A1.1 Provenance of sediments and tectonic setting

The Wollogorang Formation forms part of the middle package of the Tawallah Group. Studies by Rogers (1996), using detailed sedimentology, and Bull (1993), using paleocurrent measurements, indicate that the sediments of the Wollogorang Formation were derived from erosion of the basal package of the Tawallah Group, comprised of sandstones and mafic volcanics (Table S1). The sediments for the McArthur Group (including the Barney Creek Formation) were most likely derived from the underlying Tawallah Group as a result of uplift and erosion (Haines et al., 1993; 1994) (Table S1). The source rocks mainly comprised shallow water fluvial clastic sandstone, mudstones and dolostones along with bimodal volcanics (basalt and rhyolite) and higher level intrusives. Unlike the Wollogorang and Barney Creek Formations and their respective groups, the possible source rocks for the Roper Group are speculative (Table S1). Sediments for the Roper Group could have been derived from either the Helens Spring High (Gorter et al., 2012) or the Isan Orogen (Abbott and Sweet, 2000). Recent studies (U-Pb dating of zircons) suggest the Roper Group sediments were derived from the North Australian Craton composed of greywacke-siltstones, tuffs, BIFs and mafic-felsic volcanic rocks (Munsen et al., 2016). Both Tawallah and McArthur Groups are associated with rift to post rift related deposition (Rogers, 1996; Giles et al., 2002). The Roper Group was deposited in an intracratonic, siliciclastic ramp setting developed in response to tectonic and eustatic changes (Abbott and Sweet, 2000) (Table S1).

Table A1 Comparison of source rocks and tectonic setting between three black shale formations

Formation (Age)	**Group**	**Lithology**	**Depositional environment**	**Source rocks**	**Tectonic setting**	**Major Orogenies**
Velkerri (~1400 Ma)	Roper	Grey and black mudstone and siltstone; minor glauconitic sandstone; ~**7-10 % TOC**	Most basinal facies	North Australian craton	subsidence-related	possibly Isan
Barney Creek (~1640 Ma)	McArthur	Dolomitic, carbonaceous and pyritic shale and siltstone, dololutite; **~10% TOC**	Basinal shale deposited in actively subsiding sub-basins	Tawallah Group	rift related	local uplift
Wollogorang (~1730 Ma)	Tawallah	Dolomitic, carbonaceous and pyritic shale; **~6-7% TOC**	Basinal shale	Basal Tawallah	rift related	local uplift

A1.2 Evolution of Microorganisms in the McArthur Basin between 1730-1360Ma

It is interesting to note that the Wollogorang Formation has been known to only comprise unmineralised stromatolites and filamentous microfossils bearing resemblance to those in the HYC Pyritic Shale in the Barney Creek Formation, all of which are prokaryotic in origin (Muir, 1982). The Barney Creek Formation comprises mainly bacterial and algal microfossils. Nevertheless, the assemblage differs from most Precambrian biotas being dominated by filamentous bacteria that are mostly pyritized. Most algal fossils are prokaryotic in nature except two that could possibly be of eukaryotic origin (Oehler, 1977). Interestingly, the Velkerri Formation microfossils impart remarkable complexity i.e., cytoskeletal and ecological prerequisites for eukaryotic diversification, process-bearing microfossils confirming presence of sophisticated organisms living in ecologically differentiated communities at the time (Javaux et al., 2001; 2004).

A1.3 Statistical tests on sedimentary pyrite analyses from McArthur Basin shales

Trace element concentrations of sedimentary pyrites from three different black shale formations were analysed using the Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry. Means of trace element concentrations (e.g., Se, Mo, Zn etc.) in the three black shales were compared with one another. Considering the high variability in LA-ICP-MS analyses, certain statistical tests were performed to confirm the differences in the mean were significant. They included the following:

1. Normality tests
2. T-test for equal/unequal variances

Normality tests were carried out in order to be able to apply parametric tests such as T tests. Both graphical and statistical tests (Q-Q plot and Shapiro-Wilk and Jarque-Bera tests) were performed to check for normality. Six elements (Se, Mo, Co, Ni, Bi, Zn) were included for the tests. The concentration (in ppm) was log transformed prior to normality tests. Results of the test indicate that all the elements in the Velkerri Formation impart normal distribution based on the Q-Q plot and the Shapiro-Wilk and Jarque-Bera tests. Elements in the Barney Creek Formation do not indicate a normal distribution according to the tests. In the Wollogorang Formation, Se, Ni, Bi, Co show a normal distribution whereas Zn, Mo do not. Please refer normality tests excel sheets for the three black shale formations.

