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Integration of Ichnology and Geochemistry: Evidence for Oxygen Fluctuation During the Deposition of the Middle Triassic Sunset Prairie Formation, British Columbia, Canada

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Introduction

Ichnological trends in decreased oxygen conditions have been analyzed in modern settings and linked to the rock record. Foundational oxygen-related ichnological models stem from work by Rhoads and Morse (1971), Savrda and Bottjer (1986, 1987, 1989), Ekdale and Mason (1988) and Wignall and Myers (1988). Generally, aerobic or well-oxygenated facies are recognizable by their heavily bioturbated appearance and diverse trace fossil suites, whereas dysoxic environments can exhibit a variable degree of bioturbation (Savrda and Bottjer, 1986, 1989; Wignall, 1994; Martin, 2004). Low dissolved oxygen conditions exhibit trace fossil suites that are reduced in diversity and abundance, have decreased depth/tiering of trace fossils, and decreased burrow diameters (e.g., Rhoads and Morse, 1971; Bromley and Ekdale, 1984; Savrda and Bottjer, 1987, 1989, 1991, 1994; Diaz and Rosenberg, 1995), although others suggest that reduced oxygenation does not always exhibit these characteristics (Hudson and Martill, 1991; Wignall, 1991; Wignall and Pickering, 1993). Under anoxia, no bioturbation is present (Savrda and Bottjer, 1986, 1991; Savrda, 1992, 1995; Buatois and Mángano, 2011). The integration of ichnological and geochemical data has only been conducted by a handful of authors (Wignall and Myers, 1988; Werne et al., 2002; Algeo et al., 2004; Martin, 2004; Izumi et al., 2012; Kemp and Izumi, 2014; Dashtgard and MacEachern, 2016; Haddad et al., 2018), although geochemical datasets have been primarily used in interpreting palaeoredox conditions (e.g. Calvert and Pedersen, 1993; Tribovillard et al., 2006; Little et al., 2015). The purpose of this study is to present empirical data demonstrating the connection between ichnological characteristics and geochemical responses to redox conditions during the deposition of the Middle Triassic Sunset Prairie Formation in the Western Canada Sedimentary Basin. Observations and interpretations here can be used to help understand the trends in palaeoenvironmental conditions and biotic recovery associated with the end-Permian mass extinction.

Method and Materials

High-resolution ichnological and geochemical analyses were taken from three continuous drill core of the Sunset Prairie Formation in British Columbia. From distal to proximal, the cores investigated include: 16-02-078-22W6, 16-29-079-20W6 and 04-11-081-21W6. Facies characteristics, facies associations and interpreted depositional environments for the Sunset Prairie Formation follow descriptions by Furlong et al. (2018b).

Ichnological characteristics were collected within each 10 cm intervals along the surface of the core and data was continuously collected unless intervals had been removed. Ichnological characteristics considered within the dataset of this study include: 1) bioturbation intensity (BI); 2) diversity of ichnogenera; 3) diameter of burrows; and 4) Size Diversity Index. Diversity Index (SDI) (*sensu* Hauck et al., 2009) was calculated by multiplying ichnodiversity (number of ichnogenera observed) by the maximum burrow diameter (irrespective of ichnogenus) within each 10cm interval. Fluctuations in BI and SDI have been associated with changes in physico-chemical stresses acting on a depositional environment (Hauck et al., 2009; Gingras et al., 2011; Botterill et al., 2015; Timmer et al., 2016a, 2016b) and are inferred to represent a disturbance gradient proxy for palaeoenvironmental settings.

Geochemical data was collected every 10cm along the slabbed core using a Thermo Scientific NITON XL3t 900 Analyzer hand-held X-ray fluorescence (XRF) gun. Empirical calibrations of the XRF data were generated by a linear regression between the XRF data and ICP-MS from 28 samples from the Sunset Prairie Formation. A variety of elements and ratios have been reported as useful marine redox proxies to infer bottom water dissolved oxygen concentrations (e.g. Jones and Manning, 1994l; Algeo and Tribovillard, 2009). Within this study, Mo, V and V/Cr concentrations/ratios are used as redox proxies. Although it is best to use relative trends in elemental variability, instead of absolute concentrations, to interpret redox fluctuations through the vertical succession of the core, each redox-sensitive element has had threshold concentrations suggested for different redox states. Reported Mo concentrations associated with oxic conditions are below ~2ppm, Mo content between ~2 and 30ppm are recognized in dysoxic bottom water, Mo values above 30ppm are interpreted to represent intermittent/seasonal euxinia and permanent euxinic conditions correspond to enriched Mo values exceeding 100ppm (e.g., Scott and Lyons, 2012). Vanadium enrichment is associated with concentration higher than the baseline content of the average shale (V = 130 ppm). The ratio of V/Cr below 2 is associated with oxic conditions, 2-4.25 with dysoxic conditions and >4.25 with suboxic to anoxic conditions (Rimmer, 2004).

