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Basin scale distribution of organic matter in marine fine-grained sedimentary rocks: Insight from sequence stratigraphy and multi-proxies analysis in the Montney and Doig formations

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1 **Basin scale distribution of organic matter in marine fine-grained**
 2 **sedimentary rocks: insight from sequence stratigraphy and multi-**
 3 **proxies analysis in the Montney and Doig Formations**

4
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41 ABSTRACT

42 The occurrence of hydrocarbons in self-sourced reservoirs strongly depends on the concentration
43 and maturity of organic matter in sediments. Therefore, understanding the distribution of organic
44 heterogeneity at the time of deposition is key to reduce the risk in exploration and development of
45 unconventional resources. This study focuses on the Lower and Middle Triassic Montney and Doig
46 Formations (Alberta and British Columbia). Samples from outcrops, cores and cuttings were analyzed
47 for organic content with a Rock-Eval VI and for major and trace element concentration using ICP-MS
48 and ICP-AES techniques. The interpretation of the analysis results in relation with the stratigraphic
49 architecture provides a mean to better understand the distribution of the organic heterogeneities
50 and the variations of primary productivity, sedimentation rates and anoxia that control the
51 development of source rocks.

52 The key findings of this analysis are:

- 53 - The basin-scale distribution of the organic matter suggests that the two major source-rock
54 intervals of the Lower and Middle Triassic correspond to the sequence 3 (Spathian Montney
55 unit) and to the transgressive systems tract of sequence 4 (Doig phosphate zone).
- 56 - The dominant controls on organic matter accumulations vary through time. The Montney
57 source-rock interval is interpreted to be associated with a major basin restriction triggering
58 anoxia during a second-order falling stage of relative sea level. The organic accumulation of
59 the Doig phosphate zone is interpreted as being controlled by a sharp decrease of the
60 sedimentation rate, combined with an increase of the primary productivity.
- 61 - The spatial and temporal variations of anoxia, primary productivity and dilution reflect the
62 geodynamic evolution of the basin that ultimately controls the basin physiography as well as
63 the sources of nutrient and sediments.

64 HIGHLIGHTS

65 The Montney and Doig Formations mainly present amorphous organic matter.

66 Rock-Eval data integration in stratigraphic framework shows two organic rich layers.

67 Ni and Cu variations suggest an increased primary productivity in the Doig Phosphate.

68 Redox proxies suggest anoxic intervals in the Upper Montney and the Doig Phosphate.

69 **KEYWORDS**

70 Petroleum source rocks; Triassic; Montney and Doig Formations; Organic matter; Primary
71 productivity; Redox conditions; Sedimentation rates; Canada.

72 **1. INTRODUCTION**

73 With the development of self-sourced and closely associated tight reservoirs, there is a need for a
74 better understanding of the origin and distribution of primary organic matter (OM) in source rocks
75 (Schwarzkopf, 1993; Tommeras and Mann, 2008; Ducros *et al.*, in press). Stratigraphic framework
76 characterization is the first and main step needed to quantify and discuss the processes controlling
77 the distribution of OM (Creaney and Passey, 1993; Myers, 1996; Huc *et al.*, 2005; Van Buchem *et al.*,
78 2005; Slatt and Rodriguez, 2012). Such integrated workflow gathering information on organic
79 productivity, preservation and dilution at basin scale remains a challenge especially as geodynamic
80 and climatic setting induce a large diversity of organic-rich deposits (Huc *et al.*, 2005).

81 Our work focuses on one of the largest unconventional play of Canada: the Montney and Doig
82 Formations of the Lower and Middle Triassic interval (~ 252 - 235 Ma) of Western Canada. The
83 amount of data available due to an extensive oil and gas exploration in the area and the presence of
84 time equivalent outcrops in the fold and thrust belt of the Canadian Cordillera, makes this interval an
85 attractive case study to analyze OM distribution in sedimentary basins. This study is built on a
86 database including core, cutting and outcrop descriptions and samples as well as wireline logs.
87 Geochemical and organic petrographical analyses (palynofacies, Rock-Eval, Major and Trace Metal
88 Elements) were then performed on selected samples. Finally, the results were integrated in a

89 sequence stratigraphic framework in order to discuss the main factors controlling the distribution of
90 OM in the studied interval.

