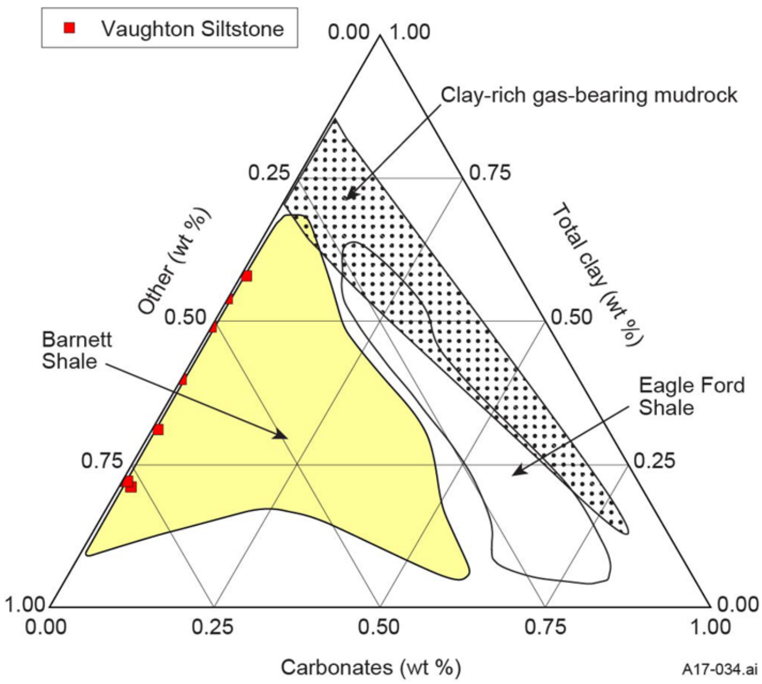
NTGS Technical Note 2017-002

The Vaughton Siltstone of the northern McArthur Basin: Preliminary data and issues related to assessing its potential as a petroleum source rock



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NORTHERN TERRITORY GOVERNMENT

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ABSTRACT

The Vaughton Siltstone BLUE MUD BAY[1] is a recessive carbonaceous shale unit of the Balma Group (McArthur Basin). Its mineralogy bears similarity to unconventional self-sourcing petroleum shales seen elsewhere in the McArthur Basin. A number of samples from weathered exposures of this formation were analysed in order to assess their hydrocarbon potential. Analyses consisted of X-ray diffraction, shale rock properties, total organic carbon content, programmed pyrolysis, CHONS elemental kerogen content, organic petrography, and gas chromatography. Initial results indicate that petroleum generation has occurred, but very little petroleum has been retained such that the remaining hydrocarbon generative potential is considered negligible. The presence of bitumen within the samples indicates that thermal maturation has occurred, possibly from burial of the siltstone or from exposure to hydrothermal fluids. However, the use of weathered samples, exposed to atmospheric levels of oxygen and large volumes of meteoric water, creates uncertainty within the results; therefore sub-surface samples of fresh material would be required to determine the true petroleum potential.

1 Names of 1:250 000 mapsheets are in large capital letters.

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REGIONAL GEOLOGY OF THE VAUGHTON SILTSTONE

The Paleoproterozoic Vaughton Siltstone was named by Plumb and Roberts (1965) and formerly defined by Plumb and Roberts (1992). The formation is a dominantly carbonaceous shale unit within the Balma Group in the northern McArthur Basin. The Balma and laterally equivalent Habgood groups outcrop within the north–south-trending Walker Fault Zone; they are broadly correlated with the McArthur Group, which outcrops in the Batten Fault Zone in the southern McArthur Basin (**Figure 1**). All three groups are included within the Glyde package of Rawlings (1999). The Vaughton Siltstone is disconformable on the Strawbridge Breccia and is conformably and gradationally overlain by the Conway Formation, or locally unconformably, by the Yarrawirrie Formation (Haines 1994). The formation is generally very recessive and exposures are sparse. Some relatively fresh exposures have been mapped from the middle and top of the formation, but its surface extent is otherwise inferred from the distribution of more resistant overlying and underlying units (**Figure 2**). There is no complete section through the unit and only limited shallow percussion and auger drilling by BHP conducted in the 1970s (BHP 1972, 1973, 1974); core and chips from these drillholes have not been preserved.

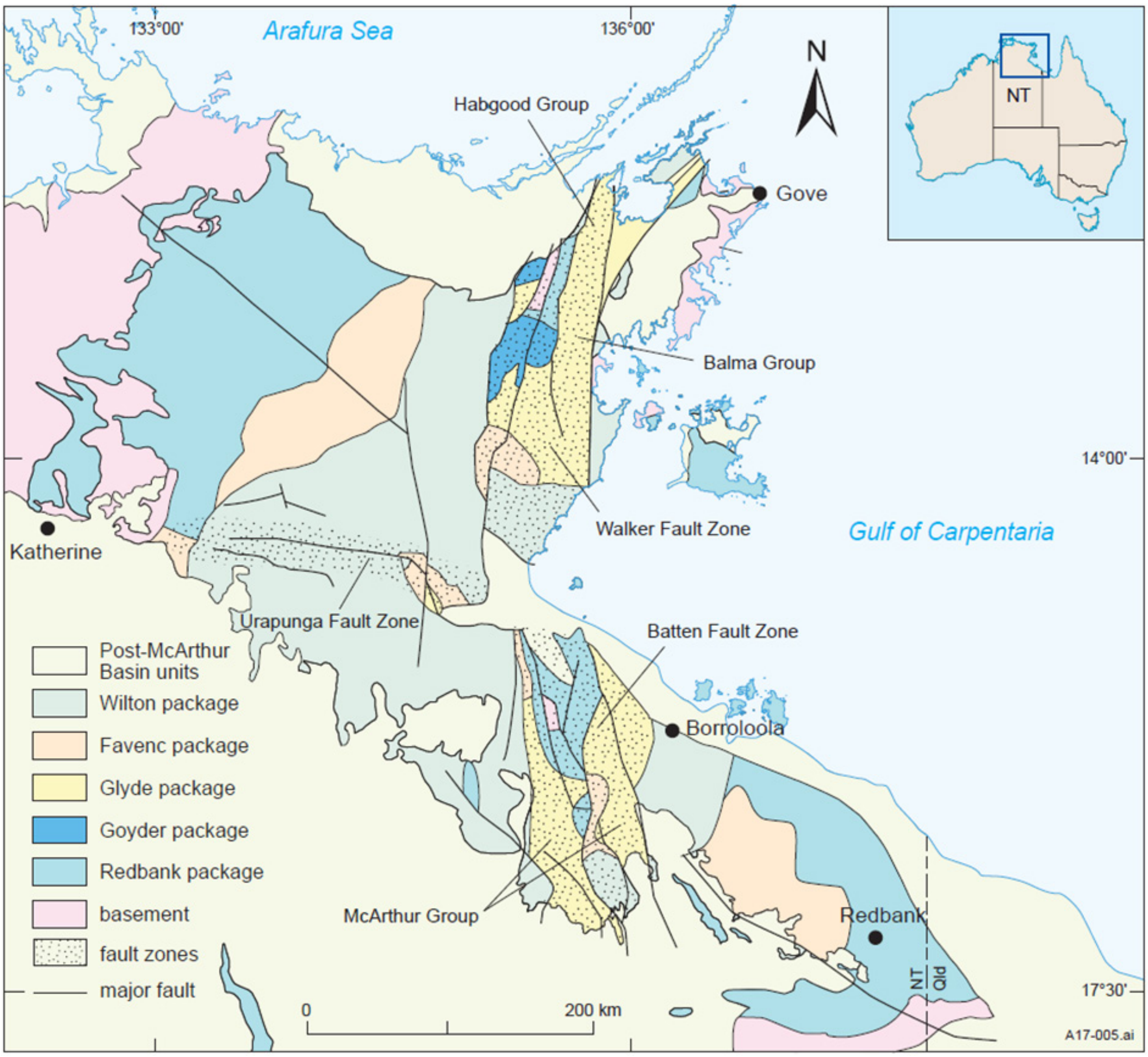


Figure 1: Spatial distribution of stratigraphic packages across McArthur Basin (modified after Rawlings 1999). Showing distribution of Balma and McArthur groups and locations of major fault zones (stippled).