Results

Seven lithofacies have been described within the Sunset Priaire Formation (Furlong et al., 2018b). Ichnological characteristics (bioturbation intensity, maximum burrow diameter, number of ichnogenera and SDI) associated with each facies vary and are summarized in Table 1. A description of each facies is outlined below:

- **Facies 1**: Dark to medium grey, bituminous fine- to coarse-grained siltstone with planar-planar-wavy and wavy-laminae. Rare low and high angle planar cross laminae, asymmetric ripples, hummocky cross stratification, soft sediment defromation are observed. Isolated pyrite grains, beds rich in calcispheres, and phosphate material (silt, nodules, clasts, ooids) are present. Bioturbation is rare (BI = 0-2). Ichnological assemblage includes *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites* and *Chondrites*. No body fossils are observed. Facies 1 is interpreted to be deposited in the offshore to lower offshore transition.

- **Facies 2**: Dark to medium grey, fine- to coarse-grained siltstone with pinstripe-, planar- and wavy laminae. Rare asymmetric ripples and soft sediment deformation are present. Bioturbation is rare (BI = 0-2). Ichnological assemblage includes *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites* and *Chondrites*. No body fossils are observed. Facies 2 records deposition in the lower offshore transition.
- **Facies 3**: Dark to light grey, bioturbated fine-grained siltstone to very fine-grained sandstone. Phosphate material (silt, sand, nodules) is present. Bioturbation is high (BI = 5-6). Ichnological assemblage includes *Phycosiphon*, *Helminthopsis*, *Teichichnus*, *Palaeophycus*, *Planolites*, *Chondrites* and *Zoophycos*. No body fossils are observed. Facies 3 is interpreted to be deposited in the lower to upper offshore transition.
- **Facies 4**: Medium to light grey, bioturbated fine-grained siltstone to very fine-grained sandstone. Rare planar laminae are observed. Bioturbation is high (BI = 4-6). Ichnological assemblage includes *Phycosiphon*, *Helminthopsis*, *Palaeophycus*, *Planolites*, and *Chondrites*. Body fossils of bivalve, gastropods, brachiopods (lingulid, spiriferid terebratulid), cidaroid echinoid skeletal fragments and isocrinid crinoid ossicles are observed. Facies 4 represents deposition in the lower to upper offshore transition.
- **Facies 5**: Medium to light grey bioturbated fine-grained siltstone to very fine-grained sandstone with rare planar- and wavy- laminae. High and low angle cross laminae, asymmetric ripples and soft sediment defrormation are observed. Phosphate material (silt, sand, nodules, clasts) is present. Bioturbation is high (BI = 5-6). Ichnological assemblage includes *Phycosiphon*, *Rosselia*, *Cylindrichnus, Asterosoma, Teichichnus*, *Palaeophycus*, *Planolites*, *Skolithos, Rhizocorallium* and *Diplocraterion*. Body fossils of bivalve, gastropods, brachiopods (lingulid, spiriferid terebratulid), cidaroid echinoid skeletal fragments and isocrinid crinoid ossicles are observed. Facies 5 represents deposition in the upper offshore transition or lower shoreface.
- **Facies 6**: Burrowed firmground separating bioturbated facies (above) from non-bioturbated facies (below). The surface represents a *Glossifungites* demarcated discontinuity surface.
- **Facies 7**: Sand to gravel sized clasts with phosphate nodules, phosphatic ooids and rip up clasts. Bone and shell fragments are observed. This facies is interpreted as a lag deposit.

Redox-senstitive elements and ratios vary in range for the different facies (Table 1). Overall, Facies 1 and 2 are characterized by a wide range in concentrations of each element, Facies 4 has a more narrow range of concentrations, and Facies 3 and 5 have the narrowest range of concentrations.

Interpretation

Redox-sensitive trace metals tend to be more soluble under oxidizing conditions and less soluble in reducing conditions, resulting in the enrichment of these elements in oxygen-depleted sedimentary deposits (Tribovillard et al., 2006; Little et al., 2015). Within the Sunset Prairie Formation elemental dataset, it is interpreted that the diminutively bioturbated facies (Facies 1 and 2) were deposited under a wide range of redox consitions. Facies 4 was deposited under oxic to dysoxic conditions, whereas Facies 3 and 5 were deposited under oxic conditions.

