Unbioturbated Carbonaceous Shales in the Cretaceous Western Interior Seaway Record Oxic Bottom–Water Conditions*

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Abstract

Dark gray to black shales are prevalent in the Cretaceous Western Interior Seaway (WIS). Many of these shales are unburrowed suggesting that macrofauna were unable to survive in the paleo-environment, and this has led to interpretations that deeper parts of the WIS may have varied from suboxic (0.2 – 2.0 mg l-1) to anoxic (< 0.2 mg l-1). A comparison of micropaleontological, geochemical, and ichnological datasets from the Joli Fou, Viking, and Westgate formations, Alberta, Canada (Albian to Cenomanian) is undertaken to determine the oxygenation of bottom waters at the time of shale deposition. These shales occur in environments interpreted as upper offshore through to shelf, and the shales are sedimentologically and ichnologically similar to carbonaceous shales preserved throughout the WIS from the Late Albian to the Santonian. Geochemical proxies (e.g., Fe/Al and Mo/Al ratios, Re concentration) and foraminiferal data indicate that the under- and unbioturbated, carbonaceous shales tested in this study were actually deposited under oxic bottom water conditions. Based on this and the results of recent work from the Gulf of Mexico, we conclude that the paucity of burrowing is a manifestation of reduced oxygenation (low oxic: 2.0 < DO < 5.0 mg l-1), which was sufficient to support diverse benthic foraminiferal communities but not burrowing macrofauna. From these data, we propose a hierarchy of datasets for recognizing decreasing oxygen saturation. 1) Highly burrowed sediments (BI ≥ 3) indicate the presence of macrofauna on the seafloor and dissolved oxygen (DO) contents likely exceeding 80% saturation (> 5.0 mg l-1). 2) Under- and unbioturbated carbonaceous shales (BI 0-2) with diverse foraminiferal contents suggest low-oxic conditions (< 80% saturation, but > 2 mg l-1 DO). 3) Sub-oxic and anoxic conditions can be determined from geochemical proxies (e.g., Fe/Al > 0.5, Mo/Al > 0.001). These sediments will show low diversities of foraminifera and be unbioturbated (BI 0). 4) Euxinic bottom water (H₂S present) is best determined from Mo (> 15 ppb) and Re (> 15 ppb) enrichment, coupled with a complete lack of benthic foraminifera and no bioturbation (BI 0).

References Cited


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SFU
Objective

Is a paucity of bioturbation in marine mudstones indicative of anoxia?

If not, what does a paucity of burrowing represent?

Compare ichnological, foraminiferal, and geochemical datasets from the Western Interior Seaway
Study Area & Interval

Lower Cretaceous: Joli Fou – Viking – Westgate Formations, Alberta

From Dashtgard and MacEachern, 2016
Mudstone Facies

36 mudstone / shale samples

Characterize ichnological, foraminiferal, and geochemical signatures by facies:

Highly bioturbated mudstone [Upper & Lower Offshore]
Mudstone Facies

36 mudstone / shale samples

Characterize ichnological, foraminiferal, and geochemical signatures by facies:

Unbioturbated dark mudstones & shale [Fully Marine / Shelf]
Ichnological Characteristics

- Highly bioturbated mudstone
- Abundant oxygen in water column = support burrowing infauna
- Healthy ecosystem

Indicative of high oxic conditions
Ichnological Characteristics

Low BI and Unburrowed mudstone

Burrowing infauna rarely present and, if so, are small.

Apparent lack of bioturbation attributed to unhealthy environment

Suboxia? Anoxia?
"…foraminifera are potential proxies for the lower limits [of $O_2$] but once levels rise to values of perhaps >1 to 2 ml l$^{-1}$ (1.3 or 2.7 mg l$^{-1}$), there is no longer a relationship between oxygen levels and abundance." – Murray (2001) and Kaiho, 1994
In fact, foraminifera are more abundant in low BI mudstones vs their highly bioturbated counterparts!

From Dashtgard and MacEachern, 2016
Geochemical Characteristics

Lack of Rhenium (Re) and Molybdenum (Mo) enrichment reflects oxygenated seafloor

[Rhenium]
> 6 ppb recognized in suboxic settings (Crusius et al., 1996)

[Molybdenum]
>20 ppm recognized in euxinic sediments (Crusius et al., 1996)
Geochemical Characteristics

Iron/Aluminum (Fe/Al) and Molybdenum/Aluminum (Mo/Al) ratios also indicate an oxygenated seafloor.

Fe/Al Ratio
Ratio > 0.50 recognized as low O$_2$ (Crustal concentration) (Gordon et al. 2009)

Mo/Al ratio
Ratio > $1 \times 10^{-3}$ recognized as low O$_2$ (Gordon et al. 2009)
Summary of Results

Both **burrowed** and **unburrowed** samples deposited below oxic bottom waters

Why the major difference in bioturbation then?
Gulf of Mexico

30 **Box Cores:** 12 to 50 cm high, 12 to 140 m WD

26 **Pipe Cores:** 70 – 200 cm high, 13 to 133 m WD
Bioturbation Intensity

BI 1 to 2 in sediments below 35 m water depth
BI of 1 typical for sediments below 100 m WD

Data from Snedden (1985) and White (1985)
Bioturbation Diversity

Trace diversity below 35 m WD < 50% of the diversity above 35 m WD. Decreases offshore.

(From Dashtgard et al., 2015)
Dissolved Oxygen

Below 35 m WD: DO is consistently < 80% saturation and decreases offshore

BUT – Water is still **OXIC**! [Low oxic 2 < DO < 5 mg L\(^{-1}\)]

(From Dashgard et al., 2015)
Bioturbation trends track major decrease in infauna density and diversity when:

Dissolved Oxygen decreases from 100% saturation to < 80% saturation
Major decrease in average bioturbation intensity (and trace diversity) correlates to:

Decrease in Dissolved Oxygen from 100% saturation to < 80% saturation
Infauna are not prevalent when Dissolved Oxygen saturation drops below 80% saturation [Low oxic 2 < DO < 5 mg L\(^{-1}\)]

A lack of infauna = a lack of bioturbation (low BI mudstones)
Gulf of Mexico

Semi-enclosed seaway

Surface water T: 27 °C

T at 200 m: 15 °C

Low oxic conditions prevalent below storm-wave base to > 200 m water depth.

Dashtgard and MacEachern, 2016
Antarctic Ocean

Open polar ocean

Surface water T: -0.5 °C

Water T at 200 m: 2 °C

Cold waters sustain high oxic conditions. No low oxic zone developed.
Black Sea

Surface water $T$: 15 $^\circ$C

$T$ at 200 m: 9 $^\circ$C

Low oxic conditions developed in a narrow vertical zone. Likely not well expressed. Mostly anoxic.
Arabian Sea

Open tropical ocean

Surface water T: 26 °C

Water T at 200 m: 18 °C

Low oxic conditions prevalent in shallow water (below storm-wave base)
Summary of Ocean Oxygenation

Low oxic conditions are expected in **warm, shallow** basins [with ocean circulation]

From Dashtgard and MacEachern, 2016
Decrease in bioturbation correlates to a reduction in dissolved oxygen in oxygenated (oxic) seawater = low oxic conditions! [Low oxic \( 2 < \text{DO} < 5 \text{ mg L}^{-1} \)]
Propose that most unburrowed dark shales simply reflect development of low oxic conditions rather than suboxia/anoxia especially in the Western Interior Seaway.

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Maximum Water Depth for the Western Interior Seaway from Plint et al., 2012.
Thank you