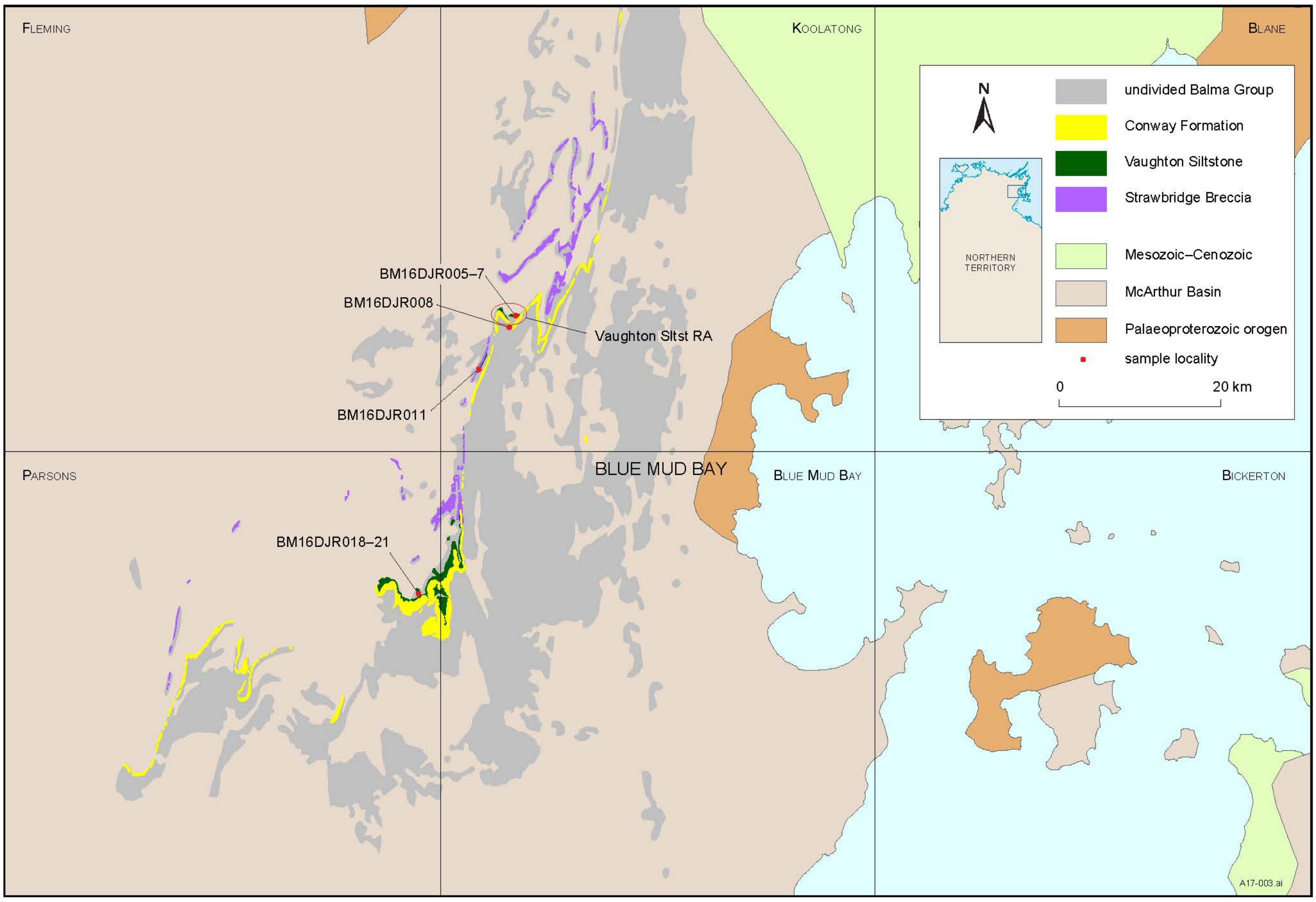


Figure 2. Distribution of exposures of Vaughton Siltstone, underlying Strawbridge Breccia and overlying Conway Formation within undivided Balma Group in BLUE MUD BAY. Base map derived from NT geological regions from NTGS 1:2.5M geological regions GIS dataset. RA = reference area.

The reference area for the formation, nominated by Plumb and Roberts (1992, **Figure 2**), provides good exposures of the top of the formation immediately underlying the Conway Formation, as well as small scattered outcrops lower in the succession. Sparse exposures of the lower and middle portions of the formation occur in other areas, mostly in creek beds and wash-outs. The thickness of the Vaughton Siltstone is uncertain but was estimated by Plumb and Roberts to vary in the range 600–1000 m. Haines (1994) tentatively correlated the Vaughton Siltstone with the lower part of the Yarawoi Formation of the Habgood Group in ARNHEM BAY–GOVE (**Figure 3**). This recessive interval is not exposed and is undrilled but is assumed to be dominated by fine-grained siliciclastic rocks (Rawlings *et al* 1997).

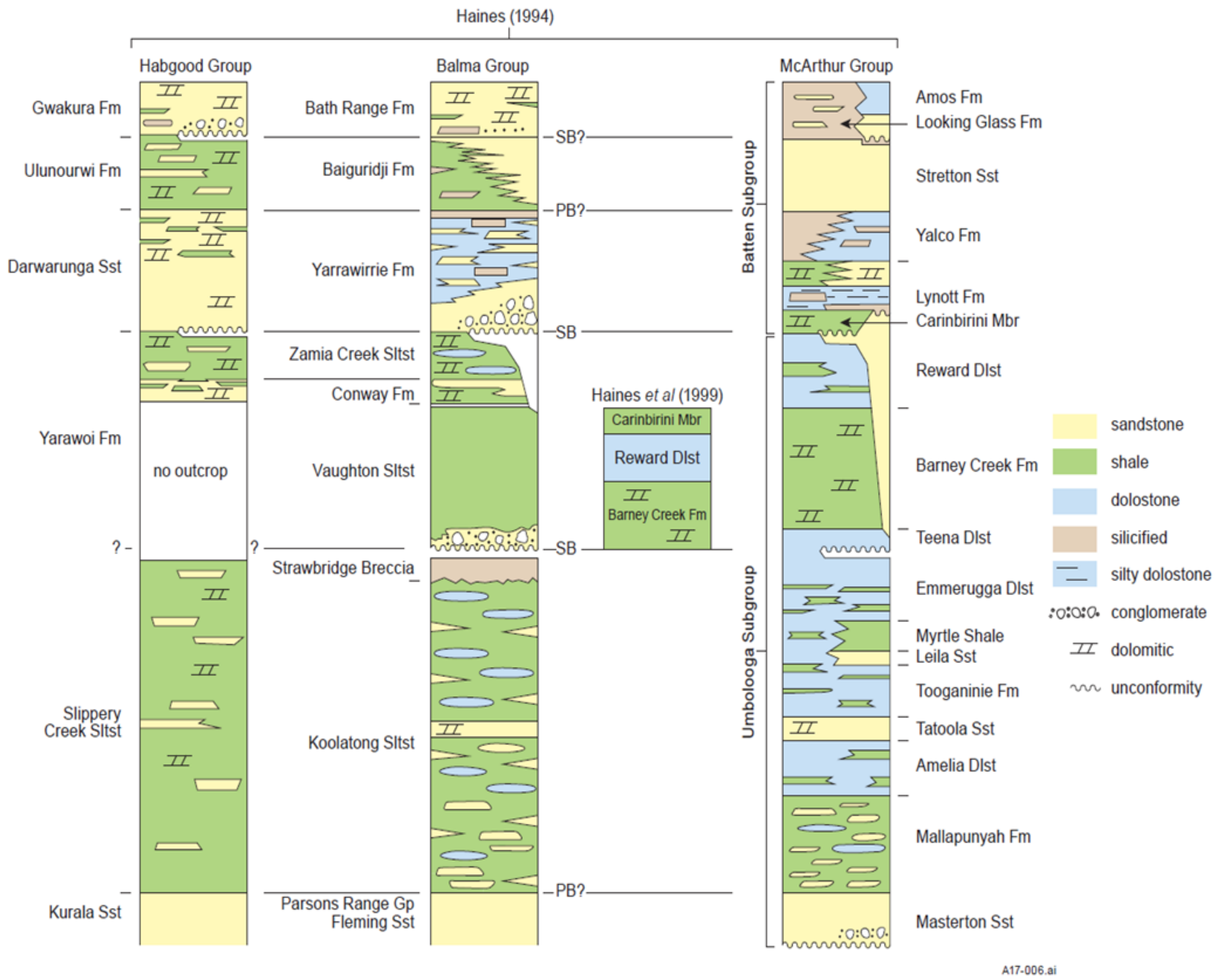


Figure 3. Schematic chart detailing the stratigraphic successions of the McArthur, Balma and Habagood groups (modified from Haines 1994: figure 2). Showing possible sequence stratigraphic correlations. Alternative correlation of Vaughton Siltstone with McArthur group units, after Haines et al (1999), is also shown. SB = sequence boundary; PB = parasequence boundary.

Plumb and Derrick (1975) proposed that 'black shales' in the upper Vaughton Siltstone might correlate with the Barney Creek Formation of the McArthur Group in the southern McArthur Basin. Haines (1994) suggested that the basal contact of the Vaughton Siltstone with the Strawbridge Breccia is a sequence boundary of tectonic origin; he tentatively correlated it with a major sequence boundary in the McArthur Group between the Emmerugga and Teena dolostones, as interpreted by Jackson and Southgate (1997) and Southgate *et al* (1997a, b). The Vaughton Siltstone to Zamia Creek Siltstone interval of the Balma Group was thus inferred by Haines (1994) to be a time equivalent of the upper Umbolooga Subgroup of the McArthur Group above the Emmerugga Dolostone (**Figure 3**). A possible alternative correlation was subsequently proposed by Haines *et al* (1999, **Figure 3**) in which the lower part of the Vaughton Siltstone equates with the Barney Creek Formation and the upper part equates with the Caranbirini Member of the Lynott Formation of the Batten Subgroup. However, due to limited exposures and a paucity of drill intersections through the Vaughton Siltstone and adjacent units, it is very difficult to test these alternative possible correlations.

Lithology

The lithological characteristics of the Vaughton Siltstone are not well known. In outcrop, the formation is dominated by weathered, khaki green to relatively fresh, light to dark grey shale (**Figures 4**, **5**), locally interbedded with minor massive, coarse-grained, lithic and slightly dolomitic brown sandstone (Haines *et al* 1999). BHP (1974) described a 5 m-thick basal 'gravel' in a percussion drillhole; Haines *et al* (1999) also described a basal conglomerate from a number of localities, mostly inferred from scattered loose debris of rounded cobbles and sand overlying the Strawbridge Breccia and from rare outcrops of conglomerate with the same dip as the underlying unit. They interpreted the clasts as having probably been derived from the underlying Parsons Range Group.

Figure 4. Black/carbonaceous Vaughton Siltstone in hand-sample. Length approximately 12 cm. Sample BM16DJR005, BLUE MUD BAY, 53 563896.7836mE 8524007.504mN.

