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Isotopic evidence for partial geochemical decoupling between a Jurassic epicontinental sea and the open ocean

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(Article begins on next page)

1 **Isotopic evidence for partial geochemical decoupling between a Jurassic**
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32 **epicontinental sea and the open ocean**
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Abstract

We report stable isotope ratios ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$), minor and trace elements (Mn, Fe, Sr, Mg) together with Ca concentrations from bivalve shells and belemnites from the Middle-Upper Jurassic Sundance Seaway (western United States), we compare them with coeval open-ocean Tethyan data, and reconstruct the palaeo-circulation of seaway waters. The Sundance Seaway was a 2000 km long epicontinental sea with a single entrance at mid latitudes (55–60°N), which would have fostered substantial evolution of seawater chemistry relative to its open-ocean source. Samples are distributed across the 13-million-year marine history of the seaway, and across a 540 km east-west transect spanning Wyoming. $\delta^{13}\text{C}$ values are in the same range as Tethyan data, and this suggests that they might record global changes in the carbon cycle, with one exception in the Oxfordian. $\Delta^{18}\text{O}$ values from the seaway are in contrast highly depleted compared with Tethyan data (-2 to -6‰), and they indicate unrealistically high palaeotemperatures (20–40°C), assuming an isotopic composition of seawater of -1‰, as generally used for the Jurassic. Given more realistic temperature estimates from Mg/Ca ratios of bivalve shells (10–25 °C), we explain such negative $\delta^{18}\text{O}$ values by the southward inflow of normal-salinity, isotopically depleted (-3, -4‰), Arctic water into the seaway. Such water would become progressively more saline and denser as it flowed towards the southernmost portion of the seaway. In the Late Jurassic, characterised by wetter climate conditions, less dense Sundance waters may have instead exhibited a northward flow, reducing the southward surface flow from the Arctic. The observed partial geochemical decoupling of Sundance Seaway water masses from the open ocean strongly recommends caution in interpreting the geochemical record of ancient shallow seas, where local, regional and global drivers of change all need to be considered.

Keywords (6, American spelling)

bivalve, belemnite, paleoclimate, epicontinental sea, Tethys

1 Introduction

The record of marine sedimentary rocks older than *in situ* oceanic crust is predominantly known from epicontinental deposits, which formed during periods of high relative sea level, in ancient epeiric seas (Holmden et al. 1998). As such, epeiric or epicontinental seaways are the dominant source for much of our information about ancient marine biodiversity. There is, however, growing evidence that these epeiric seaways are often decoupled from normal open-ocean conditions as a result of variations in water mass, depth, salinity, and stratification (e.g., Holmden et al. 1998; Brand et al. 2009; Petersen et al. 2016; Wierzbowski et al. 2018). Inland, semi-enclosed seas also tend to be more productive than the open ocean and more prone to anoxia (e.g., Diaz and Rosenberg 2008). Hence, understanding these systems is critical to reconstruct the temporal changes and biogeographic patterns of marine biodiversity as well as the role epeiric seaways play in terms of ocean circulation, carbon cycling, and climate change.

This research sets out to examine the Jurassic Sundance Seaway, an epicontinental sea that developed on the North American craton from the Bajocian to the Oxfordian (Figure 1). The palaeogeography of the Sundance Seaway had a greatly elongated shape and is inferred to have had a single entrance located at a mid latitude, which was the only connection to the open ocean. Because of this, pronounced latitudinal temperature and salinity gradients have been suggested for the seaway (Stanley 2010; McMullen et al. 2014; Danise and Holland 2017), which would have in turn controlled patterns of faunal diversity, distribution, and immigration into the seaway. However, no detailed palaeoenvironmental reconstruction of the seaway based on geochemical proxies has been performed so far to test these hypotheses, and to better understand the connection of the Seaway to the open ocean, previous studies having focused only on sparse oxygen stable isotope analyses of belemnite rostra (Bowen 1961, Longinelli 1969, Longinelli et al. 2002). To characterise the palaeoceanography and climatic setting of the Middle–Late Jurassic Sundance Seaway, a record of oxygen and carbon isotopes, Ca, minor and trace elements ((Mn, Fe, Sr, Mg) is presented is

presented here from well-preserved bivalves (family Gryphaeidae) and belemnite rostra from the Twin Creek, Gypsum Spring and Sundance Formation (Figure 2). This record covers the 13 million year marine history of the seaway and spans 540 km across the seaway from westernmost to eastern Wyoming (USA).

2 Geological Setting

During the Middle–Late Jurassic (Bajocian to Oxfordian, ~170–157 Ma), the Sundance Seaway extended for nearly 2000 km from southern Utah northward into Alberta and British Columbia (Figure 1; Imlay 1957; 1980; Blakey 2014). It was bounded to the west by a volcanic arc and a fold and thrust belt that separated it from the proto-Pacific Ocean, to the east by the North American craton, and to the south by the ancestral Rockies uplift that separated it from the Gulf of Mexico (Imlay 1980). Most reconstructions of the seaway depict a single, narrow entrance at approximately 55–60°N palaeolatitude, with the seaway stretching southward through the Twin Creek Trough into Utah at ~ 30°N palaeolatitude (e.g., Blakey 2014). The Sundance Seaway formed within a retroarc foreland basin, with the thrust loads to the west creating the deeper water Twin Creek Trough along the western margin, in which water depth was perhaps at most 100 m (Imlay 1980; Kvale et al. 2001). The single entrance, length, and shallowness would likely have inhibited extensive tidal exchange, and it would likely have allowed for strong gradients in temperature and salinity to develop along the great length of the seaway (Tang and Bottjer 1996; Stanley 2010; McMullen et al. 2014; Danise and Holland 2017).

Initial flooding spread southward from the northern proto-Pacific Ocean, reaching southeastern British Columbia during the Early Jurassic (Imlay 1957). The seaway continued to extend southward, reaching Wyoming during the Early Bajocian, as evidenced by deposition of marine sediments (Imlay 1957; Brenner and Peterson 1994) in the Gypsum Spring Formation across most of Wyoming and the Twin Creek Formation in westernmost Wyoming and Idaho. Marine deposition continued in this region throughout the Jurassic, until the Late Oxfordian (Brenner and

Peterson 1994; McMullen et al. 2014), and is recorded by the Sundance Formation across most of Wyoming and the Preuss and Stump Formations in westernmost parts of the basin. In the Late Oxfordian to Early Kimmeridgian, the seaway filled with terrigenous sediment supplied primarily from the south, as the coastal plain recorded by the Morrison Formation prograded northward (Brenner and Peterson 1994; McMullen et al. 2014).

The Gypsum Spring Formation unconformably overlies the Triassic Chugwater Group in the Bighorn Basin in central Wyoming, the Triassic to Jurassic Nugget Sandstone to the west and south, and the Permian to Triassic Spearfish Formation to the east in the Black Hills (Imlay 1952; Pipiringos and O’Sullivan 1978). The Gypsum Spring Formation was deposited on a northwestward-dipping mixed evaporate–carbonate–siliciclastic ramp (Clement and Holland 2016). Of the three informal members, only the middle member is fossiliferous. This middle member contains the ammonites *Defonticeras* and *Stemmatoceras* in western Wyoming (Imlay 1952) and the ammonites *Defonticeras*, *Parachondroceras* and *Sohlites* in the western Bighorn Basin (Imlay 1956; Callomon 1982), and it is therefore regarded as belonging to the middle-upper part of the Bajocian stage (Imlay 1980).

The overlying Sundance Formation is divided into seven members (Wright 1973; McMullen et al. 2014, Danise and Holland 2018), and these record alternations between relatively shallow-water carbonate and siliciclastic environments and relatively deeper-water mudstone environments. The Canyon Springs and lower Hulett members are dominated by carbonate rocks, deposited mainly in the shallow subtidal and on ooid shoals (McMullen et al. 2014). Eastward and southward, the lower Hulett passes into a siliciclastic desert system dominated by dryland rivers and desert dunes of the Lak Member (Danise and Holland 2018). The Stockade Beaver Shale separates the Canyon Springs and Hulett, and it was deposited on a mixed carbonate–siliciclastic shelf, with offshore, carbonate mudstone facies to the west, and siliciclastic offshore and offshore transition facies to the east (Wright 1973). Ammonite biostratigraphy indicates that the Canyon Springs Sandstone was

116 deposited in the late Middle to early Late Bathonian, and the Stockade Beaver Shale was deposited
 1
 117 in the Late Bathonian (Imlay 1980). The lower Hulett Member is correlated with the Callovian
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 118 *Macrocephalites macrocephalus* Zone (Imlay 1982). The upper Hulett Member is a siliciclastic
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 119 incised-valley fill capped by transgressive ooid shoal facies (Danise and Holland 2018), and it lacks
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 9
 120 biostratigraphically useful fossils. The fossiliferous Redwater Shale Member was deposited on a
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 121 wave-dominated siliciclastic shelf, and the lower part is correlated with the Oxfordian *Cardioceras*
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 14
 122 *cordatum* Zone (Imlay 1982). The overlying Windy Hill Sandstone Member was deposited on a tidal
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 16
 123 coast and grades upward through progressive loss of tidal influence into overlying coastal plain
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 19
 124 deposits of the Morrison Formation (McMullen et al. 2014). Although the Windy Hill lacks
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 21
 125 biostratigraphically useful fossils, its stratigraphic relationship with the underlying Redwater Shale
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 126 Member in southern Wyoming suggests that it is younger than Early Oxfordian and is probably
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 26
 127 Middle Oxfordian (Imlay 1980). The Sundance Formation in Wyoming contains a rich assemblage
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 29
 128 of marine macroinvertebrates (Danise and Holland 2017 and references therein), as well as diverse
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 31
 129 but rare marine reptiles, including ichthyosaurs, plesiosaurs, and pliosaurs (McMullen et al. 2014;
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 33
 130 Massare et al. 2014).