Even though application for T-test is also not advisable with non-normal population it is usually not a major problem for when the sample size is >20. In this study, all three cases have sample size above 20. Please refer T tests excel sheet for the T test results.

The t-tests for six elements (Se, Ni, Mo, Zn, Bi, Co) are summarised below and in Table 4 in the manuscript:

Molybdenum: Mean Mo concentrations in the Velkerri Formation differ from both the Barney Creek and Wollogorang Formations. However, there is no significant difference between the mean Mo concentrations of the Barney Creek and Wollogorang Formations.

Selenium: Mean Se concentrations in the Velkerri Formation differ from both the Barney Creek and Wollogorang Formations. However, there is no significant difference between the mean Se concentrations of the Barney Creek and Wollogorang Formations.

Nickel: There is no significant differences of the mean in the three different formations

Zinc: Mean Zn concentrations in the Velkerri Formation differ from both the Barney Creek and Wollogorang Formations. However, there is no significant difference between the mean Zn concentrations of the Barney Creek and Wollogorang Formations.

Cobalt: Mean Co concentrations differ significantly in all three formations.

Bismuth: Mean Bi concentrations differ significantly in all three formation

We show the Spearman correlations (generated by SASweave; Lenth and Højsgaard, 2007) of each variable with age (from 1400 Ma to 1700 Ma) below. This is a non-parametric measure, which means that using the logged data would give the same result. For each I show the correlation, the significance, and the sample size.

The CORR Procedure

Spearman Correlation Coefficients
Prob > |r| under H0: Rho=0
Number of Observations

	Co	Ni	Cu	Zn	As	Se	Mo	Ag	Tl	Pb	Bi
Age	0.54140	0.00943	0.39375	-0.16633	0.37540	-0.24914	0.24955	0.28389	0.35966	0.14187	0.40885
Age	<.0001	0.8904	<.0001	0.0144	<.0001	0.0002	0.0002	<.0001	<.0001	0.0381	<.0001
	216	216	216	216	216	216	216	211	216	214	216

The CORR Procedure

Spearman Correlation Coefficients, N = 216
Prob > |r| under H0: Rho=0

	Se_Co	Ni_Co	Zn_Co	Mo_Co	Se_Bi	Ni_Bi	Zn_Bi	Mo_Bi
Age	-0.66702	-0.75275	-0.48966	-0.14217	-0.47688	-0.40362	-0.46517	-0.06345
Age	<.0001	<.0001	<.0001	0.0368	<.0001	<.0001	<.0001	0.3534

Results confirm that Co, Tl, Cu and Bi show positive correlation with increasing age (from 1400 Ma to 1700 Ma). Selenium and Zn show a negative correlation with increasing age. Molybdenum shows a weak positive correlation with increasing age. All the ratios (Se/Co, Ni/Co, Zn/Co, Mo/Co, Se/Bi, Ni/Bi, Zn/Bi, Mo/Bi) show negative correlation with increasing age. On the basis of the significance values, we reject the hypotheses of unvarying trace element trends from 1400 Ma to 1700 Ma (except for Ni).

A1.4 Sedimentary pyrite textures analysed for this study

Figure A1 represents some of the common pyrite textures observed in the three black shale formations. Pyrite usually occur as microcrystals disseminated in the black shale matrix with individual grain size ranging between 1-10 μ. Fine-grained pyrites in spherical and non-spherical aggregates (10-100 μ) and bedding-parallel layers were also observed. Sedimentary pyrite textures were similar in all three black shale formations. Importance of pyrite textural study prior to LA-ICP-MS analyses has been emphasized in Mukherjee and Large (2016, 2017) where TE concentrations were discussed in light of different textures (Figure S2). Both studies concluded that only sedimentary pyrites record sea water trace element chemistry and are most suitable for the LA-ICP-MS approach.

