features at 1730 nm, 2308 nm, and 2350 nm that have been identified as a hydrocarbon response in other spectral work (Smith 2014d). A sample from this zone was prepared as a thin section and studied by polarised light microscopy (**Figure 3**).

Lady Penrhyn 1 displays a greater variation in distribution of minerals within the profile compared with Bessie Creek Sandstone intercepts from the other drillholes. Four response variations (kaolin group minerals, white micas, chlorites and aspectral SWIR response) are found within short repeating intervals that typically vary from 2–5 m in width. This pattern of cyclicity contrasts with the other wells, which show a ‘block mineral’ profile of one mineral dominant over a broad interval within the succession.

Scarborough 1 samples sent for XRD analysis indicate two types of white mica. The XRD trace peak height ranges have low crystallinity that suggest the micas are illite or illitic muscovite within samples that also contain kaolin group minerals (Bottrill and Woolley 2016).

The logged thicknesses and formation tops were also noted (**Figure 1**). With the exception of Altree 2, thicknesses vary from 20 m (Friendship 1) to 61 m (Borrowdale 2). Wells within the Beetaloo Sub-basin have the deepest formation top depths (1230 m to the top of the Bessie Creek Sandstone in Altree 2). In Golden Grove 1, the top of the Bessie Creek Sandstone is at 133 m.

Discussion

The XRD and petrography results validate quartz as the dominant mineral with minor (commonly 2–15%) dickite, kaolinite, white mica, chlorite, and hydrocarbons (**Table 1**) in the composition of the Bessie Creek Sandstone. Some minor sporadic TSA (TIR) feldspar matches (as an accessory mineral with dominant quartz) were not confirmed by XRD. Petrographic work shows