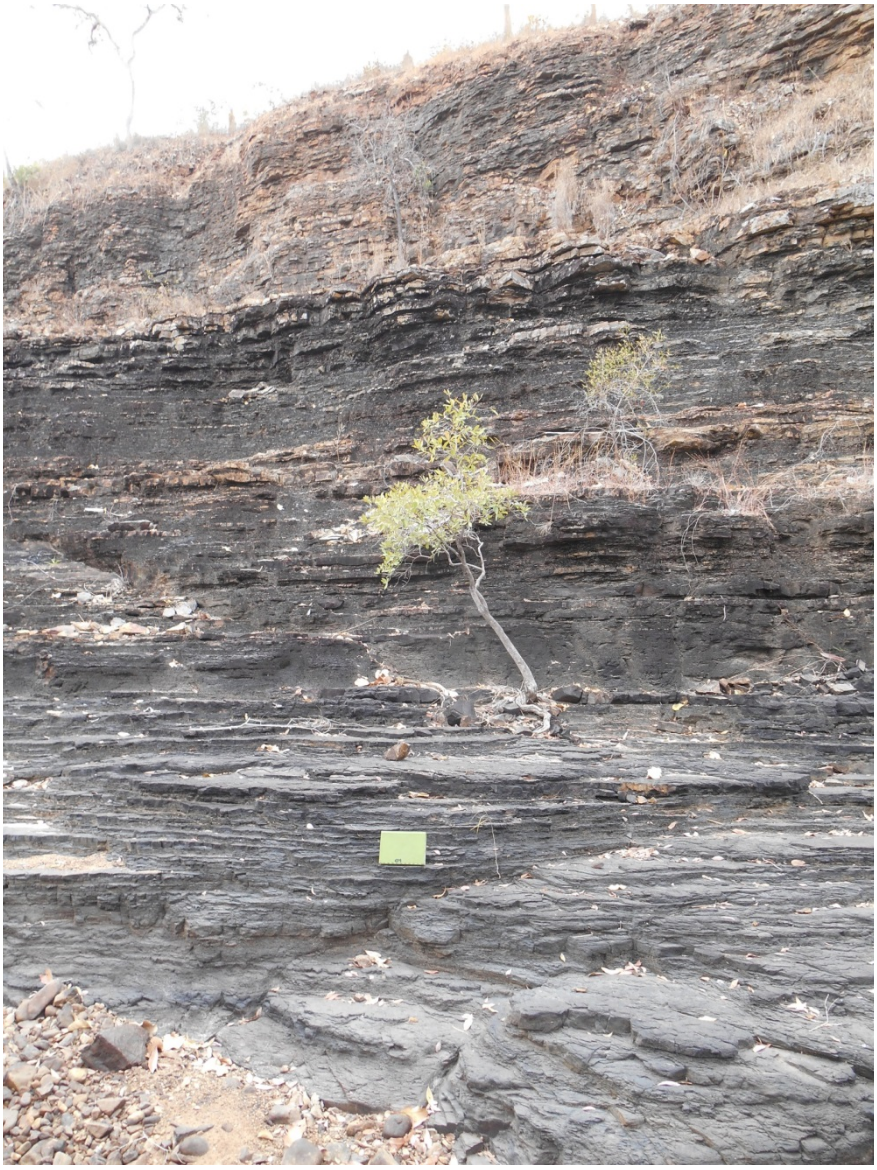
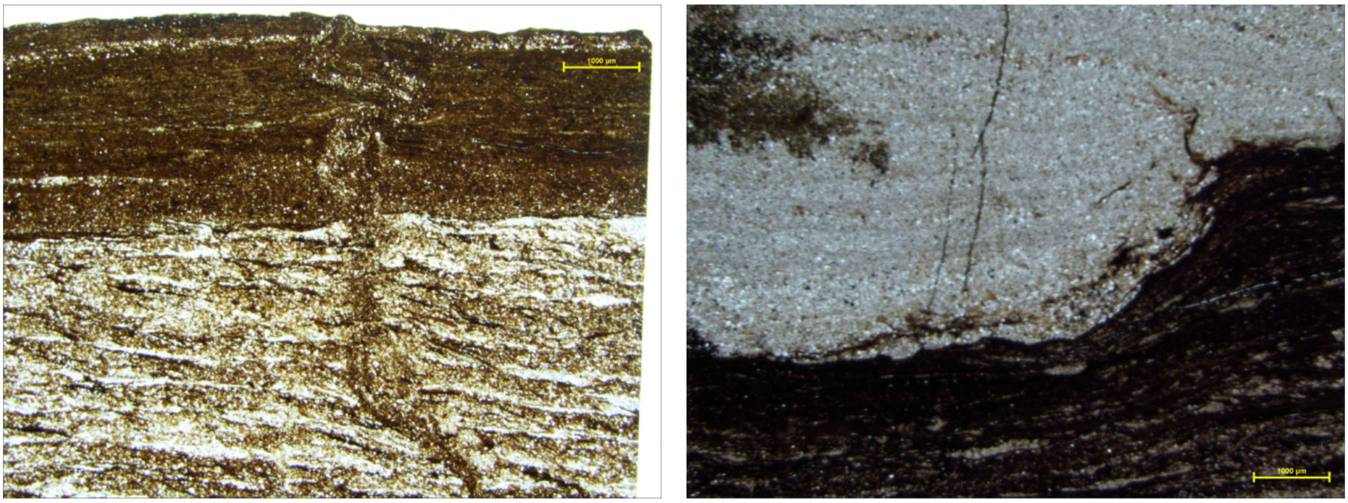


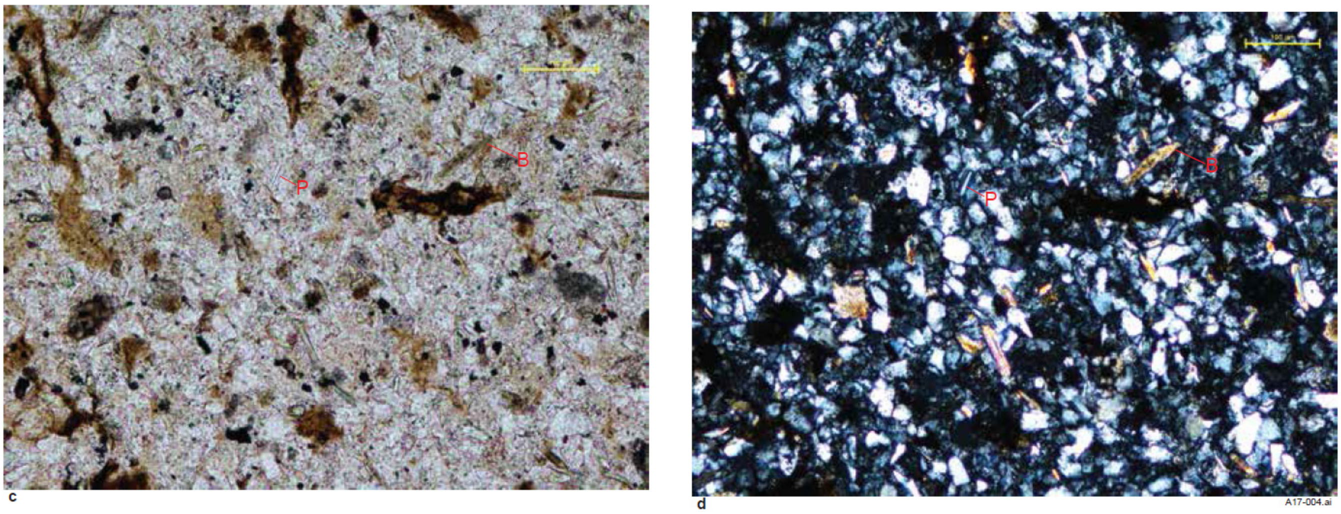
Figure 5. Riverbank exposure of Vaughton Siltstone. Field notebook is 21 cm in length. BLUE MUD BAY, 53 563891.5475mE 8524125.63mN.

The Vaughton Siltstone consists of thinly interbedded (<2 cm thick) to interlaminated siltstone and claystone. Siltstones are normally graded to claystone, or are massive with sharp tops and bases. Other sedimentary features include abundant parallel and ripple cross-lamination, climbing ripple cross-lamination, claystone rip-up clasts, interpreted synaeresis cracks, basal scours and load casts (**Figures 6a**, **b**). From thin sections, the shale from near the top of the formation are dominated by quartz and clay minerals, with lesser muscovite and rarer biotite, plagioclase, chlorite and opaque minerals, usually in a siliceous cement (**Figure 7a-b**).



a b

Figure 6. Photomicrographs of Vaughton Siltstone from BM16TJM008 from near top of formation reference area in BLUE MUD BAY at 53 563889mE 8524122mN. (**a**) Climbing ripple defined by pale laminated siltstone, overlain by laminated silty claystone with normally graded base. First order ripples defined by pale quartz-rich laminae; second-order ripples defined by aligned clay minerals and organic material. Cross-cutting convoluted structure is interpreted as possible synaeresis crack. Thin section BM16TJM008C. (**b**): Laminated siltstone forming load cast in laminated claystone. Thin section BM16TJM008B.



a b

Figure 7. Photomicrographs of Vaughton Siltstone from BM16TJM008 from near top of formation reference area in BLUE MUD BAY at 53 563889mE 8524122mN. (**c-d**): PPL and XL images respectively of siltstone, showing abundant grains of subrounded to sub-angular quartz, brown clay minerals, elongate muscovite, twinned plagioclase (P), green biotite (B), and dark opaque minerals. Thin section BM16TJM008A.