131 Sediments of the Twin Creek Formation exposed in the Wyoming Range of westernmost
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 132 Wyoming and eastern Idaho consist of a thick series of marine carbonate and shale deposited on a
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 133 westward-dipping mixed evaporate–carbonate ramp. The Twin Creek Formation is subdivided into
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 134 seven members that were deposited in environments ranging from desert mudflat and sabkha to
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 135 offshore carbonate (Imlay 1967). Overlying the basal Gypsum Spring Member of the Twin Creek
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 136 Formation, the Sliderock and Rich members contain the ammonites *Stemmatoceras*,
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 137 *Megasphaeroceras* cf. *M. rotundum*, and *Sohlites spinosus* (Imlay 1952; 1967; 1980), which belong
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 138 to the middle-upper part of the Bajocian. The Leeds Creek Member has been biostratigraphically
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 139 correlated to the Stockade Beaver Member of the Bighorn Basin, which indicates that the Giraffe
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 140 Creek Member is also likely to be Late Bathonian to Callovian (Imlay 1967). The Twin Creek
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141 Formation is overlain by the Middle Callovian to Oxfordian Preuss and Stump formations, which
 142 were deposited in hypersaline intertidal mud flats (Kocurek and Dott 1983) and deltas.

143 In a recent sequence-stratigraphic interpretation of the marine Jurassic of Wyoming and
 144 adjacent states, the Twin Creek, Gypsum Spring and Sundance formations are divided into seven
 145 third-order depositional sequences, which include facies associations from offshore, carbonate ramp,
 146 siliciclastic wave-dominated shelf, siliciclastic tidal coast and mixed evaporate-siliciclastic desert
 147 depositional systems (McMullen et al. 2014; Clement and Holland 2016; Danise and Holland 2017;
 148 2018). For this study, low-magnesium calcite shells of gryphaeid bivalves and belemnites were
 149 collected from every fossiliferous marine depositional sequence, and when possible, across the
 150 onshore–offshore gradient, which deepens towards the northwest.

152 3 Analytical Methods

153 In this study, we integrate results from geochemistry of biogenic carbonate within a rigorous
 154 stratigraphic and sedimentologic framework to reconstruct palaeoenvironmental changes in the
 155 Sundance Seaway. Samples were collected from 22 locations within Wyoming, and 1 location in
 156 Montana, USA (Figure 1). From each fossiliferous bed, bivalves (*Liostrea strigilecula*, *Gryphaea*
 157 sp., *G. planoconvexa*, *G. nebrascensis* and *Deltoideum* sp.) and belemnites (*Pachyteuthis densus*)
 158 were collected for stable isotope and elemental analysis. 88 *L. strigilecula*, 5 *Gryphaea* sp., 28 *G.*
 159 *planoconvexa*, 53 *G. nebrascensis*, 59 *Deltoideum* sp., and 96 *P. densus* were analysed, for a total of
 160 329 specimens. When possible, replicate analyses of the same shell for each species were performed
 161 to check the accuracy of the analyses, resulting in 371 analyses on 329 specimens (Supplementary
 162 Table 1).

163 The degree of diagenetic alteration of belemnite and bivalve shells was initially assessed on
 164 selected specimens through scanning electron microscope (SEM, Supplementary Figure S1),

165 cathodoluminescence (CL, Supplementary Figure S2) and observations on thin sections, and then
1 routinely performed on all specimens through minor and trace elements analysis (Supplementary
166 2 Table 1). CL analyses were performed with a CITL MK5 cold cathodoluminescence instrument
3 4
167 5 Table 1). CL analyses were performed with a CITL MK5 cold cathodoluminescence instrument
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168 7 equipped with a Nikon microscope and digital camera, at the University of Plymouth, United
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169 9 Kingdom, on polished thin sections of shells cut longitudinally along the axis of maximum growth
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170 11 (perpendicular to the growth lines). CL is widely employed as a screening technique to identify
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171 13 diagenetically altered shell material (e.g., Wierzbowski and Joachimski 2007; Price and Teece 2010;
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15 16 Alberti et al. 2012). The CL behaviour of marine carbonates is a good indicator of diagenetic
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172 18 alteration since many secondary calcites exhibit luminescence that is activated by Mn^{2+} which enters
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20 21 the calcite crystals after burial of the shell (e.g., Savard et al. 1995; Fürsich et al. 2005; Wierzbowski
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23 24 et al. 2009). As a result, non-luminescent shells are generally considered to be unaltered (but *see*
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26 27 Barbin 2013 for a critical review of the method), compared with poorly preserved shells (showing
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29 30 the extensive presence of microborings, luminescent microfractures and alteration associated with
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32 33 the apical area of belemnites). SEM observations, another excellent tool to detect post-depositional
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35 36 alteration of the shells (e.g., Korte and Hesselbo 2011), were performed on the same thin sections,
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38 39 etched with 5% hydrochloric acid for 2–3 seconds in order to reveal the detail of the microstructure,
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41 42 gold-coated with a Quorum Q150R ES, and studied with a ZEISS EVO MA15 at the University of
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44 45 Florence, Italy.

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47 48 A microdrill and optical microscope were used to collect powder for stable isotopic and
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50 51 elemental analysis. Areas of the belemnite rostrum and the outer and inner surface of bivalves
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53 54 typically most prone to diagenesis and to the presence of possible microborings and microfractures
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56 57 (e.g., Ullman and Korte 2015) were avoided. Between 0.3 and 0.5 mg were collected for each
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59 60 sample. Carbonate powders were reacted with 100% phosphoric acid at 90 °C. Evolved CO_2 was
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62 63 analysed on a GV Instruments Isoprime mass spectrometer with a Gilson Multiflow carbonate
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65 66 autosampler at the University of Plymouth. Results were calibrated against Vienna Pee Dee

190 Belemnite (VPDB) using the international standard NBS-19 (National Bureau of Standards 19; $\delta^{13}\text{C}$
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191 = 1.95‰ $\delta^{18}\text{O}$ = -2.20‰). Reproducibility of replicate analyses for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ was better
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192 than 0.1‰. Each fossil shell was also sampled for Ca, minor and trace elements (Mn, Fe, Sr, Mg).
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193 Sample powders (between 3 and 10 mg) were reacted with 0.2 M HNO_3 and measured at the
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194 University of Plymouth using an Inductively Coupled Plasma-Atomic Emission Spectrometer
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195 (ICP-AES) using a PerkinElmer 3100. Repeat analyses of standards JLS-1 and BCS CRM 393 were
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196 within 2% of the certified values for Sr, Mn, Ca and Mg and 10% for Fe.
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197 Four specimens of *Gryphaea nebrascensis* were selected for high-resolution stable isotope
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198 analyses. The shells were cut parallel to the major growth direction, embedded in epoxy resin, and
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199 the cut surfaces were polished. Each specimen was examined under a cold CL microscope at the
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200 GeoZentrum Nordbayern of the Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany. The
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201 shells of *G. nebrascensis* were largely non-luminescent and therefore considered to be well-
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202 preserved; three specimens were selected for high-resolution stable isotope analyses. After
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203 identifying well-preserved sampling areas, the selected shells were sampled using a computer-
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204 controlled Merchantek Micromill (NewWave) at the GeoZentrum Nordbayern. Between 22 and 30
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205 samples could be collected per shell from the inside (younger) to the outside (older) side of the shells
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206 with a resolution of about 3 to 4 samples per millimetre (Supplementary Figure S3). The stable
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41
207 isotope composition was analysed using a carbonate preparation device (Kiel IV) connected to a
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208 ThermoScientific MAT 253 mass spectrometer at the Leibniz Laboratory for Radiometric Dating and
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46
209 Stable Isotope Research at the Christian-Albrechts-Universität zu Kiel, Germany. The carbonate
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210 samples were reacted within the preparation device with 100% orthophosphoric acid at 75 °C, and
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211 the evolved CO_2 gas was analysed using the mass spectrometer. Laboratory internal carbonate
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212 standards and two international carbonate standards (NBS-19 and IAEA-603) were analysed
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213 regularly to control the precision of measured $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values. All values are reported in per
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214 mil relative to the Vienna Pee Dee Belemnite (VPDB) scale using NBS-19.
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Palaeotemperature estimates were derived from the equation of Anderson and Arthur (1983):

$$T(^{\circ}\text{C}) = 16 - 4.14 * (\delta^{18}\text{O}_{\text{sample}} - \delta^{18}\text{O}_{\text{seawater}}) + 0.13 * (\delta^{18}\text{O}_{\text{sample}} - \delta^{18}\text{O}_{\text{seawater}})^2$$

assuming an ice-free Jurassic world with a $\delta^{18}\text{O}_{\text{seawater}}$ of -1‰ V-SMOW (Shackleton and Kennett 1975), and also from Mg/Ca (mmol/mol) ratio of bivalve shells, and calculated using the equation of Mouchi et al. (2013) calibrated on the modern Ostreidae *Crassostrea gigas* of the northern eastern Atlantic Ocean:

$$T(^{\circ}\text{C}) = 3.77 * \text{Mg/Ca} + 1.88, \text{ (where Mg/Ca is in mmol/mol).}$$

Finally, carbon and oxygen stable isotopes of gryphaeids from this study were compared with Jurassic Tethyan oysters and belemnite isotope data derived from the literature (*see* Supplementary Material for a complete list of the published referenced used).