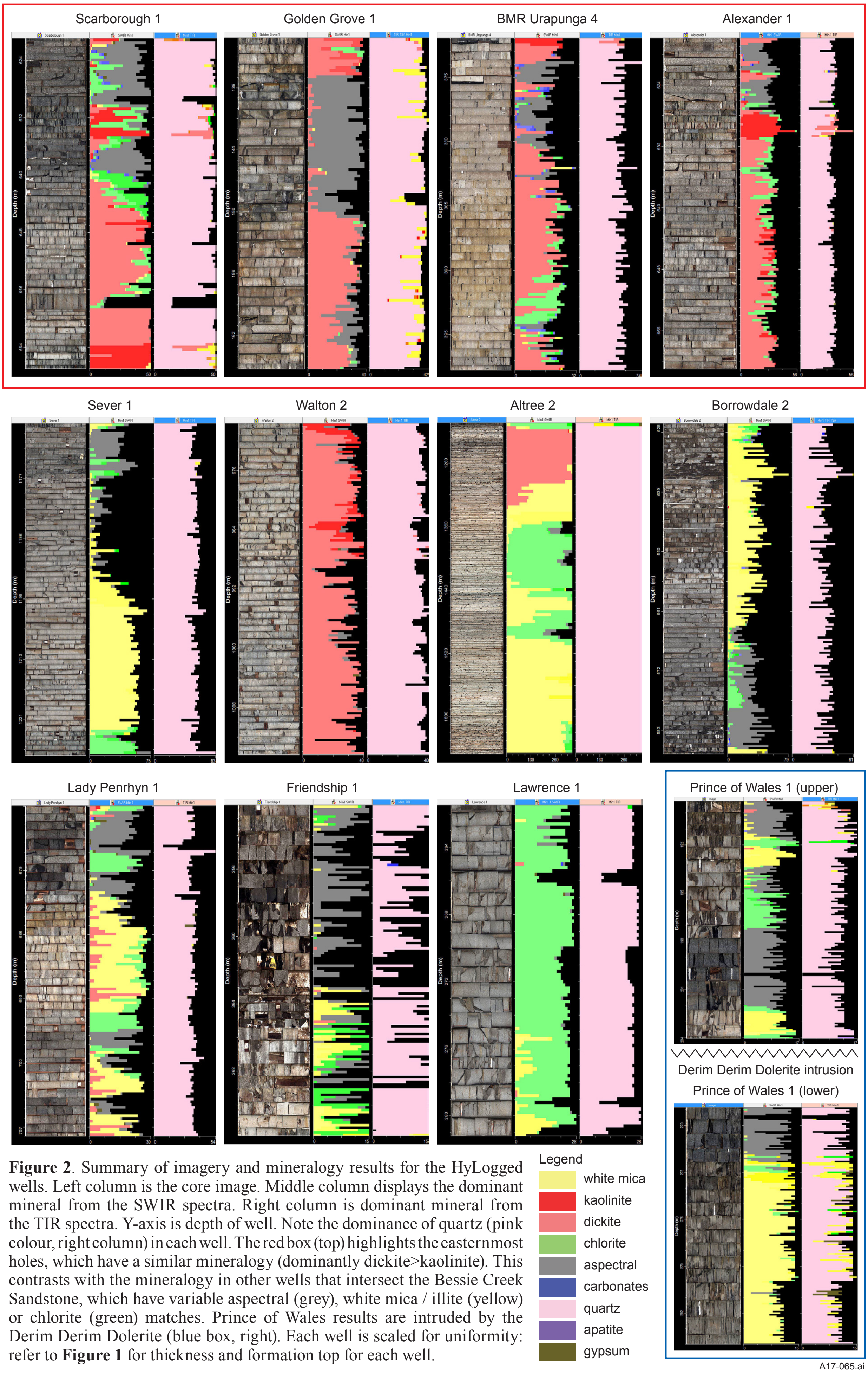

Figure 2. Summary of imagery and mineralogy results for the HyLogged wells. Left column is the core image. Middle column displays the dominant mineral from the SWIR spectra. Right column is dominant mineral from the TIR spectra. Y-axis is depth of well. Note the dominance of quartz (pink colour, right column) in each well. The red box (top) highlights the easternmost holes, which have a similar mineralogy (dominantly dickite>kaolinite). This contrasts with the mineralogy in other wells that intersect the Bessie Creek Sandstone, which have variable aspectral (grey), white mica / illite (yellow) or chlorite (green) matches. Prince of Wales results are intruded by the Derim Derim Dolerite (blue box, right). Each well is scaled for uniformity: refer to **Figure 1** for thickness and formation top for each well.

well rounded detrital quartz grains with a later stage of quartz cementation and no feldspar (**Figure 3**).

There are mineral distribution patterns; dickite is most common in the easternmost holes (and Walton 2). Dickite can be distinguished from kaolinite, both within a well profile and between wells. These easternmost holes contain little or no white mica. Holes further west (Sever 1, Borrowdale 2, Lawrence 1) have little or no kaolin group minerals. This distribution demonstrates that mineral zonations are present, both spatially and with depth. These mineral variations within the Bessie Creek Sandstone could be due to one or a combination of the following factors:

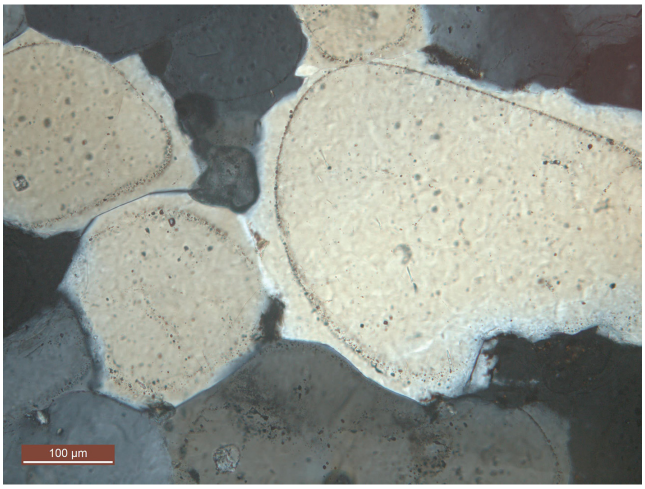

Figure 3. Petrographic sample from Friendship 1, 352.8 m (crossed polarised transmitted light). Brown hydrocarbons present as fine fluid inclusions in rims around rounded detrital quartz grains. The quartz grains show overgrowths of quartz encasing the hydrocarbons.

a) differences in provenance, leading to differences in the quantity and composition of feldspars and detrital micas during deposition, and grainsize variations
b) differences in diagenetic history across the McArthur Basin (burial depth, water influx and expulsion)
c) hydrothermal alteration effects from dolerite emplacement or other fluid movements.

Evidence for provenance

Collins *et al* (in prep) have identified spatial and temporal variations in provenance sources for several stratigraphic units, including the Bessie Creek Sandstone. Different source rocks may affect the detrital mica and feldspar composition at the time of deposition. Variations in provenance could influence the composition of authigenic minerals formed during diagenesis. This may partly account for the presence of kaolinite/dickite in the eastern wells, as opposed to white mica/kaolinite in the western wells. Differing amounts

Table 1. Comparison of mineralogy derived from HyLogger data and mineralogy identified from XRD analysis. XRD results in approximate wt%. Refer to Bottrill and Woolley (2016) for further notes on peak overlaps in individual samples.