91 **2. THE MONTNEY AND DOIG FORMATIONS**

92 **2.1. Generalities**

93 The Montney, Doig and Halfway Formations are preserved in the foreland basin of the Canadian
94 Cordillera and in time equivalent outcrops in its fold and thrust belt (**figure 1**). These Lower and
95 Middle Triassic Formations have been studied since the 60's (Armitage 1962). The Montney and Doig
96 Formations are mostly composed of fine-grained dolomitic sandstone and siltstone with subordinate
97 amount of shale and moderate clay content (Davies, 1997a; Zonneveld *et al.*, 2010; Chalmers and
98 Bustin, 2012; Euzen *et al.*, 2015). They were deposited on the western margin of Pangea (Davies *et*
99 *al.*, 1997). This location is considered as a passive margin during the Devonian and a foreland basin
100 during the Jurassic. Doubts remain on the precise paleogeographic settings: foreland basin (Golding
101 *et al.*, 2015a) versus passive margin during the time of the deposition of the studied interval (Monger
102 and Price, 2002).

103 **2.2. Stratigraphic settings and chronostratigraphy**

104 The stratigraphic framework used in this paper is based on a recent regional sequence stratigraphic
105 interpretation of the Lower and the Middle Triassic in the Western Canada Sedimentary Basin (e.g.
106 Crombez, 2016). Based on more than 400 wells, it shows that the studied interval can be subdivided
107 into two second-order sequences A and B and that sequence A can be further subdivided into three
108 third order sequences 1, 2 and 3. Within sequence A, the maximum backstepping of the sedimentary
109 system occurs during the second sequence (**figure 2**). Based on the biostratigraphic works of Orchard
110 and Zonneveld (2009) and Golding *et al.* (2015b), sequence A and B are respectively Lower Triassic
111 and Middle Triassic in age. Within sequence A, sequence 2 was deposited above the Induan-
112 Olenekian boundary and sequence 3 lays on top of the Smithian-Spatian boundary. According to
113 biostratigraphic data, the top of sequence B is older than the Ladinian-Carnian boundary (Orchard

114 and Zonneveld, 2009). Integrating these recent developments (Crombez, 2016) in Davies et al., 1997
115 stratigraphic framework, the Montney Formation corresponds to sequence A. In this first second
116 order sequence, sequence 1 can be considered as the Lower Montney, the sequence 2 as the Middle
117 Montney and sequence 3 as the upper Montney whereas the Doig and Halfway Formations are part
118 of sequence B. As the Montney Formation is interpreted as a second order cycle, the sequence 1 and
119 the transgressive system tract (TST) 2 therefore represents a second order TST, the sequence 2 a
120 second order HST and the sequence 3 a second order FSST (Crombez, 2016). From this work, as
121 sequence B records the expression of a second order cycle, TST4 and HST4 can be considered as
122 second order system tracts or third order sequences.

123 The **figure 2** illustrates the position of the studied well and outcrop (restored location) sections
124 within the stratigraphic framework of the basin. A recent study suggests that the Montney and Doig
125 Formations were deposited in a fore-arc basin connected with the open marine setting to the
126 Northwest (Rohais *et al.*, 2016). The stratigraphic architecture of sequence A suggests a basin with a
127 WNW-ESE axis and sedimentary inputs coming from East and Southeast. The distribution of thickness
128 and facies in sequence B suggests a NW-SE basin axis with an additional sedimentary source to the
129 West (**Error! Reference source not found.**). This change in sediment source areas and the clockwise
130 rotation of the basin axis are interpreted to be linked to the evolution of the proto-Canadian
131 Cordillera (Crombez, 2016; Rohais *et al.*, 2016).

132 **3. DATA AND METHODS**

133 **3.1. Data**

134 For this study, data were collected from both outcrop in the Canadian Cordillera and subsurface in
135 the foreland basin (**figure 1**). In Alberta, the cuttings from the Montney-Doig-Halfway intervals were
136 sampled in 7 wells and in addition, 14 cores were also sampled. In British Columbia, the cuttings of
137 the studied interval were sampled in 3 wells. Moreover, 4 cores including a 300m long core and one
138 outcrop (Brown Hill, BH on **figure 1**) were sampled. In total, 365 samples collected from cores, 498

139 from cuttings and 176 from outcrops were available for this work. The results of the present study is
140 illustrated along a SE-NW section composed of 7 wells with cuttings sampled each 5-10m and a 300m
141 long core, sampled each 5-10m, with additional constraints from both outcrops and subsurface
142 (figure 1).

143 **3.2. Methods**

144 The workflow developed for this study unfolds as follow: (1) The characterization of the organic
145 content in the studied interval, using Rock-Eval analyses (Espitalie *et al.*, 1986; Behar *et al.*, 2001) and
146 palynofacies study (Tyson, 1995). (2) The study of the distribution of the organic rich layers in the
147 stratigraphic framework. (3) The study of paleoenvironmental conditions through variations of major
148 and trace element concentrations and mineralogy in order to highlight the dynamic of the primary
149 productivity, the dilution by non-organic element and the O₂ levels along four sections (Brumsack,
150 2006; Tribovillard *et al.*, 2006; Algeo and Tribovillard, 2009 and references herein).