4 Results

4.1. Bivalve and Belemnite preservation

Preliminary SEM observations on selected specimens indicated good textural preservation of the bivalve and belemnite samples. Observed specimens of *G. nebrascensis* and *G. planoconvexa*, belonging both to craton and foredeep settings, preserve the primary cross-foliated laminae of the inner layer (Supplementary Figure S1). Good preservation is also supported by the low luminescence of most shell material, with the exceptions of some *P. densus*, in which the more porous apical canal is filled with luminescent, secondary calcite, and some gryphaeids, in which a few microborings or fractures are filled with micrite or sparry calcite (Supplementary Figure S2). These areas tended to be Mn-rich as revealed bright orange luminescence (Supplementary Figure S2), and they were either removed prior to or avoided during subsampling.

Multiple studies have concluded that fossil ostreid and gryphaeid bivalves can be considered not diagenetically altered if they display Fe and Mn concentrations lower than 250 ppm, and Sr

239 concentrations higher than 350 ppm (e.g., McArthur et al. 2000; Wierzbowski and Joachimski 2007;
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 240 Price and Page 2008; Price and Teece 2010; Schneider et al. 2009; Korte and Hesselbo 2011). A total
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 241 of 55 specimens were excluded from the dataset because their elemental concentration fell outside
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 242 these values.
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 243 Similarly, several studies have shown that well-preserved belemnites typically have low
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 244 concentrations of Mn (<100 ppm) and Fe (<250 ppm) and higher concentrations of Sr (c. 800–1600
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 14
 245 ppm; e.g., Wierzbowski 2002; Wierzbowski et al. 2009; Price and Page 2008; Price and Teece 2010;
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 16
 246 Voigt et al. 2003). All the investigated belemnites in this study had Fe concentrations below or equal
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 247 to 250 ppm and Mn concentrations below 100 ppm (Supplementary Table S1). Only one specimen
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 248 was excluded for having Sr concentration lower than 800 ppm.
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25
 249 Other evidence that the bivalves and belemnite shells are not diagenetically altered, aside
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 27
 250 from the low concentrations of Fe and Mn, are the low correlation between Fe and Mn
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 29
 251 concentrations and Sr/Ca ratios (Supplementary Figure S4), and the scattered distribution of $\delta^{13}\text{C}$
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 252 versus $\delta^{18}\text{O}$ values for each species (Figure 3; *see* also Ullmann and Korte 2015).
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 253 After microscopic and geochemical screening of the specimens, 312 of the initially prepared
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 254 371 specimens were retained for subsequent data analyses and interpretation.
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256 4.2. Carbon and oxygen isotopes through time and space

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 257 The variation in carbon and oxygen isotopic ratios (Figure 3, 4, Supplementary Figure S5, S6
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 258 Table S1) reflects the depositional environment and depositional sequence in which each species
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 259 occurs in the Sundance. Most species in the Sundance Formation occur in only one depositional
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 54
 260 sequence and depositional environment, except *Liostrea strigilecula* which occurs in all the
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 261 fossiliferous sequences of central Wyoming. In contrast, *Gryphaea planoconvexa* is limited to
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 262 offshore facies of sequence J1a (Rich and Sliderock Member, Twin Creek Formation), which occurs
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263 only in the westernmost part of the studied area (Wyoming Range area, Figure 1C, Figure 4,
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 264 Supplementary Figure S6). Sequence J2 is only represented by samples of *L. strigilecula* collected
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 265 from shallow subtidal facies in central Wyoming (Canyon Spring Member, Sundance Formation).
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 266 Sequence J2a is mostly represented by *G. nebrascensis*, which occurs in offshore facies of central
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 9
 267 and western Wyoming (Cabin Creek Member of the Twin Creek Formation and Stockade Beaver
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 268 Shale Member of the Sundance Formation), and by some *L. strigilecula*. Sequence J4 is very
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 14
 269 fossiliferous and contain specimens from *L. strigilecula*, *Gryphaea* sp., *Deltoideum* sp. and *P. densus*
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 16
 270 from offshore facies in central Wyoming (Redwater Shale Member, Sundance Formation). J5 is the
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 271 only sequence from a tidal environment, and it contain fossils of *L. strigilecula*, *Deltoideum* sp., and
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 272 *P. densus* from central Wyoming (Windy Hill Sandstone Member, Sundance Formation; Figure 4,
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 273 Supplementary Figure S6). No data are present for sequence J3, as it is mostly characterized by
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 274 terrestrial facies, coastal mudflat facies, and poorly fossiliferous oolitic carbonates (Kocurek and
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 295 Dott 1983; McMullen et al. 2014), as such, the Callovian is not represented in our study.
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326 Because of the high turnover of species through time, and the differences in preserved
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 357 depositional environments through time, it is difficult to discern well-defined temporal trends in
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 378 carbon and oxygen stable isotope ratios (Figure 4A, B). $\delta^{13}\text{C}$ values for *L. strigilecula*, the only
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 409 species which occurs in all sequences, albeit from different depositional settings, become
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 420 progressively more positive from the Bajocian (median $\delta^{13}\text{C}$ 2.5‰) to the Oxfordian (median $\delta^{13}\text{C}$
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 44
 451 3.3‰). In the offshore facies association of sequence J4, the three different bivalve species display
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 478 different mean values of $\delta^{13}\text{C}$, although their distributions partially overlap. *Deltoideum* sp. shows
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 508 the most positive values of the three species (median $\delta^{13}\text{C}$ 5.6‰), followed by *Gryphaea* sp. (median
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 524 $\delta^{13}\text{C}$ 4.9‰) and *L. strigilecula* ($\delta^{13}\text{C}$ 4.0‰), and the belemnite *P. densus* has lower values (median
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 545 2.4‰) than bivalves.
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 56

578 Oxygen stable isotope values for *Liostrea* become slightly more positive from the Bajocian
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 607 (median $\delta^{18}\text{O}$ -3.7‰) to the Bathonian (median $\delta^{18}\text{O}$ -2.7‰), and more negative again in the
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288 Oxfordian (median $\delta^{18}\text{O}$ -3.3‰). In sequence J4, the three bivalve species show comparable values
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 289 of $\delta^{18}\text{O}$, while samples from the belemnite *P. densus* are more positive (Figure 3). Values of *G.*
 3
 290 *planoconvexa* from the offshore facies association of sequence J1a of western Wyoming have the
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 291 most negative $\delta^{18}\text{O}$ values (median $\delta^{18}\text{O}$ -5.6‰; min -8.1‰; Figure 4A, Supplementary Figure S6).
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 292 The same very negative values only occur again in sequence J2a, in samples of *G. nebrascensis* from
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 1293 the offshore facies association of western Wyoming (Figure 4B, Supplementary Figure S6).
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154 Focusing on *L. strigilecula* to compare the same species through time, the temperature trend
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 295 obtained from $\delta^{18}\text{O}$ values shows cooling from the Bajocian to the Bathonian, slight warming in the
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 296 Late Bathonian, steady temperature until the Early Oxfordian, and slight warming in the Middle–
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 2297 Late Oxfordian. All *L. strigilecula* samples come from an open-marine environment, except from
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 298 those of sequence J5 that come from a tidal siliciclastic coast, where salinity levels may have
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 299 affected $\delta^{18}\text{O}$ values. Assuming a $\delta^{18}\text{O}_{\text{seawater}}$ value of -1‰ V-SMOW, extremely high temperatures
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 300 are implied by the $\delta^{18}\text{O}$ values of samples of *Gryphaea* from western Wyoming of sequence J1a and
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 301 J2a (up to 45–50°C; Figure 4B). Palaeotemperature estimates calculated using the equation of
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 302 Mouchi et al. (2013) on bivalve shells Mg/Ca ratios, which applies a Mg/Ca-temperature calibration
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 303 for the extant oyster *Crassostrea gigas*, show values around 10°C lower than those obtained from
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 304 oxygen stable isotopes (Figure 4C, Supplementary Figure S6). Other Mg/Ca temperature equations
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 405 provide different absolute temperatures, as it is known that Mg/Ca calibrations are highly species-
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 406 dependent (*see* Bougeois et al 2016). For example, applying the equation of Lear et al. (2002) for
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 407 low-Mg calcite (benthic foraminifera) to our fossil bivalve data results in temperatures that are
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 408 slightly colder (by ~3–4°C) than those derived using the equation of Mouchi et al. (2013;
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 509 Supplementary Table S1).
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511 4.3 High-resolution carbon and oxygen isotopes on *G. nebrascensis*

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High-resolution isotopic analysis was performed on three specimens of the thick-shelled gryphaeid *G. nebrascensis*, with 30, 22, and 27 isotopic measurements made on each (Figure 5). Values of the carbon and oxygen stable isotopic ratios are within those obtained from bulk sampling of the same species (Figure 4A, B, Supplementary Figure S6). $\delta^{13}\text{C}$ values range between 2.75 and 4.02‰ (average 3.60‰), and $\delta^{18}\text{O}$ range between -1.50 and -3.59‰ (average -2.50‰). The $\delta^{18}\text{O}$ of the three shells show a cyclical pattern. Three main cycles are clearly seen in the first shell, and two cycles in the remaining two. That the shown cyclicity is strictly connected with the growth of the shell, is confirmed by the evidence that the amplitude of the cycles decreases with ontogeny, as expected because younger shells have a higher growth rate (Ivany 2012). More positive $\delta^{18}\text{O}$ values form a rounded, sinusoidal shape, while very negative values are truncated. The more negative peaks correspond to dark bands on the shell that are interpreted as periods of slowed shell growth (Jones and Quitmyer 1996).