DEPOSITIONAL ENVIRONMENT

Haines *et al* (1999) considered the basal conglomerate of the Vaughton Siltstone to possibly be, at least in part, fluvial, or a high-energy transgressive deposit. They considered the rest of the unit to represent a quiet subtidal anoxic environment below storm wave-base due to the abundance of reduced and carbonaceous mudstone and

the fine laminations. Sedimentary structures, including graded bedding, basal scours, rip-up mud clasts and ripple cross-lamination from shales at the top of the formation, show abundant evidence for periodic and regular current activity, and indicate that at least this part of the unit was deposited from muddy turbidites and mass flows, rather than from suspension only. A generally quiet environment affected by regular current activity is therefore inferred, most likely in a shallow marine setting.

ECONOMIC POTENTIAL OF THE VAUGHTON SILTSTONE

The Blue Mud Bay area is a frontier region and remains vastly underexplored; the only significant exploration targeting the Vaughton Siltstone has been for base metals by BHP in the early 1970s (BHP 1972, 1973, 1974). No exploration for petroleum has been undertaken in the region.

The Vaughton Siltstone has significant potential for McArthur River-style deposits (stratiform sediment-hosted base metals) and other styles of mineralisation, as well as for petroleum. The unit is very thick and contains pyritic carbonaceous shale, a potential host for mineralisation and a potential a source rock for petroleum. As noted above, the formation is a probable time correlative of the economically important Barney Creek Formation in the Batten Fault Zone in the southern McArthur Basin; this formation hosts large base metals deposits, including the world-class McArthur River deposit, and is also regarded as a significant petroleum source rock (Munson 2014).

The tectono-stratigraphic setting appears to be similar for both the Vaughton Siltstone and the Barney Creek Formation in that they are located in major north-south-trending fault zones. Haines *et al* (1999) noted that wrench-faulting was probably active during sedimentation of the Balma Group, and that parts of this succession were formed by the accumulation of carbonaceous sediments in restricted water bodies in possible third-order basins within the Walker Fault Zone, similar to those in the Batten Fault Zone. These similarities are encouraging for future investigations into the economic potential of the region.

SAMPLING AND ANALYSES OF OUTCROPPING SAMPLES

Nine samples of Vaughton Siltstone were collected from various locations in BLUE MUD BAY during 2016 (**Table 1**) and investigated for petroleum source rock potential. Analyses consisted of X-ray diffraction (XRD), shale rock properties (SRP), total organic carbon content (TOC), programmed pyrolysis, CHONS elemental kerogen content, organic petrography, and gas chromatography (GCMS).

Table 1: Sample numbers and locations

Sample ID	Unit	Easting	Northing
BM16DJR005	Vaughton Siltstone upper	563896.7836	8524007.504
BM16DJR006	Vaughton Siltstone	563891.5475	8524125.63
BM16DJR007	Vaughton Siltstone	563197.5112	8523904.425
BM16DJR008	Vaughton Siltstone upper	562970.9072	8522910.707
BM16DJR011	Vaughton Siltstone lower contact	559039.4206	8517509.027
BM16DJR018	Vaughton Siltstone middle	551423.0558	8489516.975
BM16DJR019	Vaughton Siltstone middle	551434.567	8490095.257
BM16DJR020	Vaughton Siltstone upper	551778.5836	8489535.961
BM16DJR021	Vaughton Siltstone	551192.4113	8489483.691

RESULTS OF ANALYSES

X-RAY DIFFRACTION

XRD results (**Figure 8**) are shown in wt% for collated total clay, carbonates and other minerals (mainly quartz and other brittle minerals). In general, currently producing shales from continuous, self-sourced, unconventional petroleum source rock/reservoir systems require 40% brittle material content (carbonate minerals and quartz; Jarvie 2012) for economic recovery of hydrocarbons using current technology.

Figure 8 is a ternary diagram showing brittle mineral content (other minerals), clay mineral content and carbonate content of the Vaughton Siltstone samples (see **Table 2**). The majority of the samples are composed of brittle minerals such as quartz, potassium feldspar and plagioclase. These results are plotted in comparison to the mineralogy of producing unconventional petroleum plays in the USA (Barnett Shale and Eagleford Shale) that indicate the range of mineral assemblages needed for economic production from these self-sourced petroleum shales. The Vaughton Siltstone outcrop samples all fall within the range of the Barnett Shale mineralogy. The Barnett Shale has substantial economic hydrocarbon reserves (predominantly gas) therefore this comparison is an encouraging base indicator for the prospectivity of the Vaughton Siltstone.

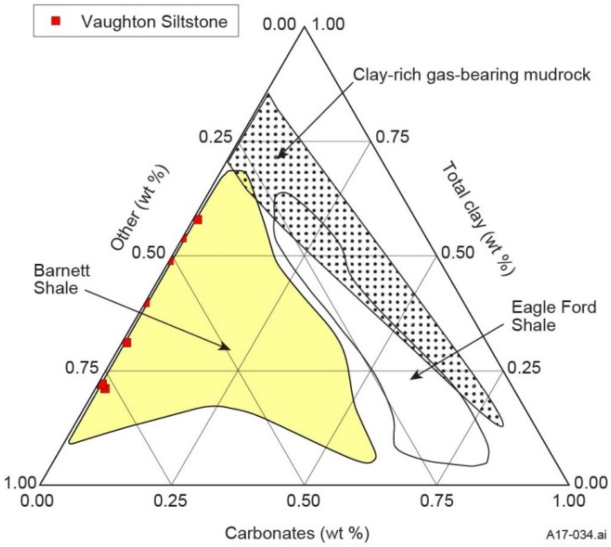


Figure 8. Ternary diagram of collated XRD results of 9 samples from Vaughton Siltstone
Superimposed in the XRD mineralogy results from the Barnett Shale and the Eagle Ford Shale, USA (QR Passy, 2010). Samples generally have high clay content (>30 wt.%) and very low carbonate content. Full sample descriptions can be found in **Table 2**.

Table 2: XRD results for Vaughton Siltstone outcrop samples.
Clay composition, carbonate composition and other minerals (measured in wt%)

	Clays					Carbonates			Other minerals			
Sample ID	**Chlorite**	**Corrensite***	**Kaolinite**	**Illite/ muscovite**	**Saponite**	**Calcite**	**Siderite**	**Dolomite[1]**	**Quartz/ mono-crystalline**	**K-feldspar**	**Plagioclase**	**Pyrite**
BM16DJR005-A	1	0	Tr	14	7	Tr	0	Tr	61	16	1	Tr
BM16DJR006-A	1	0	Tr	9	11	1	0	1	59	17	1	Tr
BM16DJR007-A	Tr	0	Tr	52	6	1	0	Tr	34	6	1	Tr
BM16DJR008-A	1	0	Tr	16	5	1	0	Tr	65	12	Tr	Tr
BM16DJR018-A	1	5	Tr	35	13	Tr	0	Tr	38	6	2	Tr
BM16DJR019-A	2	0	Tr	33	14	Tr	0	Tr	45	5	1	Tr
BM16DJR020-A	11	0	1	23	5	Tr	0	Tr	54	5	1	Tr
BM16DJR021-A	6	0	1	16	8	1	0	Tr	57	5	6	Tr

Notes:
*Corrensite is a Chlorite/Smectite; 50% expandable interlayers.
[1] Dolomite species interpretation based on the d-spacing of the highest intensity peak of dolomite group minerals; other dolomite species may be present.

Vaughton Siltstone samples contain muscovite and illite as the most abundant clays (average 24.75 wt%); these clays do not swell so are not detrimental to source rock potential. The amount of saponite (8.625 wt%) in the samples is on average lower than that of muscovite and illite. Saponite is a member of the smectite family of swelling clays and its presence is unfavourable for unconventional petroleum extraction (Gaudette 1964). Analysis of failed land-based wells with 20% to 30% mixed-layer clays indicates that these clays tend to swell in the course of deep matrix invasion during hydraulic stimulation (Gdanski 1999).

Total Organic Carbon and Pyrolysis

TOC values of the Vaughton Siltstone samples are in the range 0.3–1.31 wt% (**Table 3**); however, as these samples are weathered and have been exposed to the atmosphere and meteoric waters, TOC is likely to be diminished relative to unweathered Vaughton Siltstone. The weathering of siltstones and shales substantially reduces the present-day TOC and other petroleum indicators, inhibiting the accuracy and reliability of defining source rock potential (see below).

Table 3. Leco TOC (wt%) and programmed pyrolysis data for Vaughton Siltstone										
Sample ID	**Leco TOC**	**S1**	**S2**	**S3**	**T_{max} (°C)***	**HI**	**OI**	**S2/S3**	**S1/TOC x 100**	**PI**
BM16DJR005-A	0.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR005-B	0.31	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR005-C	0.33	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR006-A	1.31	0.1	0.12	0.25	522**	9	19	0	8	0.45
BM16DJR006-B	1.24	0.02	0.05	0.42	519**	4	34	0	2	0.29
BM16DJR006-C	1.33	0.03	0.11	0.46	525**	8	35	0	2	0.21
BM16DJR007-A	0.36	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR007-B	0.38	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR007-C	0.34	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR008-A	0.41	0.08	0.02	0.48	303**	5	116	0	19	0.8
BM16DJR008-B	0.52	0.04	0.02	0.42	316**	4	80	0	8	0.67
BM16DJR008-C	0.33	0.04	0.02	0.32	496**	6	97	0	12	0.67
BM16DJR018-A	0.26	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR018-B	0.28	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR018-C	0.25	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR019-A	0.25	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR019-B	0.25	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR019-C	0.26	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
BM16DJR020-A	0.72	n/a	n/a	0.52	458**	n/a	72	n/a	n/a	n/a
BM16DJR020-B	0.71	n/a	n/a	0.59	433**	n/a	83	n/a	n/a	n/a
BM16DJR020-C	0.79	n/a	n/a	0.56	319**	n/a	71	n/a	n/a	n/a
BM16DJR021-A	0.62	n/a	n/a	0.45	323**	n/a	72	n/a	n/a	n/a
BM16DJR021-B	0.59	n/a	n/a	0.46	469**	n/a	78	n/a	n/a	n/a
BM16DJR021-C	0.54	n/a	n/a	0.42	389**	n/a	78	n/a	n/a	n/a