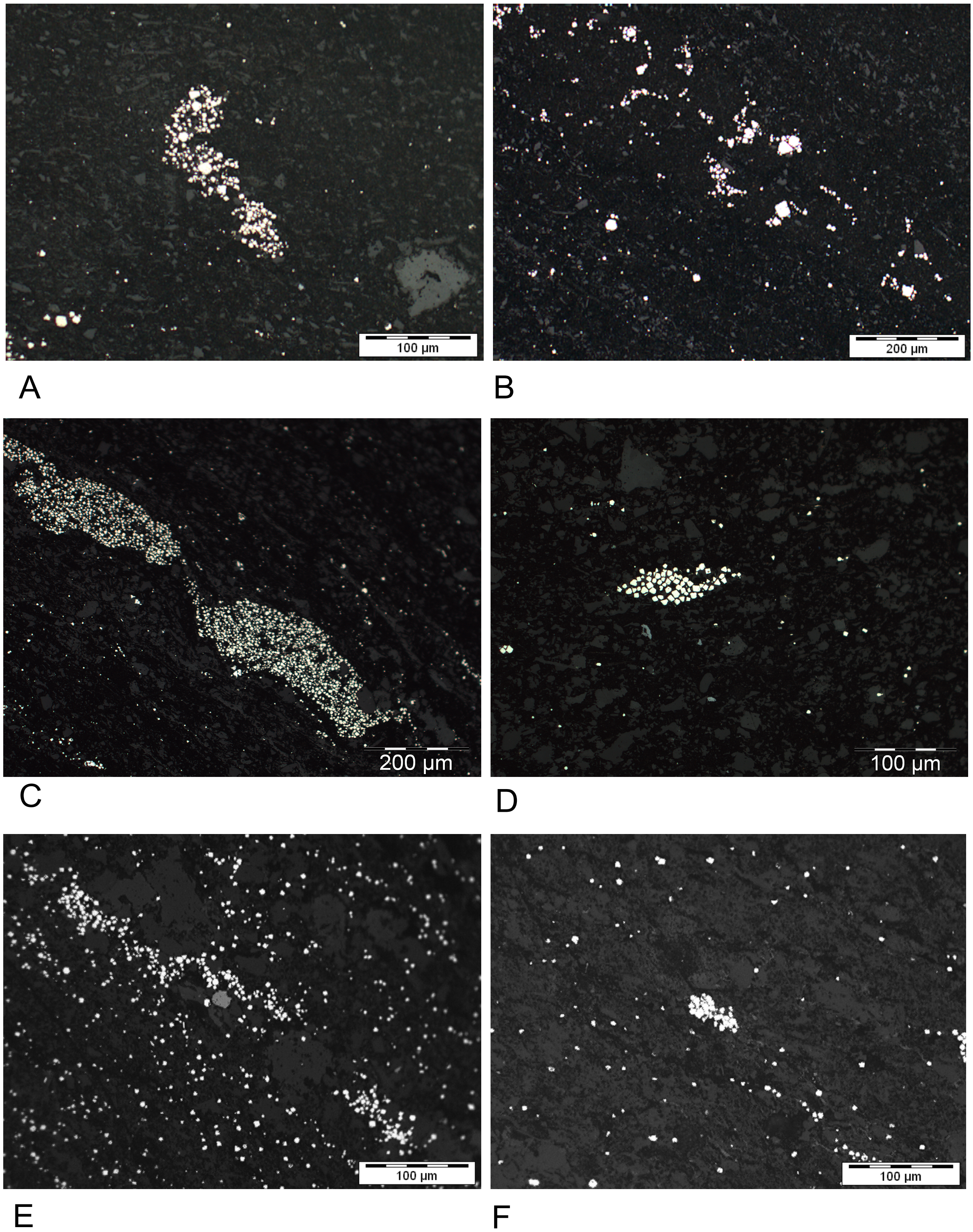
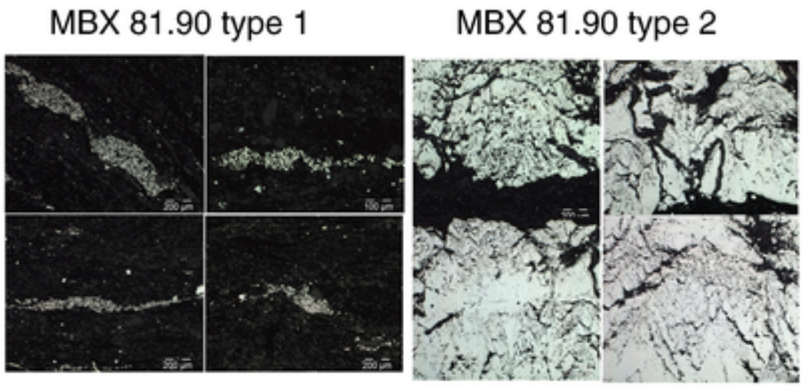


Figure A1 Pyrite textures observed in the three black shale formations (A, B: Velkerri Formation; C, D: Barney Creek Formation; E, F: Wollogorang Formation)



	MBX 81.90 type 1	MBX 81.90 type 2
Co	137	6
Ni	330	11
Cu	99	30
Zn	71	9
As	373	38
Se	6	5.07
Mo	214	4
Ag	2	0.08
Tl	7	39
Pb	409	37

Figure A2 Trace element concentrations of fine-grained sedimentary pyrite (type 1) and coarse grained pyrite (type 2) in the Barney Creek Formation (Mukherjee and Large, 2017).

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