4.4 Comparison with Tethyan carbon and oxygen isotopes

Irrespective of sampling level, oxygen isotopic ratios from the gryphaeid bivalves in this study are consistently lighter than values reported from the Tethys, with little overlap in the data (Figure 6C). In contrast, the carbon isotopic ratios coincide with Tethyan data, with the exception of those very positive $\delta^{13}\text{C}$ values derived largely from *Deltoideum* from sequence J4 (Oxfordian, Redwater Shale Member; Figure 6A). Oxygen isotope data from the belemnites in this study are also consistently lighter than those reported from Tethys, again with little overlap in the distributions (Figure 6D). Similarly, carbon isotopic ratios in the belemnites from the Sundance Seaway coincide with Tethyan carbon isotope data (Figure 6B). The same pattern (light $\delta^{18}\text{O}$ data derived from the belemnites and $\delta^{13}\text{C}$ data that is similar to coeval Tethyan data) has also been observed in the Bajocian portion of the Fernie Formation of Alberta and British Columbia, Canada, deposited in the Sundance Seaway just to the north of the study area (Figure 1; Hall et al. 2004).

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5 Discussion

5.1 Isotopic composition of seawater and palaeotemperatures in the Sundance Seaway

The good preservation of our analysed low-Mg calcite bivalve and belemnite shells allow us to use their oxygen isotopic composition to infer the temperature and the oxygen isotope composition of ambient seawater when the shells formed. Compared with Tethyan oxygen isotope data, the oxygen isotope data derived from the *Gryphaea*, oysters and belemnites from the Jurassic Sundance Seaway are rather depleted in ^{18}O . Using an isotopic composition of seawater of -1‰ (assuming an ice-free Jurassic world) and considering the full range of oxygen values (-0.5 to -8.6‰), the equation of Anderson and Arthur (1983) would indicate a temperature range of 10 to 50°C (Figure 4B). The upper range of these estimates is unrealistically high. Because screening of the shells with SEM, cathodoluminescence and trace elements argues against diagenetic effects, it suggests that the oxygen isotopic composition of seawater of the Sundance Seaway was substantially lighter than open ocean seawater. Using palaeotemperatures calculated from Mg/Ca ratios of bivalve shells and the equation of Anderson and Arthur (1983) to derive $\delta^{18}\text{O}_{\text{seawater}}$ suggests that the oxygen isotopic composition of seawater of the Sundance Seaway was much reduced (Figure 4C, D).

Continental runoff potentially provides a relatively light oxygen isotope source. Several studies (e.g., Wright 1987; Petersen et al. 2016 for the Cretaceous Western Interior Seaway) have documented relatively depleted $\delta^{18}\text{O}$ values from calcareous fossils and proposed that these suggest the influence of fresh water. A seaway with a $\delta^{18}\text{O}_{\text{seawater}}$ of -3.0 to -4.0‰ would greatly decrease estimates of water temperature in the Sundance Seaway, putting them in line with the $10\text{--}26^{\circ}\text{C}$ temperature range derived from general circulation models of the Middle Jurassic for the region (e.g., Gugliotta et al. 2016), as well as palaeotemperatures derived from our Mg/Ca ratios of bivalves (Figure 4C). The fully marine fauna of the Sundance Seaway (Imlay 1957; McMullen et al. 2014;

361 Danise and Holland 2017) presents two challenges to invoking continental runoff. A seaway with a
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 362 $\delta^{18}\text{O}$ value of -4.0‰ would imply salinity substantially below normal-marine conditions ($\sim 18\text{-}30$
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 363 PSU). Second, the carbon isotopic composition of Sundance Seaway bivalves are similar to those of
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 364 age-equivalent Tethyan calcitic bivalves, and both support positive fully marine values (Figure 6A;
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 365 *see below*). Furthermore, if reduced salinity was a significant factor, the greatest isotopic depletion
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 366 would be expected in gryphaeids sampled from open shallow subtidal and tidal channel facies that
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 367 are closer to land and freshwater influence. Instead, the lightest $\delta^{18}\text{O}$ values occur in *Gryphaea* from
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 368 the offshore facies from westernmost Wyoming (Figure 4B, Supplementary Figure S6). These
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 369 offshore facies from westernmost Wyoming also have the greatest diversity in the Sundance Seaway
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 370 (Danise and Holland 2017), indicating that the light isotopic composition was not caused by
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 371 freshwater input. Moreover, high runoff in the Middle Jurassic would be unlikely, given the arid
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 372 environment indicated by the extensive salinas, sabkhas, and wadi ephemeral rivers preserved in the
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 373 J1a and J2 sequences (Danise and Holland 2018). Although a fluvial system may have been present
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 374 on the north-eastern borders of the seaway (*see Dickinson and Gehrels 2003*) the direct impact of
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 375 these freshwater influxes on salinity of this southern part is considered to be minor.
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376 In modern oceans, isotopically light seawater can also be observed in the Arctic Ocean (e.g.,
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 377 Bauch et al. 2015; Thomas and Mol 2018). For example, the oxygen isotope composition of the
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 378 modern Arctic Ocean, in the salinity range of 30-35 PSU (the Laptev Sea and the Mackenzie Shelf of
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 379 the Beaufort Sea) can be as light as -4.5‰ , with DIC carbon isotopic ratios being typically around
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 380 1.5‰ , but in some cases exceeding 2.0‰ . Similar isotopically light values for Arctic seawater have
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 381 been hypothesised for the Cretaceous (Zhou et al. 2008), and these could reasonably be extended to
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 382 the Middle to Late Jurassic. Although, Jurassic belemnite derived $\delta^{18}\text{O}$ values from Arctic and boreal
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 383 domains are often more positive, ranging from 1.6 to -2.5‰ in the studies of Ditchfield, (1997),
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 384 Zakharov et al. (2005), Rogov and Price (2010), Zak et al. (2011) and Dzyuba et al. (2013), and this
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 385 does not preclude light $\delta^{18}\text{O}_{\text{seawater}}$ values as temperatures were presumably a little cooler in these
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386 Arctic latitudes. The single entrance of the Sundance Seaway, located at a mid-latitude, would have
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 387 been adjacent to a cool open shelf region occupied by a Boreal fauna that ranged southward from
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 388 Alaska in cool waters sustained by the same southern Coriolis-driven current as today (Stanley
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 389 2010). In contrast, the southern terminus of the seaway lay within the subtropical arid belt (Kocurek
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 390 and Dott 1983; Kvale et al. 2001), where warm hypersaline conditions are supported by extensive
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 391 evaporites and carbonate facies (Danise and Holland 2018). If isotopically light seawater was derived
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 392 from the Arctic, it would imply a southward flow into the seaway. North–south density differences
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 393 and hence differences in hydrostatic level may have had an impact on water circulation. In the
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 394 relatively arid Middle Jurassic, when Sundance Seaway water would have been more saline and
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 395 therefore denser (creating a low hydrostatic sea level), surface water flow would have been
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 396 southward, giving the water in the seaway Arctic characteristics, specifically light oxygen isotope
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 397 ratios and typical marine DIC values (Figure 7A). During the southerly transit along the length of the
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 398 seaway, these normal-salinity waters would have warmed and evaporation would have increased
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 399 their salinity. This is supported by an increase in $\delta^{18}\text{O}$ of around 4‰ of Middle Jurassic species from
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 400 west to east within the seaway (Supplementary Figure S6, sequences J1a, J2, J2a), towards areas that
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 401 are associated with extensive desert mudflats, sabkhas, and wadi plain (Danise and Holland 2018).
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402 The temporal transition from Middle Jurassic carbonate-evaporite platform to a siliciclastic
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 403 shelf towards the end of the Jurassic suggests regional climate change from subtropical arid
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 404 conditions to temperate winter-wet conditions (Brenner 1983), caused in part by the northward
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 405 migration of the North American plate (Johnson 1992). Increasingly temperate and wetter conditions
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 406 may have increased freshwater runoff into the seaway. This freshening would have decreased
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 407 seawater density in the seaway, reducing the net southward flow of water, possibly leading to net
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 408 northward flow (Figure 7B). The oxygen isotope data from bivalves of the Oxfordian Redwater
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 409 Shale and Windy Hill Sandstone members show values that are closer to the Tethyan values (Figure
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 410 6A). The $\delta^{18}\text{O}_{\text{seawater}}$ during this time was also likely to be close to typical Tethyan $\delta^{18}\text{O}_{\text{seawater}}$ values
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411 too. An additional contributing factor to the resemblance between Tethyan and Sundance $\delta^{18}\text{O}$
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 412 values, may result from a wider opening of the Sundance Seaway during the Late Callovian – Early
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 413 Oxfordian (Imlay, 1980) due to sea level highstand (Hallam 2001; Wierzbowski et al. 2009), causing
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 414 an increased connection to the open ocean.
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 415 Notwithstanding the isotopic decoupling between the Sundance Sea and the open ocean at the
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 11 same mid-latitudes, and the resulting low isotopic ratios, the temporal trends in palaeotemperature
 416 indicated by $\delta^{18}\text{O}$ of bivalves and belemnites and Mg/Ca ratios of bivalves, partially agree with those
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 417 reconstructed for the Tethys. A Tethyan cooling event from the Bajocian to the Middle Bathonian
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 418 has been inferred from the geochemistry of European bivalves and belemnites (Brigaud et al. 2008;
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 419 Wierzbowski and Joachimski 2007; Dera et al. 2011). The slight warming recorded in Europe in the
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 420 latest Bathonian to the Early Callovian (Brigaud et al. 2008) is not observed in Sundance Mg/Ca
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 421 data, but only in $\delta^{18}\text{O}$ values, and the concomitant change towards more negative isotope values of
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 422 seawater (Figure 4D), casts doubts on the validity of Sundance $\delta^{18}\text{O}$ values as a palaeothermometer
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 423 in this instance. Both Sundance Mg/Ca and $\delta^{18}\text{O}$ record a slight warming from the Middle to the Late
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 424 Oxfordian, which has been also recorded in Europe and in the Russian Platform (Brigaud et al. 2009;
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 425 Dera et al. 2011, Wierzbowski et al. 2013).
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426 5.2 Carbon cycle in the Sundance Seaway