This data exhibits TOC, S1 (existing petroleum within rock measured in mmHC/g rock), S2 (hydrocarbon generating potential measured in mgHC/g rock), S3 (CO2 produced mg carbon/g rock), Tmax values for a range of samples, HI (Hydrogen Index), OI (Oxygen Index), S2/S3, S1/TOC*100 and PI (Production Index).
Notes:
'n/a' – not measured or invalid value
TOC - Total Organic Carbon, wt%
S1 - volatile hydrocarbon (HC) content, mg HC/ g rock
S2 - remaining HC generative potential, mg HC/ g rock
S3 - carbon dioxide content, mg CO_2 / g rock
* - low S2, T_{max} is unreliable
HI - Hydrogen index = S2 x 100 / TOC, mg HC/ g TOC
OI - Oxygen Index = S3 x 100 / TOC, mg CO_2/ g TOC
PI - Production Index = S1 / (S1+S2)

The results from programmed pyrolysis are inconclusive. Low or absent measured S1 (existing petroleum within rock measured in mmHC/g rock) values coupled with poor to good TOC content (**Table 3**) could be interpreted as indicative of degradation of the organic content of the siltstone. The riverbed locations of the outcrops sampled for the study coupled with the seasonal high rainfall in this region are likely to have exposed the siltstone to significant water-washing. The low S2 (hydrocarbon generating potential measured in mgHC/g rock) values (<2 mg HC/g rock) indicate that the siltstone currently has low generative potential; this could be interpreted as either: (1) the rock is thermally matured and the potential has been exhausted; or (2) exposure to meteoric water has destroyed generative potential. Unreliable S1 and S2 values also result in inaccuracies in T_{max}, HI (hydrogen index) and (Production Index) PI values (**Table 3**).

The presence of bitumen is an indicator that thermal maturation has occurred, and that hydrocarbon has been generated. Trace indicators (S1 content is poor but present) of hydrocarbons produced by the Vaughton Siltstone have been preserved in samples; however, all remaining generative capacity (S2 values) is absent. Lack of high HI values is another indicator for thermal maturation.

Plotting TOC wt% versus the remaining hydrocarbon potential from pyrolysis results (S2 mg HC/g rock) indicates that the organic matter of the Vaughton Siltstone is presently in the dry gas window and is composed of inert Type IV kerogen (**Figure 9**). However, these results are not considered reliable as S2 and TOC values likely to be affected by weathering. Two results returned PI values (**Figure 10**), but due to weathering or the low S2 results, the PI results are unreliable.

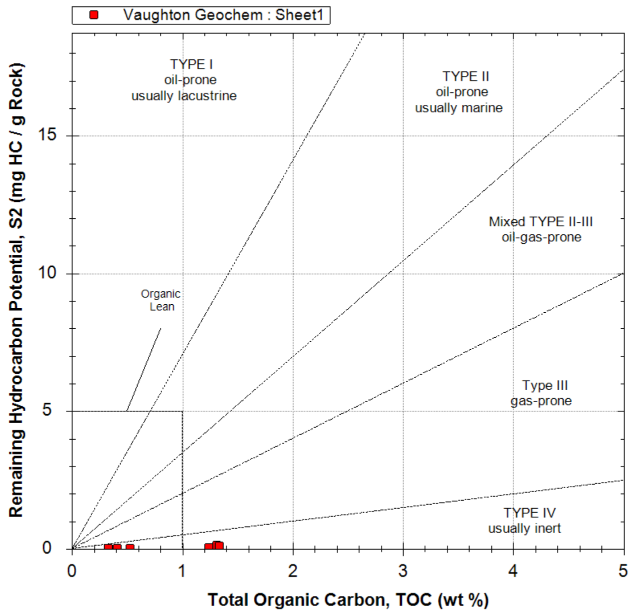


Figure 9. S2 vs TOC plot for Vaughton Siltstone.

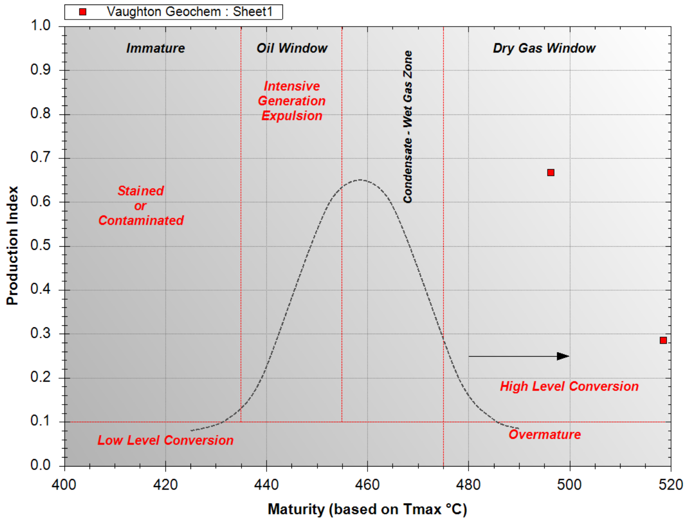


Figure 10. PI vs Maturity plot for Vaughton Siltstone

The Vaughton Siltstone samples are characterised as containing present-day organic matter that presents as Type IV kerogen; they are inert, CO_2 prone and absent of petroleum generative potential (**Figure 11**). Type IV kerogen does not generate hydrocarbons, except possibly small amounts of methane in combination with some CO_2 and H_2O formation during thermal maturity; it indicates reworked and highly oxidised organic matter. However, it is likely that the macerals were originally Type I or Type II marine oil-prone kerogen due to: (a) the interpreted anoxic sub-tidal marine depositional environment (Haines *et al* 1999, Ahmad *et al* 2013); (b) the Palaeoproterozoic age of the unit; and (c) the presence of bitumen within the samples. Type IV kerogen is difficult to discern from Type III kerogen through pyrolysis alone and is generally considered to be a non-source inert end-member reflecting very low H/C ratios and high O/C ratios. Potential petroleum generation and expulsion through thermal maturity could be responsible for the regression of the hydrogen content to Type IV kerogen. The impact of weathering may also have been responsible for destroying the generative capacity of the macerals.

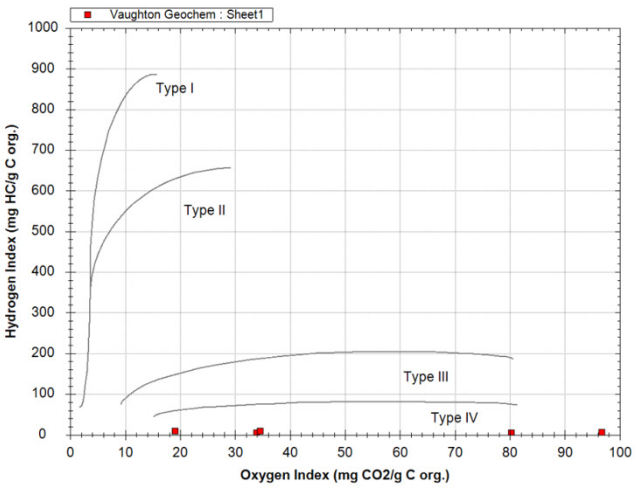


Figure 11. HI vs OI plot for Vaughton Siltstone.

ELEMENTAL KEROGEN ANALYSIS - CHONS

In addition to the HI vs OI plot (**Figure 11**) and the T_{max} vs PI plot (**Figure 10**), a Van Krevelen plot of elemental ratios of the isolated kerogens within the Vaughton Siltstone also indicates the presence of Type IV kerogen (**Figure 12**). Atomic H/C values of approximately 0.7 or less are prone to dry gas, which is compatible with the rest of the data. Elevated oxygen content indicates that substantial oxidation has occurred; this is likely a factor of weathering in combination with loss of hydrogen through thermal maturation and hydrocarbon generation. However, these results may be erroneous as the relatively thermal immaturity of the plotted results is not consistent with the organic maceral reflectance values.

SHALE ROCK PROPERTIES

SRP testing (porosity, permeability, fluid saturations of pore space) yielded results that are consistent with weathering (raw data can be seen in **Table 4**). Gas saturation of pore volume (% PV) of the Vaughton Siltstone samples is in the range 14.4%–61.9%; these values are relatively high, consistent with sub-aerially exposed siltstones outcropping above the water table. They indicate that the siltstone has likely undergone significant oxidation. Water saturation is high (ranging from 37.8% to 84.6% of PV), most likely from exposure to meteoric water (annual rainfall of up to 1200 mm). Oil saturation varies from 0% to 1% of PV. If these oil traces were sourced from within the Vaughton Siltstone, it would indicate thermal maturation and expulsion of hydrocarbons; however, the oil traces might also have been derived from a number of other sources. Further investigations (eg, gas chromatography) are required to confirm whether the Vaughton Siltstone is the parent source rock for these oil traces.