Fluctuations in redox-sensitive element concentrations occur on a stratigraphic scale and can be correlated between cored wells. Each core exhibits fluctuations in geochemical and ichnological data (Figure 1). The basal parasequence of the formation is characterized by thicker packages of bioturbated facies, and low concentrations of redox-sensitive elements (average Mo = 43.10ppm, V = 68.16ppm, V/Cr = 1.07), suggesting that the interval was mainly deposited under oxic condtions. The upper two parasequences have decreased thickness of bioturbated facies, increased thickness in non-bioturbated to minimally bioturbated facies and increased concentrations of redox-sensitive elements (middle parasequence: average Mo = 41.25ppm, V = 262.45ppm, V/Cr = 2.79; upper parasequence: average Mo = 44.39ppm, V = 871.39ppm, V/Cr = 8.74). The upper two parasequences are interpreted to represent an increase in occurrence of intervals associated with dysoxic to anoxic conditions; however, intervals of bioturbated facies are present within the upper intervals, which correlate to lowered concentrations of redox-sensitive elements and is interpreted to have been deposited under oxic conditions.

Broader Implications

Biotic recovery following the end-Permian mass extinction have been said to be delayed due to prolonged, global anoxic water conditions (Hallam, 1991; Wignall et al., 1998; Beatty et al., 2008; Zonneveld, 2011). Trace fossils in the Lower Triassic Montney Formation are sparse, but when present, ichnological assemblages favoured a “refuge zone mode,” where narrow mid-water regions within shallow marine settings were locally devoid of anoxic water conditions (Beatty et al., 2008; Zonneveld et al., 2010a; Song et al., 2014). Conversely, the Sunset Prairie Formation preserves a regionally extensive, diverse assemblage of marine trace fossils in western Canada. However, ichnological assemblages are still primarily associated with shallow marine settings (lower shoreface and offshore transition).

It has been suggested that faunal recovery to pre-extinction levels likely did not occur until the end of the Middle Triassic or later (Twitchett, 1999; Hofmann et al., 2015). However, trace fossil recovery was probably faster than the recovery of species diversity. This is due to trace fossil morphology being fundamentally linked to organism behaviours and is largely independent of species diversity, since multiple tracemaking organisms can produce similar traces.

Conclusions

The relationship between redox-sensitive elements and ichnological characteristics were investigated within the Sunset Prairie Formation. This study shows that pervasively bioturbated intervals correlate to low concentrations of redox-sensitive elements, interpreted ro repersent deosition under oxic consitions; whereas non-bioturbated to minimally bioturbated facies correspond to increased concentrations of redox-sensitive elements and are interpred to represent deposition under oxic, dysoxic and anoxic conditions. Whether or not the relationship between bioturbation characteristics and oxygen availability can provide a predictable function for the determination of dissolved oxygen concentrations remains as of yet uncertain. Through this study, a fluctuation in redox conditions can be associated with the deposition of the Middle Sunset Prairie Formation.

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Variable	Facies	Minimum	Maximum	Average	Standard Deviation
Maximum Bioturbation Intensity	Facies 1	0	3	0.23	0.69
	Facies 2	0	3	0.62	0.99
	Facies 3	4	6	5.25	1.04
	Facies 4	3	6	5.81	0.55
	Facies 5	4	6	5.97	2.57
Maximum Burrow Diameter (mm)	Facies 1	0	2	0.09	0.25
	Facies 2	0	3	0.24	0.42
	Facies 3	0.5	12	3.69	4.28
	Facies 4	0.5	6	1.15	0.86
	Facies 5	1	15	4.10	2.67
Number of Ichnogenera	Facies 1	0	5	0.32	0.98
	Facies 2	0	5	0.73	1.12
	Facies 3	4	6	5.25	0.71
	Facies 4	3	5	3.61	0.79
	Facies 5	2	7	4.11	1.11
Size Diversity Index (SDI)	Facies 1	0	10	0.26	0.91
	Facies 2	0	6	0.52	1.03
	Facies 3	2.5	72	21.4	26.21
	Facies 4	1.5	25	4.23	3.71
	Facies 5	3	91	18.15	15.56
Mo (ppm)	Facies 1	31.80	82.20	44.22	10.39
	Facies 2	31.94	61.63	38.89	7.21
	Facies 3	31.94	32.53	33.34	2.03
	Facies 4	32.21	62.35	42.90	16.87
	Facies 5	31.96	32.48	32.22	0.37
V (ppm)	Facies 1	8.13	5113.02	654.26	926.96
	Facies 2	14.78	4442.10	175.71	541.23
	Facies 3	4.09	34.20	15.60	9.51
	Facies 4	4.09	519.65	59.12	60.02
	Facies 5	11.08	131.29	38.51	26.54
V/Cr	Facies 1	0.18	39.83	6.07	7.86
	Facies 2	0.25	39.90	1.95	4.49
	Facies 3	0.18	0.90	0.37	0.27
	Facies 4	0.16	6.46	0.99	0.79
	Facies 5	0.25	1.93	0.69	0.41

Table 1. Ichnological and geochemical characteristics by facies. Minimum, maximum, average and standard deviation are preocided for each variable.