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 427 The isotopic data presented here generally overlap those of the Tethys (Figure 6), despite the
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 428 potentially dynamic setting of the semi-enclosed Sundance Seaway. This suggests that the observed
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 429 carbon isotope changes are not entirely decoupled from the open ocean (cf., Holmden et al. 1998).
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 430 Moreover, these synchronous changes in $\delta^{13}\text{C}$ indicate global changes in the carbon cycle. Carbon
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 431 cycling over timescales of millions of years results mainly from changes in the size and rate of the
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 432 exchange between the Earth's surface carbon reservoirs and the lithosphere (e.g., Kump and Arthur
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 433 1997), specifically the relative ratio of carbon stored in organic matter versus carbonates. For
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436 example, if relatively more carbon is removed from the oceans as organic matter that becomes
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 437 buried, the $\delta^{13}\text{C}$ value of DIC in the ocean increases. If the observed $\delta^{13}\text{C}$ isotope data are linked to
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 438 marine carbon burial, continental margins and inland seas tend to be more productive than the open
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 439 ocean (e.g., Diaz and Rosenberg 2008) and more prone to anoxia. This raises the question of whether
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 440 the shallow Sundance Seaway was a significant locus of organic carbon burial. In the northern part
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 441 of the Seaway, Lower Jurassic organic-rich mudstone and limestone accumulated in west central
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 442 Alberta and British Columbia (the Gordondale Member of the Fernie Formation), and these were
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 443 deposited in a predominantly anoxic marine basin (Riediger and Bloch 1995). These sediments
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 444 contain up to 20 wt. % TOC (Riediger and Bloch 1995). Although, much of the Fernie Formation
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 445 generally contains rocks with moderate to low concentrations of TOC (avg, 1.6 wt. %), they are over
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 446 mature, and their content is enough to be the source rock for several oil fields (Ryan and Morris
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 447 2006).
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448 In contrast, very positive $\delta^{13}\text{C}$ values (up to +6.4‰) found largely in *Deltoideum* from the
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 449 Oxfordian Redwater Shale Member are much more positive than the Tethyan data (Figure 6). Given
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 450 that these values exceed those in the Tethyan and are younger than the $\delta^{13}\text{C}$ excursion recognised in
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 451 the Tethys during the Middle Oxfordian at the boundary between the *plicatilis* and *transversarium*
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 452 ammonite zones (Główniak and Wierzbowski 2007), the most parsimonious interpretation of the data
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 453 from the Sundance Seaway is that it reflects a regional carbon isotope excursion caused by burial of
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 454 organic matter in the Sundance Seaway (e.g., Immenhauser et al. 2003). To date, no TOC data is
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 455 available from the Redwater Shale Member. Higher $\delta^{13}\text{C}$ values, compared with Middle Jurassic
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 456 records, are also observed in *L. strigilecula* and *Gryphaea* sp., even if less pronounced than in
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 457 *Deltoideum* sp. Differences in $\delta^{13}\text{C}$ among these the three species might be linked to species-specific
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 458 vital effects (Immenhauser et al. 2016).
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460 5.3 Seasonality in the Middle Jurassic

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461 The growth of bivalve shells is strongly regulated by temperature and food availability (*see*
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462 Killam and Clapham 2018), which vary periodically with tides, diurnal cycles, and seasons. Such
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463 variations are intimately related to the accretionary fabrics within the shells, which become high-
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464 resolution biogeochemical recorders of the environmental and climatic conditions experienced
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465 during their lifetime (Schöne and Surge 2012). The high-resolution isotope curves from *G.*
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466 *nebrascensis* of sequence J2a (Figure 5) show cyclical patterns that we interpret as annual cycles, as
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467 observed in most fully marine bivalves (*see* Schöne and Surge 2012), and the presence of these
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468 cycles argues that the isotopic composition of these shells has not been diagenetically reset. Minimum
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469 $\delta^{18}\text{O}$ values, which correspond to the warmest recorded water temperature, are associated with major
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470 darker bands on the shell (Figure 5). This correspondence implies slower shell growth during the
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471 highest summer temperatures, as observed in modern bivalves (Killam and Clapham 2018) and other
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472 species of fossil gryphaeids (Early Jurassic *Gryphaea arcuata*, Jones and Quitmyer 1996). Peak
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473 temperatures probably coincided with periods of food limitation, which inhibited the growth of the
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474 shell, as supported by the correlation of many negative peaks in $\delta^{18}\text{O}$ with low $\delta^{13}\text{C}$ values, probably
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475 linked to lower productivity. This implies that our *G. nebrascensis* shells provide a more complete
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476 record of the cooler portions of the year than the warmer parts, suggesting that peak temperatures in
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477 the Sundance Seaway may have been somewhat higher than what is recorded in shells. This tendency
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478 for shells to reflect some portions of the year better than others, undetectable through bulk sample
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479 analysis, need to be considered when reconstructing past climates (*see* Ivany 2012).
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481 6 Conclusions

482 Carbon and oxygen stable isotope and elemental analyses on bivalve and belemnite shells
483 from Middle–Upper Jurassic rocks of Wyoming allow for inferences on the climate, oceanography,
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484 and seasonality in the inland Sundance Seaway. These inferences are made possible by sampling
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485 within a rigorous sedimentologic and sequence-stratigraphic framework.
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486 Oxygen isotopes are overall highly depleted (between -8.1 and 0.6‰) compared with coeval
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487 Tethyan data, suggesting that the Sundance Seaway was partly decoupled from the open ocean, and
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488 that the seawater within it had a light isotopic composition (between -3 and -4‰). The lowest
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489 isotopic ratios are observed in Middle Jurassic samples from the westernmost part of the basin
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490 deposited within the foredeep, and these decrease towards the east, where water depths were
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491 shallower. Given the fully marine conditions indicated by the diverse fauna, we hypothesise that the
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492 isotopically light seawater in the Middle Jurassic is best explained by the southward inflow of
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493 normal-salinity Arctic waters into the seaway, characterised by light oxygen isotope values. This
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494 seawater would have become progressively more saline and denser as it flowed towards the southern
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495 end of the seaway, which occupied an arid setting in the Middle Jurassic. In the Late Jurassic when
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496 the southern end of the seaway had a semi-arid winter-wet climate, increased freshwater run off
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497 would have made water in the Sundance Seaway less dense, reducing the southern flow and possibly
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498 leading to net northward flow of water.
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499 Estimates of palaeotemperatures from Mg/Ca ratios of gryphaeid shells, indicates
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500 temperatures ranging from 10 to 26 °C, in agreement with temperature estimates from global
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501 circulation models for the Middle to Late Jurassic at the same palaeolatitudes.
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502 Carbon isotopic ratios from shells in the Sundance Seaway are closely similar to those from
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503 the Tethys, suggesting that observed synchronous changes in $\delta^{13}\text{C}$ reflect global changes in the
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504 carbon cycle through most of the Middle to Late Jurassic. The exception to this pattern is in the Early
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505 Oxfordian, where $\delta^{13}\text{C}$ ratios from the Sundance Seaway exceed those of the Tethys up to 2‰,
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506 which suggests a regional carbon isotope excursion caused by organic matter burial in the Sundance
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507 Seaway.
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508 Because epicontinental seas may have had reduced or limited exchange with the open ocean,
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509 it is important to consider that their geochemical history reflects regional processes as well as a
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510 global signal. Moreover, the results of this study imply caution when interpreting long-term trends in
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511 global climate and environmental change from large datasets.
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736 Figures