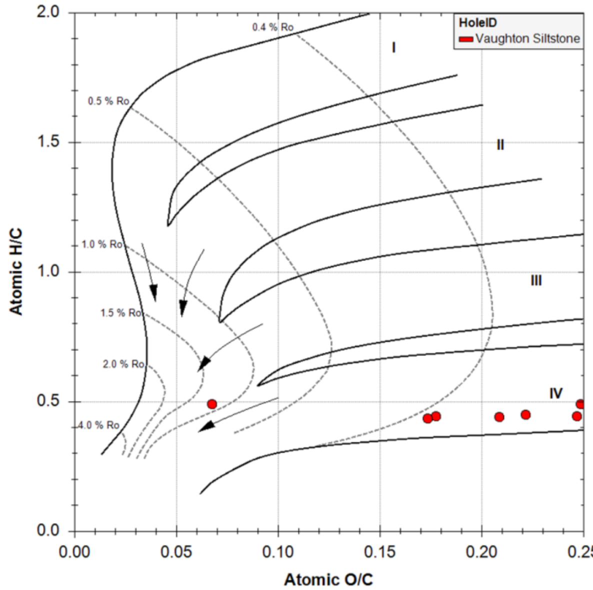


Figure 12. Van Krevelen plot of elemental ratios for Vaughton Siltstone.

Table 4: Shale rock properties table for Vaughton Siltstone

Sample ID	A-R bulk density (gm/cc)	A-R water saturation (% of PV)	A-R oil saturation (% of PV)	A-R gas saturation (% of PV)	A-R gas saturation % of BV	A-R press decay permeability (md)	Dry bulk density (gm/cc)	Dry grain density, (gm/cc)	Dry helium porosity (% of BV)	Dry press decay permeability (md)
BM16DJR005-B	2.58	84.6	1.0	14.4	0.4	1.14E-05	2.55	2.62	2.7	7.96E-05
BM16DJR006-B	2.52	55.6	0.4	44.0	1.9	7.34E-05	2.50	2.61	4.4	2.20E-04
BM16DJR007-B	2.24	39.1	0.1	60.8	12.7	1.63E-03	2.15	2.72	21.0	2.83E-03
BM16DJR008-B	2.46	37.8	0.3	61.9	5.5	2.16E-03	2.42	2.65	8.8	3.11E-03
BM16DJR018-B	2.44	64.0	0.1	35.9	4.5	6.46E-04	2.35	2.69	12.6	5.34E-03
BM16DJR019-B	2.49	73.4	0.2	26.4	2.8	4.83E-04	2.41	2.69	10.6	4.20E-03
BM16DJR020-B	2.53	79.3	0.0	20.7	1.6	2.73E-04	2.47	2.67	7.6	3.38E-03
BM16DJR021-B	2.53	65.4	0.0	34.6	2.7	1.23E-03	2.47	2.68	7.7	4.31E-03

REFLECTANCE OF SOLID BITUMEN

Bitumen is a precursor component in the generation of hydrocarbons within a petroleum system. Bitumen formation results from thermal maturation of kerogen within a source rock (Hunt 1995). Bitumen reflectance measurements can be used as an indirect thermal maturity proxy. The presence of solid bitumen and thucholite-filling voids in the matrix of the Vaughton Siltstone samples indicates that hydrocarbons have been generated. Solid bitumen filling the voids in fractures within the samples has an unknown origin, and is a migrated product of thermal maturation and expulsion of hydrocarbons. Results of bitumen reflectance analysis from reflected light microscopy are summarised in **Table 5**. Bitumen reflectance values from the Vaughton Siltstone samples vary from oil-bearing to dry gas-bearing (**Figure 13**). Values for low-reflectance solid bitumen contrast with previous data (**Figures 9**–**12**) that suggest that the Vaughton Siltstone is solely dry gas prone and overmature. Low-reflectance solid bitumen values falling within the oil and gas/condensate windows give a variation to the high reflectance results, and indicate values in the lower thermal maturity range. High reflectance solid bitumen results complement previous data (**Figures 9**–**12**) by suggesting that the Vaughton Siltstone has been thermally matured within the dry gas window (1.4–4.0 BR_o%). Bitumen reflectance bins can be seen in **Table 5**.

Table 5: Bitumen reflectance bin range

Maturity:	**VRE Value bin**
Immature	0–0.6
Oil	0.6–1.1
Wet gas	1.1–1.4
Dry gas	1.4–4
Postmature	>4

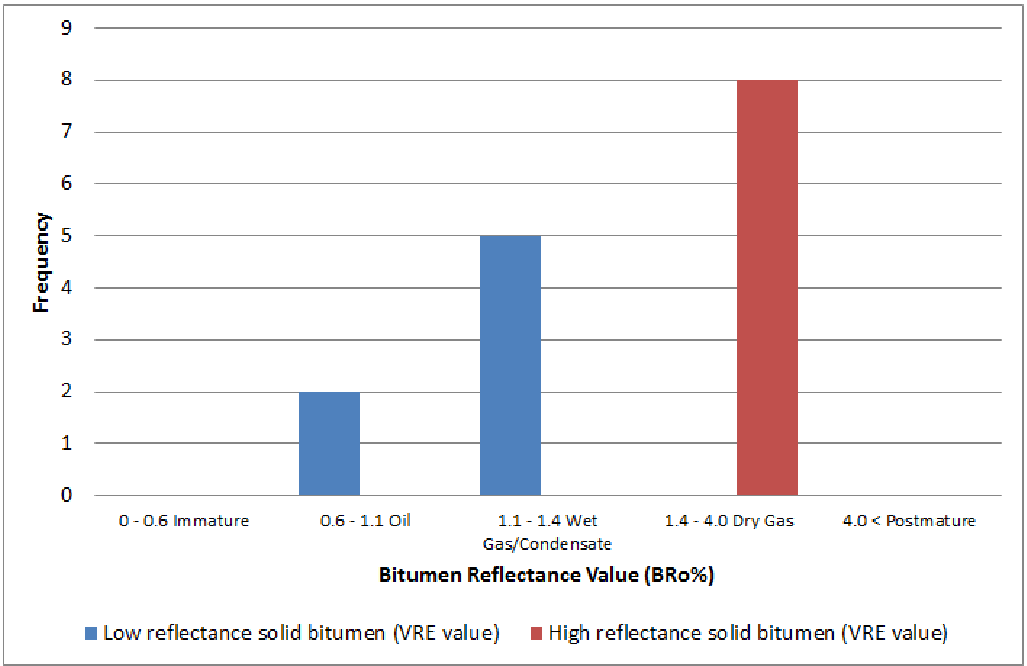


Figure 13. Reflectance of Solid Bitumen (Vitrinite Reflectance equivalent or VRE Values) for Vaughton Siltstone. Both low and high reflectance analyses of solid bitumen.

REFLECTED LIGHT MICROSCOPY

Examination of Vaughton Siltstone samples under the reflected light microscope shows that the majority of samples are pyrite-rich (**Figure 14–17**), with some samples containing abundant siderite. Up to 10% pyrite was also reported in BHP exploration drillholes (BHP 1972, 1973, 1974). Iron oxide replacement of pyrite in the Vaughton Siltstone samples has occurred as a product of weathering; this was noted in samples BM16DJR006-D and BM16DJR021-D **(Figure 18).** The weathering processes have also affected the organic materials present in samples. Lamalginite has been altered through weathering; the reflectance is quite low and it is notably absent of fluorescence (**Figure 19**).

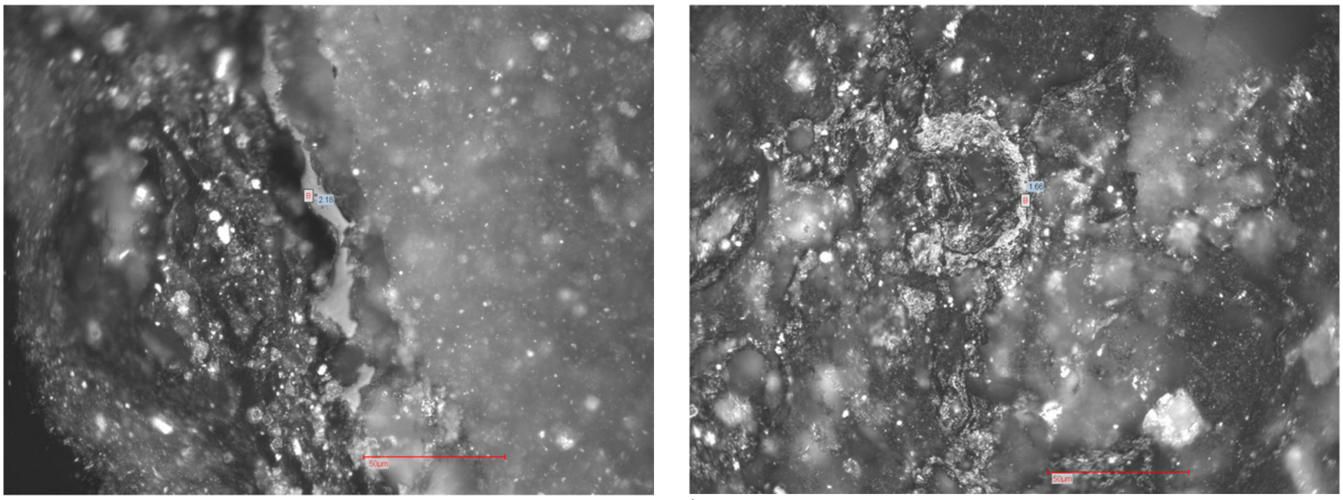


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Figure 14. Solid bitumen in pyrite-rich silty rock fragments.
Pyrite shows are present throughout (bright white reflections). NTGS Organic Petrography Report Batch 6. Reflected light microscopy. (**a**) BOe% 2.18. Sample BM16DJR005-C, AB-74329 NTGS. All images from Barcelona (2016). (**b**) BOe% 1.66. Sample BM16DJR006-C, AB-74329. All images from Barcelona (2016).