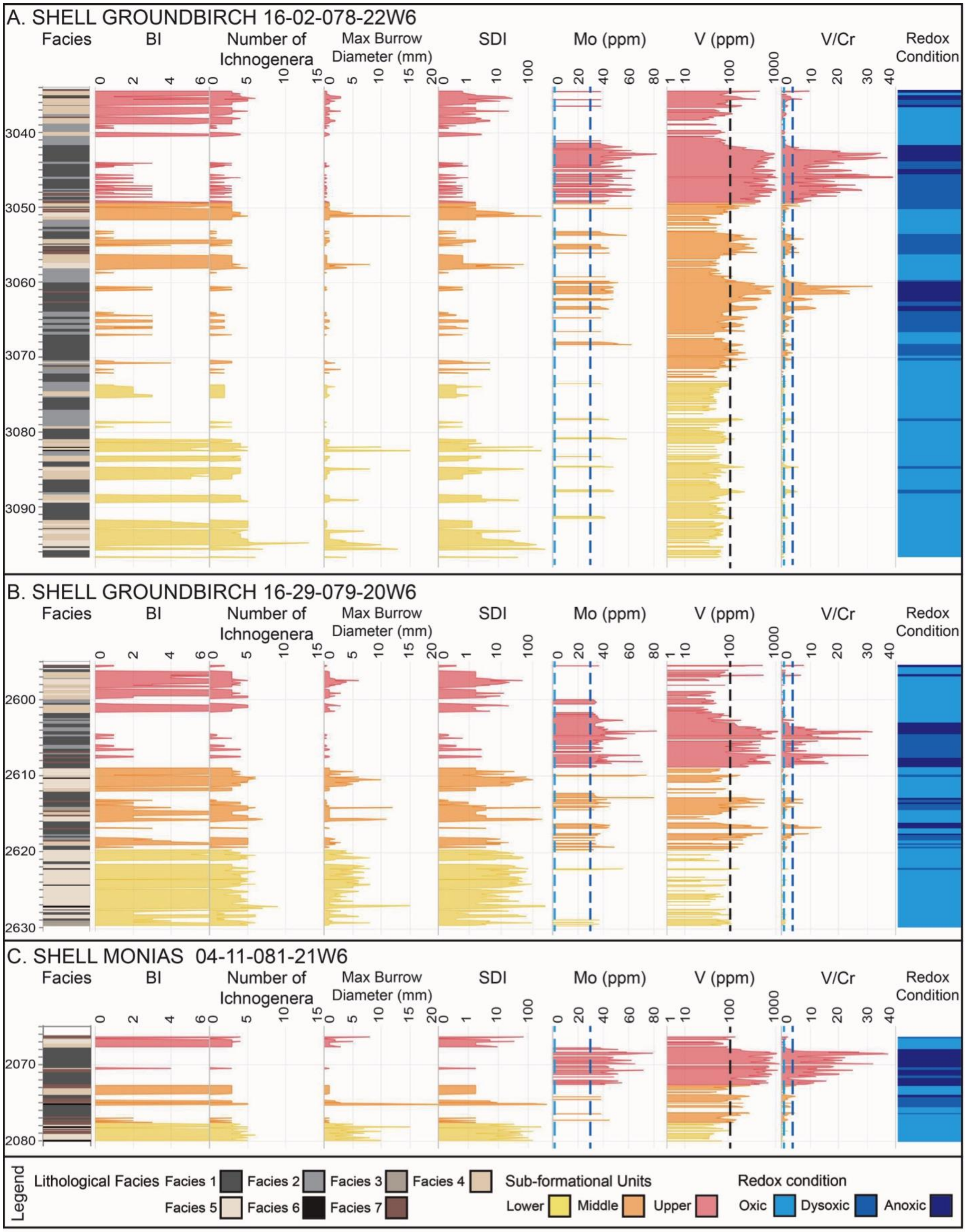

Figure 1. Composite lithological, ichnological and geochemical records. Dashed lines represent redox thresholds associated with the different redox-sensitive elements.