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737 **Figure 1.** Palaeogeographic reconstruction of western North America in the Middle Jurassic showing
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738 the Sundance Seaway and study area (A) and location map of the study area (B, C). A, modified
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739 from Blakey 2014. Localization of desert, ergs and mountain ranges from Kocurek and Dott (1983);
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740 presence of a hypothetical transcontinental river from Dickinson and Gehrels (2003).
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741 **Figure 2.** Summary of the chronostratigraphic and sequence-stratigraphic framework of the Jurassic
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742 Twin Creek Formation in western Wyoming and Idaho and the Sundance Formation in central and
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743 eastern Wyoming. Chronostratigraphy of units is based on Pipiringos and O'Sullivan (1978), Imlay
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744 (1952, 1967, 1980), Brenner and Peterson (1994) and Kvale et al. (2001).
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745 **Figure 3.** Scatter plot of carbon isotopes versus oxygen isotopes of the studied fossil shells, with
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746 samples coded by species.
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747 **Figure 4.** Record of carbon isotopes (A), oxygen isotopes and $\delta^{18}\text{O}$ temperatures (B), Mg/Ca
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748 temperatures (C), and $\delta^{18}\text{O}_{\text{seawater}}$ (D) plotted against the chronostratigraphic and sequence-
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749 stratigraphic framework of the Jurassic Twin Creek Formation and the Sundance Formation.
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750 Timescale of GTS 2012. Mg/Ca temperatures estimations for *P. densus* are not shown, as the applied
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751 equation is calibrated on modern oysters.
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752 **Figure 5.** High-resolution carbon and oxygen isotope record across three specimens of *Gryphaea*
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753 *nebrascensis*. Grey lines indicate dark bands on the shells which identify breaks in shell accretion
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754 (see Supplementary Figure S3).
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755 **Figure 6.** Comparison of Sundance and Tethyan isotopes. A) Carbon isotopes of gryphaeid bivalves
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756 from this study compared with isotope data from Tethyan bivalves. B) Carbon isotopes of belemnite
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757 (*Pachyteuthis densus*) data from this study compared with isotope data from Tethyan belemnites and
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758 belemnites from the northern part of the Sundance Seaway (Fernie Formation) collected in British
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759 Columbia and Canada (Hall et al. 2004). C) Oxygen isotopes of gryphaeids from this study
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760 compared with isotope data from Tethyan bivalves. B) Oxygen isotopes of belemnite (*Pachyteuthis*
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 761 *densus*) data from this study compared with isotope data from Tethyan belemnites and belemnites
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 762 from the northern part of the Sundance Seaway (Fernie Formation) collected in British Columbia and
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 763 Canada (Hall et al. 2004). *See* Supplementary Material for a complete list of the published referenced
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 764 used. Note that Tethyan isotope data include also data from the UK, a region where, throughout the
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 765 Mid Jurassic, the fauna was characterised by both Tethyan influences from the south, and Boreal
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 766 influences from the north (e.g., Korte et al. 2015). Numeric ages are from GTS 2012.
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 767 **Figure 7.** Reconstruction of marine water circulation in the Sundance Seaway. A) Middle Jurassic,
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 768 characterised by an arid climate system, with southward flow into the seaway (blue arrows) of
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 769 isotopically light, surface marine waters from the Arctic region, and northward flow of more saline
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 770 and denser (red arrows) Sundance Seaway waters. B) Late Jurassic, characterised by a semi-arid and
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 771 winter-wet conditions, with a northward flow of less dense Sundance Seaway waters (blue arrows)
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 772 that would inhibit the southward surface flow of ocean waters into the seaway.
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Supplementary Material
Table S1. Isotopic and elemental compositions of skeletal components analysed in this study
 together with information on location, formation, member, sequence and facies.

Table S2. High-resolution stable isotope analyses of *Gryphaea nebrascensis*.

Supplementary Figure S1. SEM images of A) *Gryphaea nebrascensis*, complex cross-foliated inner
 layer, highlighted by the dashed line. B) Detail of A, with regular, low angle, foliated laminae.
 Stockade Beaver Shale Member, Sundance Formation, sequence J2a. C) *G. nebrascensis*, irregular
 cross-foliated inner layer, highlighted by the dashed line. Cabin Creek Member, Twin Creek

783 Formation, sequence J2a. D) Detail of C. E) *G. planoconvexa*, low-angle cross-foliated inner layer.

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784 Sliderock Member, Twin Creek Formation, sequence J1a. F) Detail of E.

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785 **Supplementary Figure S2.** Cathodoluminescence images of studied belemnites and bivalves. A)

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786 Well preserved, non-luminescent, belemnite rostrum of *Pachyteuthis densus*. Only the apical canal
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787 (lower left) is slightly luminescent. Redwater Shale Member, Sundance Formation, sequence J4. B)

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788 Badly preserved *P. densus*, with the central part (apical canal) highly recrystallized (c). Redwater

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789 Shale Member, Sundance Formation, sequence J4. C) Well preserved, non-luminescent, *Gryphaea*

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790 *nebrascensis*. The only luminescent part is the micritic matrix (m) filling the shell. Stockade

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791 Beaver Member, Sundance Formation, sequence J2a. D) Moderately preserved *G. nebrascensis*.

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792 Luminescence is low except for microborings (mb) filled with micrite in the outer part of the shell.

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793 E) Moderately preserved *G. planoconvexa*. Non-luminescent inner layer, with cement-filled fracture

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794 (c). Sliderock Member, Twin Creek Formation, sequence J1a. F) Moderately preserved *Deltoideum*

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795 sp. Luminescence confined to closely spaced growth lines. Redwater Shale Member, Sundance

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796 Formation, sequence J4.

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797 **Supplementary Figure S3.** Specimens of *Gryphaea nebrascensis* sampled for high-resolution stable

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798 isotope analyses. Continuous line indicates path of sampling, performed from the inside (younger) to

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799 the outside (older) side of the shells. Red lines indicate major growth bands.

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800 **Supplementary Figure S4.** Scatter plot of minor and trace elements (divided by Ca) of the studied

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801 fossil shells. A) Sr/Ca ratio versus Fe. B) Sr/Ca ratio versus Mn.

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802 **Supplementary Figure S5.** Scatter plot of carbon isotopes versus oxygen isotopes of the studied

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803 fossil shells, with samples coded by depositional sequence (A), and depositional environment (B).

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804 Colours in both plots correspond to species.

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805 **Supplementary Figure S6.** Stratigraphic patterns in oxygen and carbon isotopes, and Mg/Ca

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806 temperatures for each species and depositional sequence, with localities ordered from west to east.

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807 Grey areas indicate localities from the foredeep on the west flank of the seaway, and white areas are
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808 from the cratonic eastern side of the Sundance Seaway.