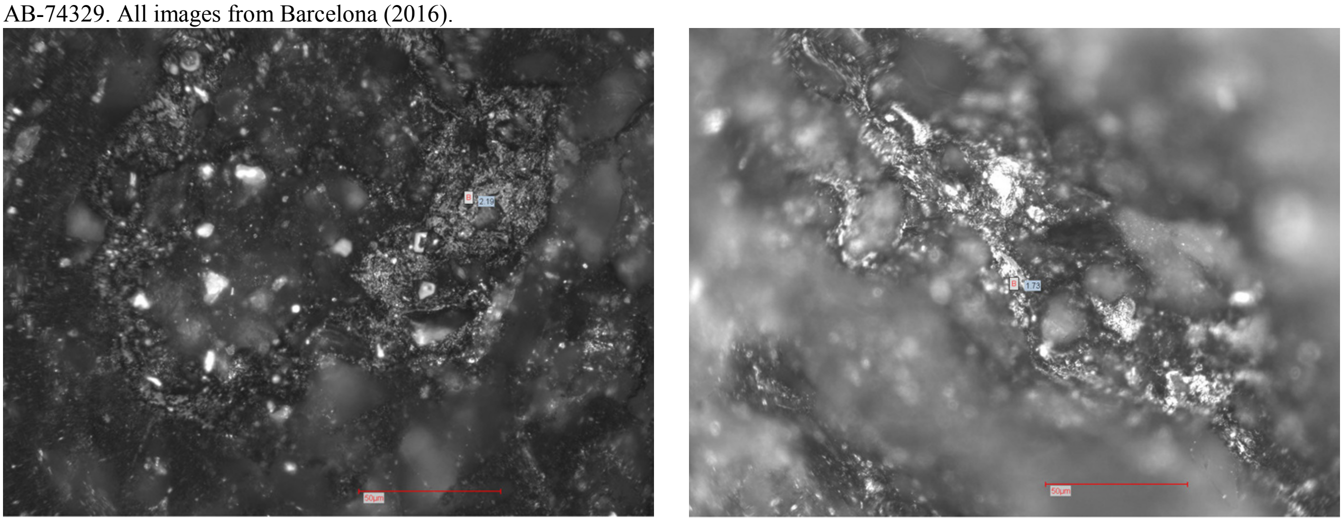

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Figure 15. Solid bitumen in pyrite-rich silty rock fragments.
Pyrite shows are present throughout (bright white reflections). NTGS Organic Petrography Report Batch 6. Reflected light microscopy. (**a**) BOe% 2.19. Sample BM16DJR006-C, AB-74329. (**b**) BOe% 1.73. Sample BM16DJR007-C, AB-74329. All images from Barcelona (2016).

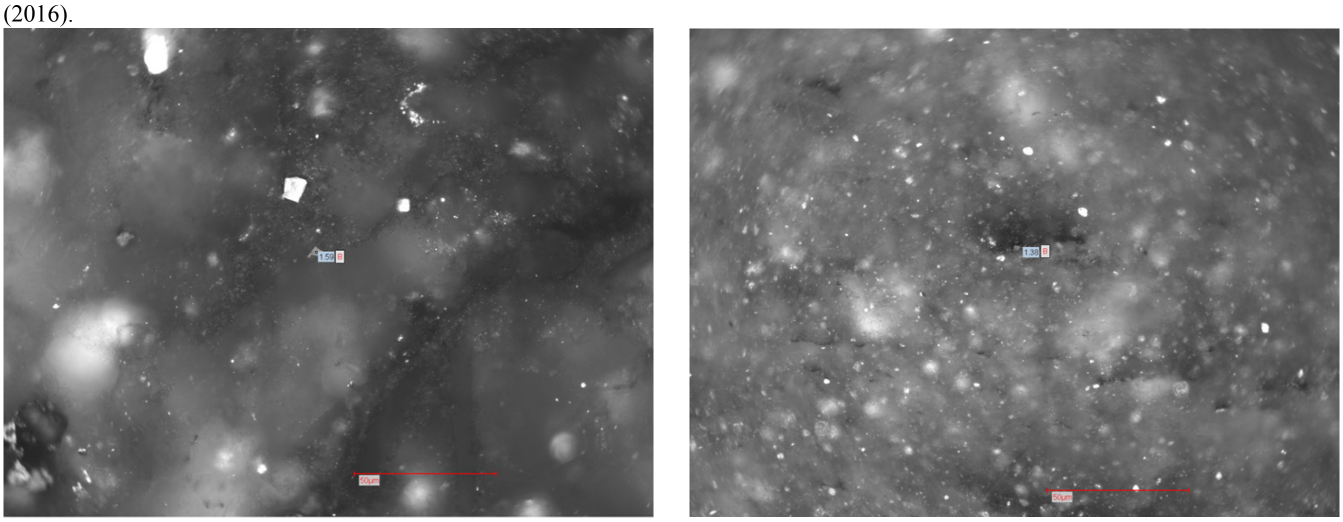

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Figure 16. Solid bitumen in pyrite-rich silty rock fragments.
Pyrite shows are present throughout (bright white reflections). NTGS Organic Petrography Report Batch 6. Reflected light microscopy.
(**a**) BOe% 1.59. Sample BM16DJR008-C, AB-74329. (**b**) BOe% 1.38. Sample BM16DJR018-C, AB-74329. All images from Barcelona (2016).

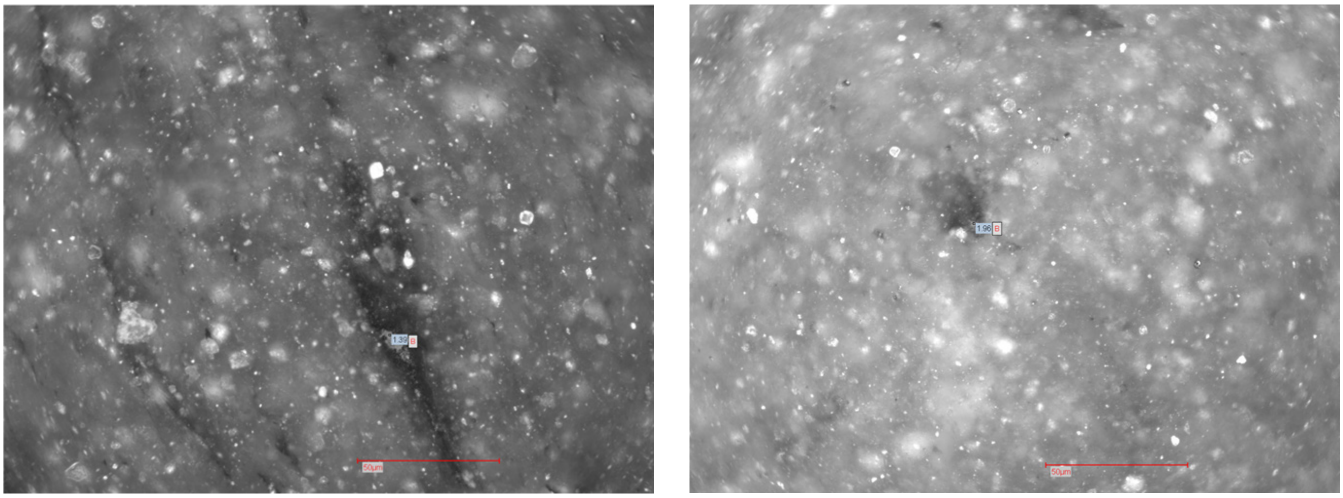

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Figure 17. Solid bitumen in siderite-rich silty rock fragments.
NTGS Organic Petrography Report Batch 6. Reflected light microscopy. (**a**) BOe% 1.39. Siderite shows are present throughout (indicated by red arrow). Sample BM16DJR019-C, AB-74329. (**b**) BOe% 1.96. Siderite shows are present throughout (large grey masses, not in focus). Sample BM16DJR019-C, AB-74329. All images from Barcelona (2016).

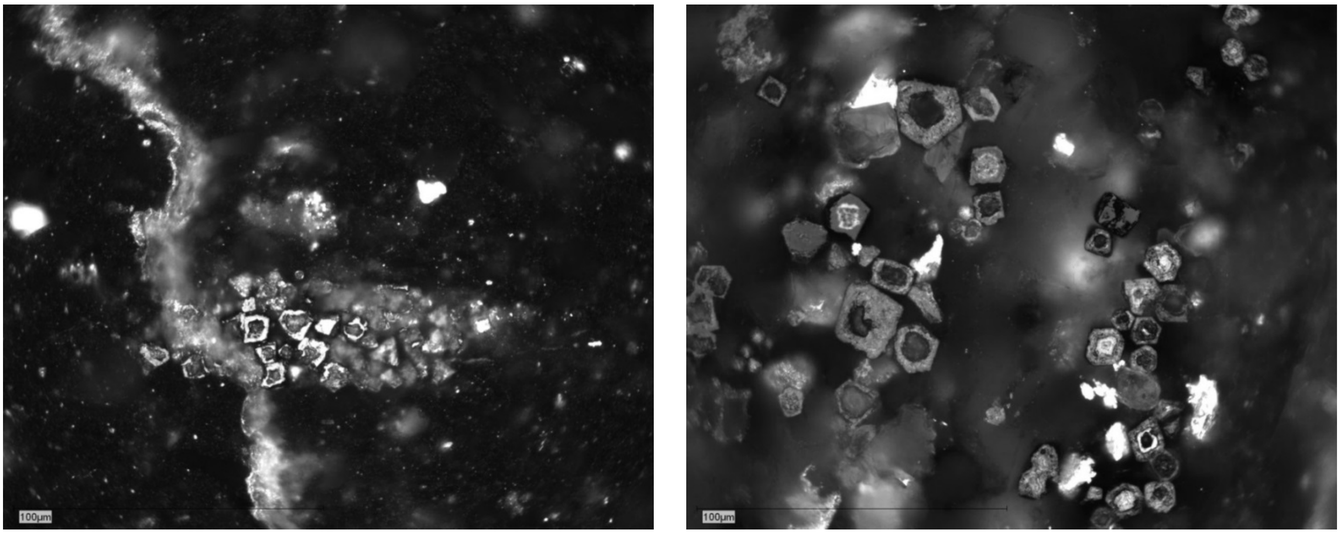

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Figure 18. Reflected light photomicrographs of Vaughton Siltstone.
(**a**) sample BM16DJR006-D and (**b**) sample BM16DJR021-D. Iron oxides have pseudomorphed cubic pyrite crystals as a result of weathering (Rodrigues 2017).