NTGS Sample ID	DDH: depth (m)	HyLogger Mineralogy	Main XRD mineralogy
UR16BRS005	Golden Grove 1: 151.98 m	quartz, dickite	quartz (>80%) dickite (10%–15%)
UR16BRS006	Golden Grove 1: 154.89 m	quartz, dickite	quartz (65%–80%) dickite (15%–25%) mica (<2%)
HD16BRS001	Scarborough 1: 656.9	quartz, dickite	quartz (>80%) dickite (5%–10%) chlorite[1] (<2%)
HD16BRS002	Scarborough 1: 663.74	quartz, dickite	quartz (>80%) mica (5%–10%), dickite (5%–10%), 'crandallite' [exact id unknown (2%–5%)] Anatase (<2%)
HD16BRS003	Scarborough 1: 664.54	wx kaolinite> muscovite (clays); with minor quartz, microcline	kaolinite (35%–50%), mica [2 types dioctahedral present (25%–35%)] quartz (25%–35%), anatase (<2%), ? [possible jarosite or crandallite-like mineral]
HD16BRS004	Scarborough 1: 665.4	quartz, kaolinite>dickite; minor muscovite, microcline	quartz (50%–65%), kaolinite (15%–25%) mica [probably 2 types dioctahedral present (10%–15%)] barite (5%–10%), dickite (2%–5%), anatase (<2%)
LH16BRS001	Sever 1: 1204.68	quartz, muscovite	quartz (>80%), mica (<2%), chlorite (<2%) [mica>chlorite]
LH16BRS002	Sever 1: 1218.5	quartz, muscovite	quartz (>80%), mica (<2%), chlorite (<2%) [mica>chlorite]
UR16BRS007	Lawrence 1: 263.37	quartz, chlorite	quartz (>80%), chlorite (<2%), mica (<2%) [chlorite>mica]
UR16BRS008	Lawrence 1: 288.31	quartz, muscovite> chlorite	quartz (>80%), mica (<2%), chlorite (<2%) [mica>chlorite]
UR16BRS009	Friendship 1: 352.58	quartz; ?hydrocarbons?	quartz (>80%), chlorite (<2%)

of transport and reworking prior to deposition may have influenced the proportion of feldspars and detrital micas in the original sediments.

Evidence for diagenesis

The most compelling evidence of diagenesis is the presence of syntaxial quartz cements on rounded quartz grains from the petrographic samples. Studies in other basins (McBride, 1989) have noted that quartz cement precipitates from the ascending formation water at burial depths of several kilometres corresponding with 60° to 100°C temperatures.

Results from Friendship 1 indicated the presence of hydrocarbons in both the petrographic and HyLogging data. The timing of hydrocarbon migration (**Figure 3**) appears to have been relatively early, as authigenic quartz cement encases the hydrocarbons. This implies hydrocarbon emplacement occurred when porosity and permeability were relatively high before occlusion by the siliceous cement. Dorrins and Womer (1983) concluded that the presence of hydrocarbons inhibits the growth of authigenic clays. This results in the preservation of an oil-saturated reservoir from the effects of authigenic clay generation during diagenesis, which explains the results from the hydrocarbon-bearing intervals in Friendship 1.

Early-stage diagenesis often leads to kaolinite development. Flushing of fluvial and shallow marine sediments by meteoric water leads to the dissolution of feldspar and detrital white mica, and the precipitation of kaolinite (Bjorlykke 1998). The high fluid flows required to dissolve significant quantities of feldspar and mica are possible in fluvial and shallow marine humid environments. The kaolinite forms in an open system with the removal of silica (which will not precipitate as quartz at low temperatures) and alkali ions. As temperature increases due to diagenetic burial, kaolinite can progressively convert to dickite [a stable kaolin polytype in deeply buried sandstones (Lanson *et al* 2002)]. The transformation to dickite is more pervasive in high permeability sandstones (coarse-grained sands) than in low permeability sandstones. Abundant dickite may therefore reflect the deep burial of coarse permeable sandstones in the presence of significant pore water.

Illite can form during diagenesis under specific conditions. Authigenic illite was not distinguished from detrital muscovite in the HyLogger data, but the XRD data (n=3) taken from Scarborough 1 indicated two types of (dioctahedral) mica, suggesting that both detrital muscovite and authigenic phengitic illite are present in the Bessie Creek Sandstone.

Illite or kaolinite can form from the breakdown of feldspars during diagenesis leading to secondary porosity. Illite will form (rather than kaolinite) if aqueous potassium is kept at an elevated level in a closed system. Other studies have shown the development of illite associated with oil zones (Worden and Barclay 2003) as potassium has been held within the sandstone in the oil zone but is allowed to escape from the sandstone in the water zone.

Evidence for hydrothermal effects

In Lawrence 1, the SWIR response is pervasively Fe chlorite, with the strongest chlorite response at the contact with the overlying Derim Derim Dolerite. The XRD results show that the chlorite is minor (<2% in 2 samples). There is also chlorite on the upper contact of the Derim Derim Dolerite with the Velkerri Formation; it is likely that this chlorite is due to alteration associated with the dolerite emplacement.

Conclusion

Reflectance spectroscopy, XRD and petrological investigations confirm the Bessie Creek Sandstone as a supermature quartzose sandstone unit with variable clay mineralogy. The variation in clay mineralogy is likely to reflect differences in diagenesis and hydrocarbon charge with local effects from hydrothermal alteration.

Acknowledgements

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