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Figure

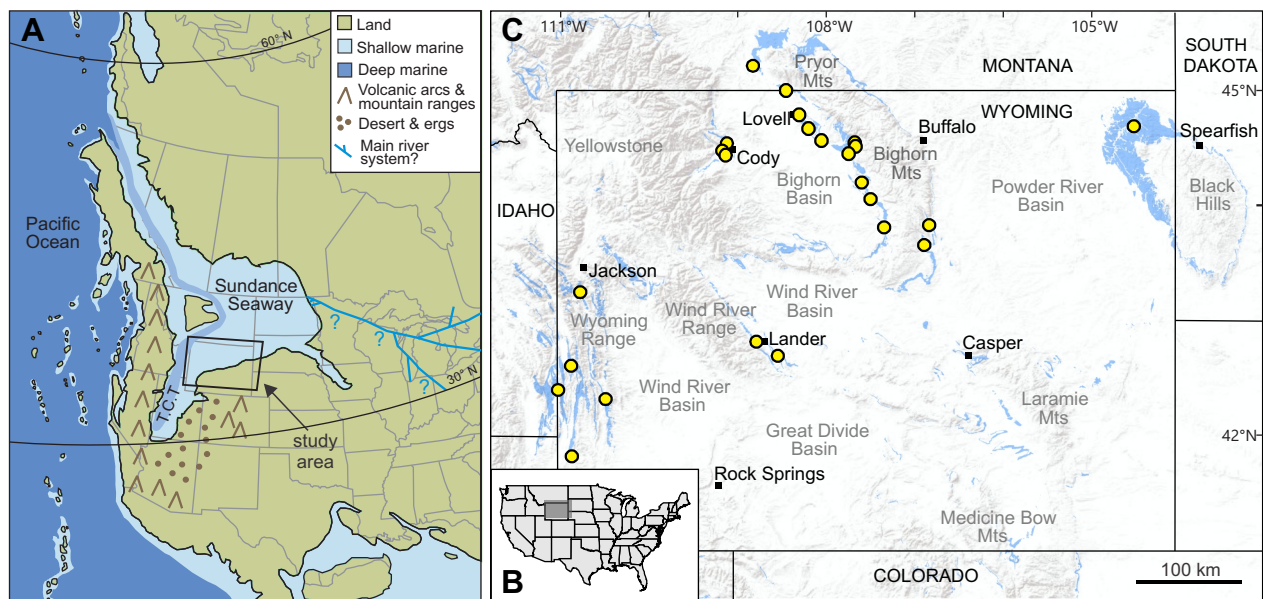


Figure 1, 1.5 columns

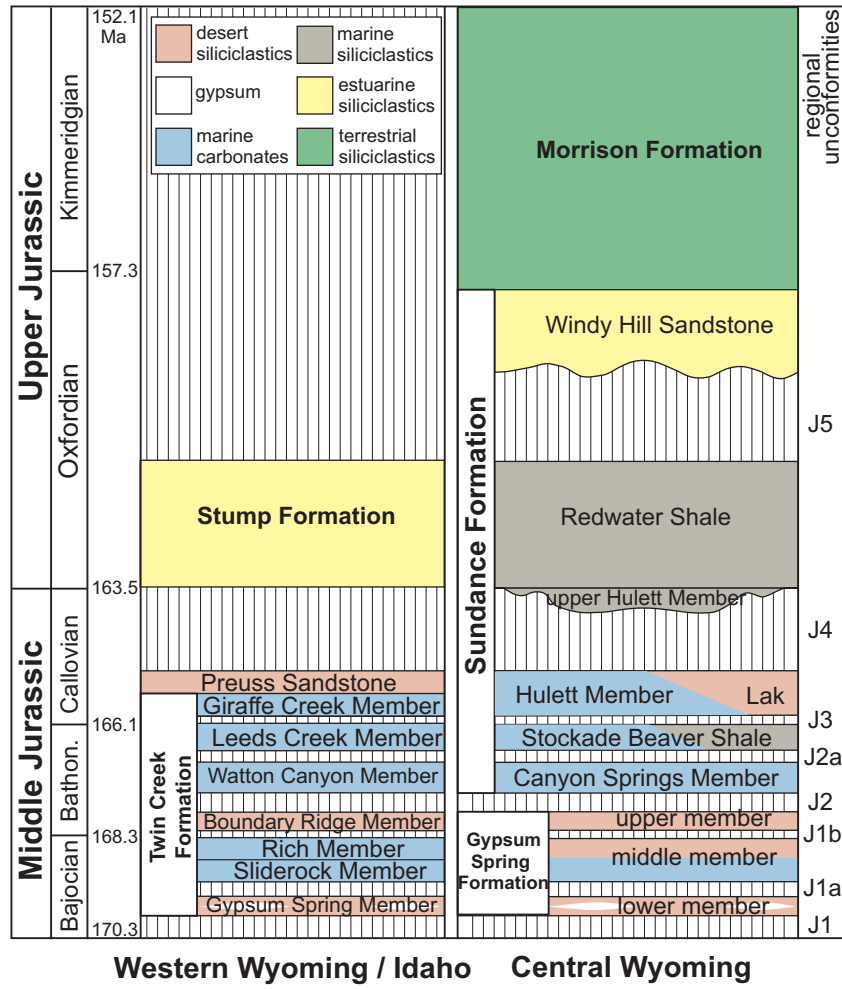


Figure 2, 1.5 columns

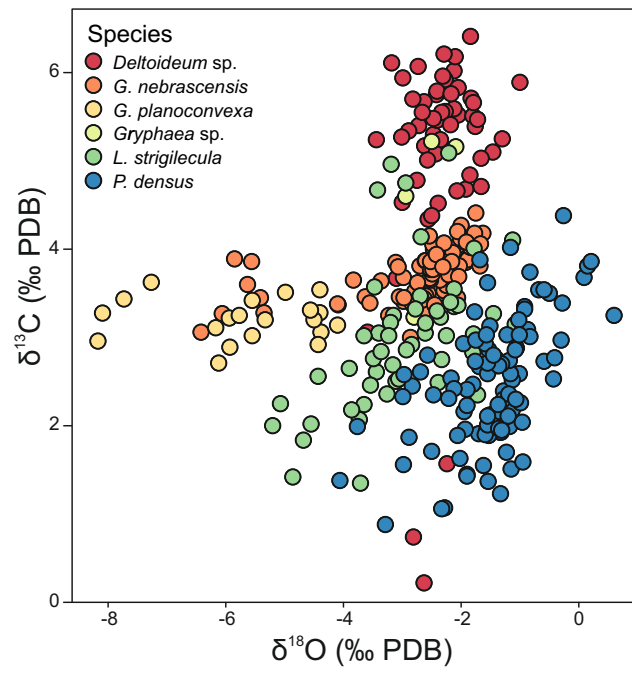


Figure 3, 1 column

Figure

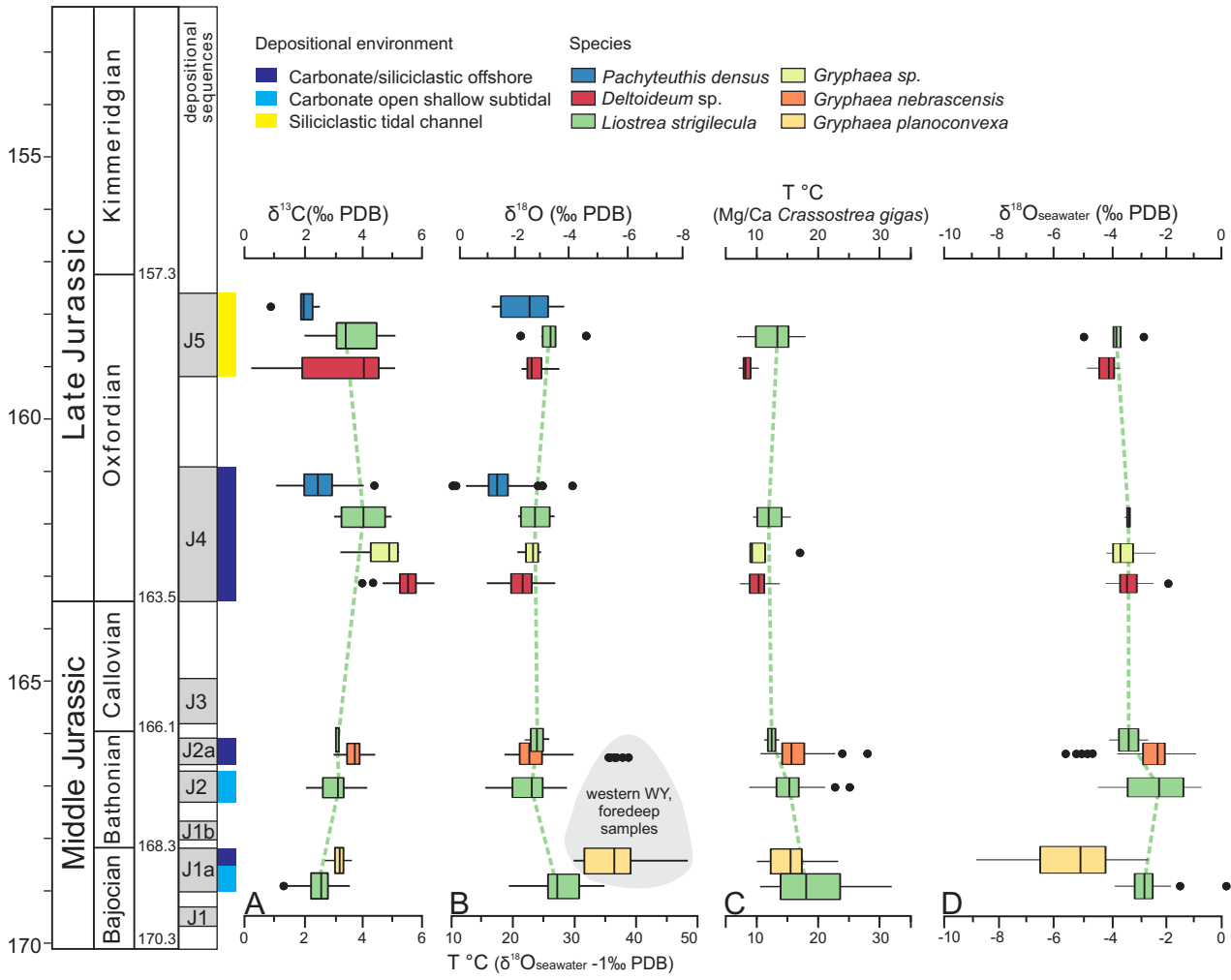


Figure 4 - 2 columns

Figure

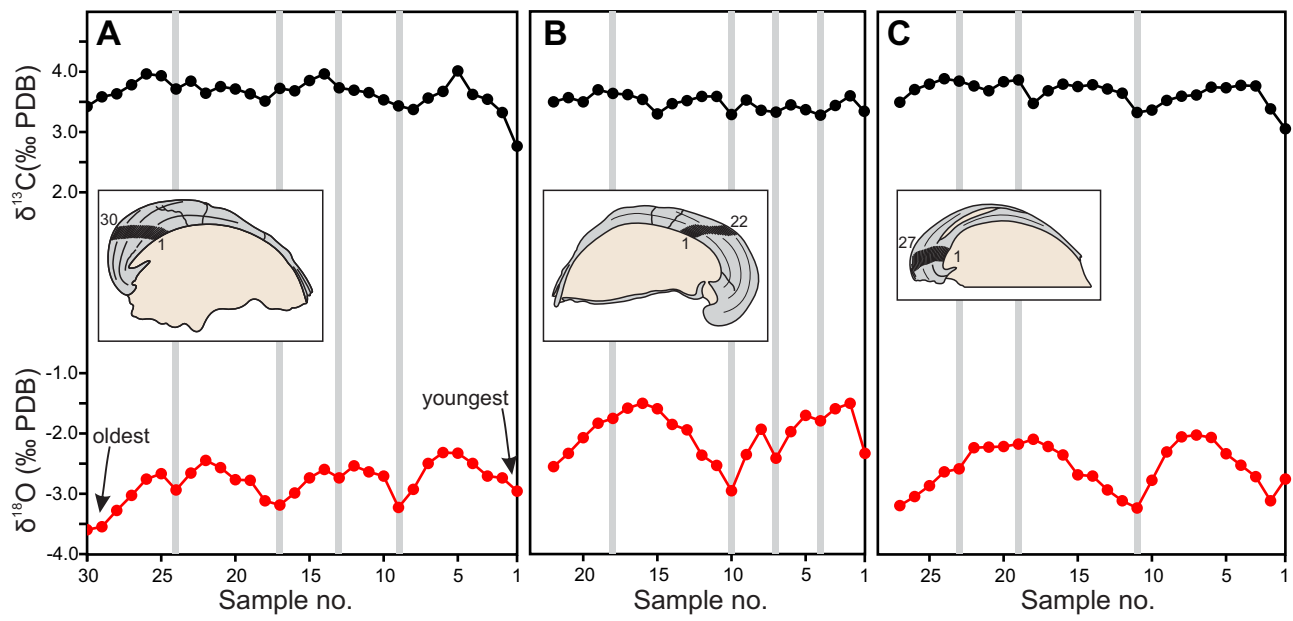


Figure 5, 2 columns