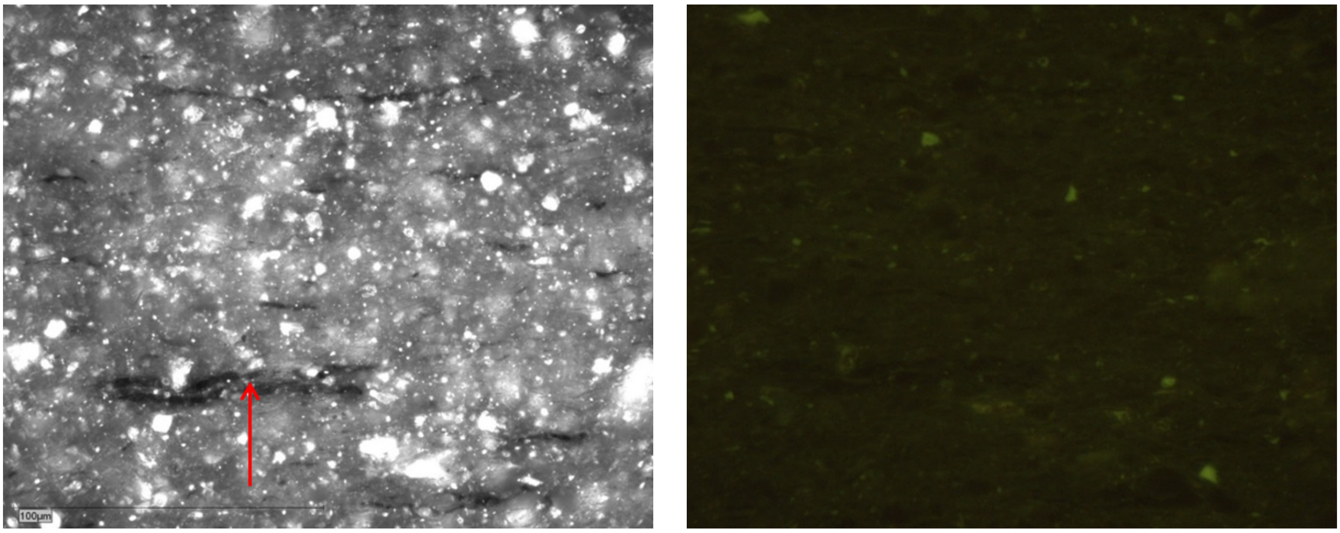

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Figure 19. Sample BM16DJR019-D
(**a**) Reflected light micrograph showing the presence of lamalginite (red arrow) and (**b**) ultra violet (UV) fluorescence micrograph showing a muted UV response as a result of weathering of the organic matter (Rodrigues 2017).

Xiangxian Ma (2016) noted that pyrite-rich source rocks have a tendency to catalyse bitumen production at lower temperatures than pyrite-poor equivalent source rocks. If this is the case within the Vaughton Siltstone, the pyrite content of could therefore potentially be beneficial to hydrocarbon generation. High-sulfur kerogens generate petroleum at lower thermal exposure than other kerogens; however, it is common for metals to outcompete organic matter for reduced sulfur, leading to low sulfur kerogens and oils. Whilst some H_2S may be oxidised under anoxic conditions by photosynthetic purple bacteria, the major sink is the reaction of sulfide with iron to form hydrotroilite, troilite and eventually pyrite (Peters *et al* 2005). The presence of pyrite and the potential effect on the sulfur content of the kerogen in the Vaughton Siltstone warrants further investigation.

The Vaughton Siltstone is siderite rich in a number of samples (**Figures 17**). Siderite can be an indicator of hydrocarbon maturity as an inverse correlation exists between siderite content and gas maturity (Milesi *et al* 2016). This inverse relationship has been found to exist in the Solimoes Basin in northwest Brazil. The high siderite content indicates that the Vaughton Siltstone samples may have generated bitumen at lower thermal maturity than is typical of Type I/II kerogens. Further investigation into the development of siderite within the Vaughton Siltstone is needed to verify this correlation.

THE EFFECT OF WEATHERING ON SILTSTONE AND ITS PETROLEUM INDICATORS

There are two main factors affecting the distribution of finely disseminated organic matter within shale: (1) variations in the depositional environment; and (2) weathering (Leythaeuser 1972). In Leythaeuser's study, all samples were taken from riverbank exposures and have been subjected to significant volumes of meteoric water and considerable weathering. It is possible to limit the effects of lateral and vertical variation in depositional environments by taking multiple samples from various locations. Access to multiple outcrops was restricted due to limited exposures and difficult terrain, resulting in samples being taken only a few kilometres apart. Leythaeuser's investigation found that TOC significantly increased with depth within the top 3 m of sampled rock as the exposure to meteoric water and weathering processes was reduced; TOC increased up to 40% with respect to surface measurements (**Figure 20**). The average TOC results from the Vaughton Siltstone samples were 0.53 wt%. If the same ratio increase (found from Leythaeuser's data) is applied to these samples, the TOC average value could potentially increase to 0.74%. It is important to note that these results may vary greatly due to multiple variables, including different weathering conditions, facies variations, mineralogical content, length of aerial exposure, hydrochemistry of meteoric and subsurface water, surface temperatures and climate.

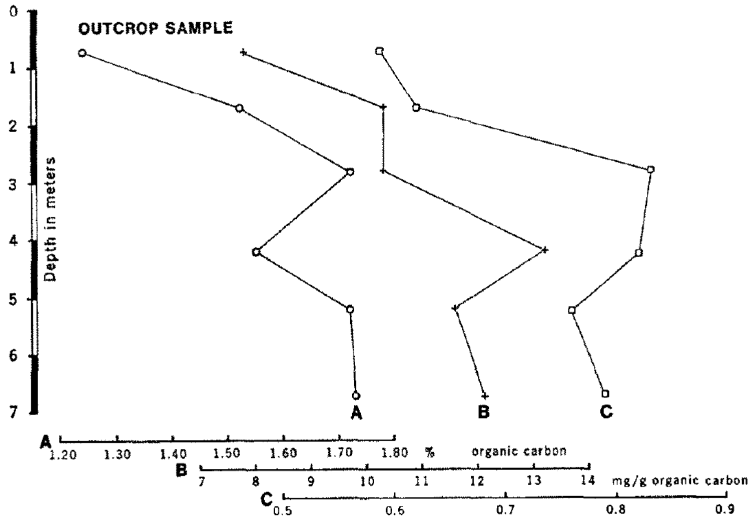

Figure 20. Plot from Leythaeuser (1972).
Displaying variation of TOC, organic carbon and mg/g organic carbon with depth (Leythaeuser concluded that depth has a direct relation to preservation of TOC)

The initial investigation undertaken by Leythaeuser (1972) analysed the properties of the Upper Cretaceous (100–66 Ma) Mancos Shale in Utah, USA. In contrast, the Vaughton Siltstone is Palaeoproterozoic (1640 Ma, if equivalent to the Barney Creek Formation) and much older than the Mancos Shale; therefore the Vaughton Siltstone has been exposed for a substantially longer period of time, further decreasing TOC values in outcrop samples. The volume and condition of meteoric water that each of these rocks has been exposed to, should also be considered as these variables could markedly influence the rate and type of weathering. In the Emery county of Utah (locality of Leythaeuser's samples), present-day average annual precipitation is 661.7 mm (26.05 inches), comprising 8.05 inches (204.5 mm) of rain and 18 inches (457.2 mm) of snow) (Climate Castle Dale – Utah 2017). The Blue Mud Bay area receives approximately 1200 mm of rainfall annually (Chatto 2006). This difference in meteoric precipitation could cause large vertical variations in the weathering of shale/siltstone and significantly impact the TOC values of each respective rock. The dynamics of weathering relating to snow in comparison to rainfall could also change the weathering rate of the Mancos Shale. The long dry season and relatively short but intense wet season of the monsoonal Northern Territory has a marked effect on the variable height of the water table. The long period of drought leads to a drop in the water table, which in turn could cause excessive leaching, degrading petroleum prospectivity. The short but substantial rainfall of the wet season results in a contrasting rise in the water table. If this fluctuation of the water table were to pass through the Vaughton Siltstone, it could cause water-washing and biodegradation of organic matter, further reducing its potential as a source rock.

CONCLUSIONS

The Vaughton Siltstone is currently an underexplored and poorly known recessive unit of the Balma group in the McArthur Basin. The preliminary analyses described in this technical report indicate that thermal maturation of the kerogens within the siltstone has occurred. A bi-product of thermal maturation is bitumen production and subsequent hydrocarbon generation. The extent of hydrocarbon generation is not known as there has been poor retention of organic matter by the weathered samples. Shale rock properties testing confirms that there is oil within the samples; however, it is not known if this oil is self-sourced. X-ray diffraction results indicate that the Vaughton Siltstone has similar mineralogical characteristics to the Barnett Shale USA, which is promising for prospectivity. However, the use of weathered samples in this study casts doubt on the accuracy of the analyses results. Overall, the Vaughton Siltstone has base unconventional petroleum source rock characteristics. Determining a more accurate petroleum potential of the Vaughton Siltstone will require access to fresh samples.

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