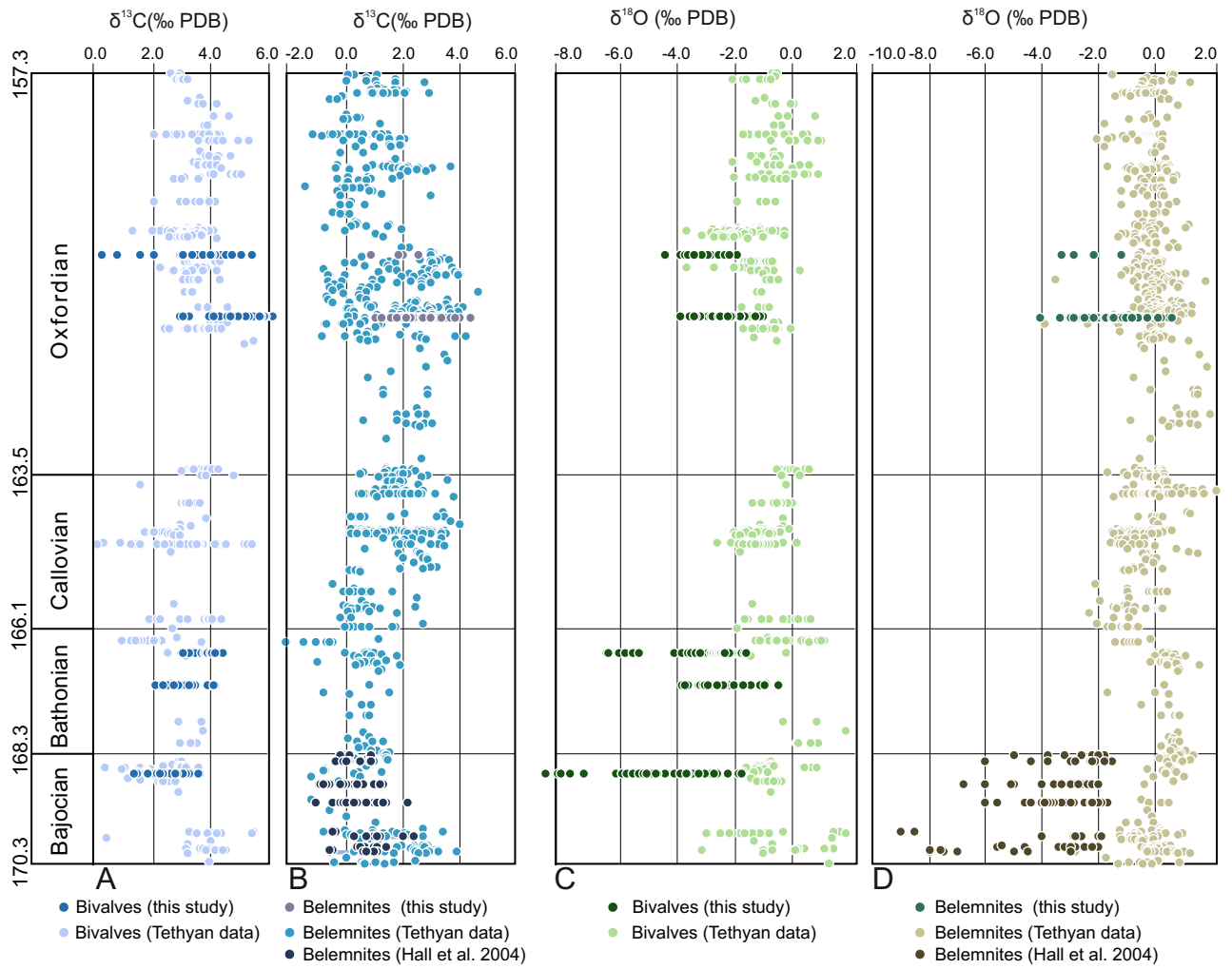


Figure 6, 2 columns

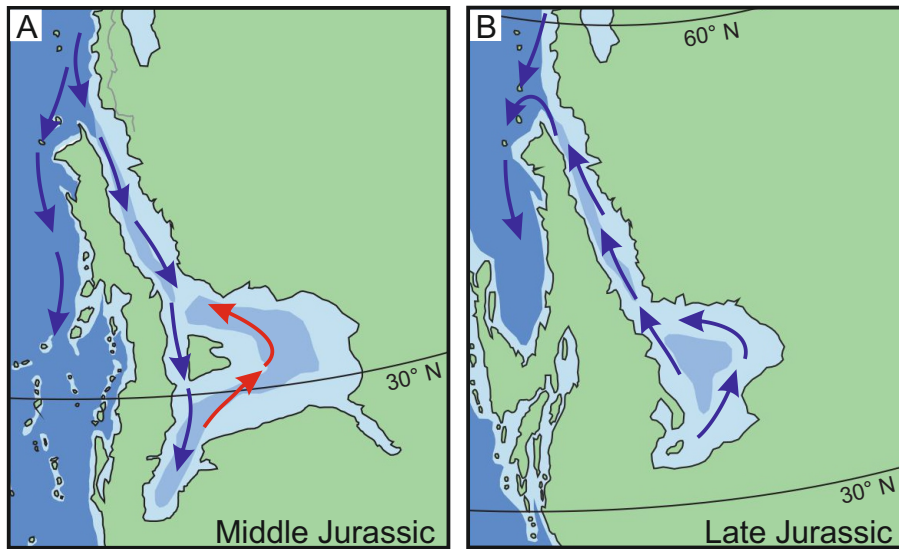
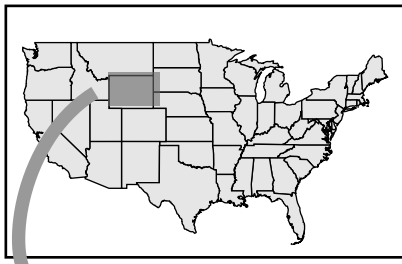
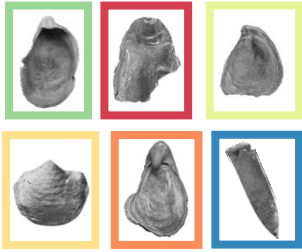


Figure 7, 1.5 column



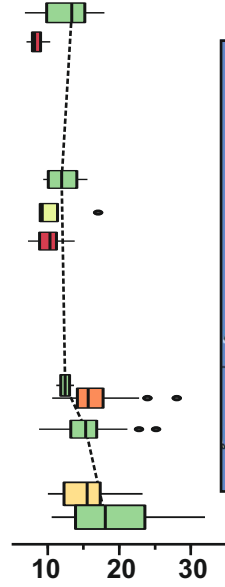
MOLLUSC SHELLS

$\delta^{13}\text{C}$, $\delta^{18}\text{O}$, Mn, Fe, Mg, Sr, Ca



Late Jurassic
Middle Jurassic

PALEOTEMPERATURE



PALEOCIRCULATION