151 **3.2.1. Rock-Eval pyrolysis and hydrocarbons extraction**

152 Routine source rock analyses were carried out on 900 samples with a Rock-Eval VI. The bulk-rock
153 basic cycle, used for these routine analyses, is described by Behar *et al.* (2001). 50 to 70 mg of
154 powdered sample is heated in an open pyrolysis system under non-isothermal condition (from 300 °C
155 to 650 °C). During this pyrolysis, the amount of hydrocarbons released is measured by a flame
156 ionization detector (FID) and CO and CO₂ release are monitored with an infrared (IR) detector. The
157 residual sample is then put in an oxidation oven where it is heated (from 300 °C to 800 °C) under
158 artificial air (N₂/O₂: 80/20). During this combustion, the amount of CO and CO₂ released are
159 monitored with an IR detector.

160 In addition to the bulk-rock samples, organic solvent extraction was performed on selected samples.
161 The powdered sample was placed in a solution of dichloromethane and methanol (1/1) in an
162 ultrasonic bath for 30 min. The sample was then filtered and placed in a drying oven for 30 min.
163 Finally the sample was analyzed with the basic Rock-Eval method described above.

164 3.2.2. Palynofacies

165 In addition to the source rock evaluation, palynofacies analyses were carried out on 26 selected
166 samples. The preparation of the samples consists in the dissolution of 2 g of crushed rock in
167 successive acid bath. The sample was placed in a cold solution of hydrochloric acid (70 %) for 180
168 min. After multiple rinsing, the residual sample was placed in a cold solution of hydrofluoric acid (70
169 %) for 180 min. Again, after multiple rinsing, the residual sample is place in a hot (40 °C) solution of
170 hydrochloric acid (70 %) for 180 min. Finally, after multiple rinsing, the residual sample was sieved
171 with a 15µm filter and the filtrate was mounted between two glass slides.

172 The slides were then observed with an optical microscope under different magnifications in order to
173 classify the organic particles in three categories following the classification of Tyson (1995): the
174 amorphous organic matter (AOM), the phytoclasts and the palynomorphs.

175 3.2.3. Initial TOC computation

176 In order to better understand the distribution of organic matter at the time of deposition (before
177 thermal maturation), Rock-Eval analysis and palynofacies were used to estimate the initial total
178 organic carbon (TOC_{ini}). The equation (Equation Error! Reference source not found.1) used for the
179 computation of the TOC_{ini} is based on carbon mass balance and is similar to the formula proposed by
180 Jarvie (2012).

$$181 \quad TOC_{ini} = \frac{TOC - (S1 + S2) \times 0.083}{1 - (HI_{ini}/1200)} \quad \text{(Equation 1)}$$

182 This equation uses the total organic carbon (TOC), the free hydrocarbons (S1) and the oil potential
183 (S2) from Rock-Eval analysis, and requires an estimation of the initial hydrogen index (HI_{ini}). The HI_{ini}
184 was estimated using the palynofacies analyses that provide insight into the nature and quality of the
185 OM. The values of HI_{ini} used in this study are 700 mgHC/gTOC for type I organic matter, 450
186 mgHC/gTOC for type II and 125 mgHC/gTOC for type III (Espitalié *et al.*, 1986; Jarvie *et al.*, 2007).

187 **3.2.4. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma**
188 **Atomic Emission Spectrometry (ICP-AES)**

189 Elementary analyses of samples from wells 0/14-14-76-12W6 and 0/06-33-72-25W5 and from Brown
190 Hill outcrop were performed with an ICP-MS for trace elements and an ICP-AES for major elements.
191 Samples were powdered with an agate mortar beforehand. Then, 50 mg of sample was solubilized
192 using a solution of hydrochloric acid (70 %) and a solution of boric acid (45 %). In order to dissolve
193 entirely the OM, 2 ml of a hydrogen peroxide solution were added to the samples with a high TOC.
194 The residual samples were then diluted 10,000 times for the ICP-MS analyses and 1,000 for the ICP-
195 AES analyses. International (ATHO-G from Borisova *et al.*, 2010; AGV-1, BCR-2, BH-VO2 and BIR-1
196 from the USGS) and in house standards were used and several duplicates were analyzed in order to
197 control the accuracy of the measurements. A total of 244 samples were analyzed with this method.
198 Elementary analyses from well 0/16-17-83-25W6 were performed by ACT Labs following their 4A-4B
199 protocols. A total of 138 samples were analyzed with this method. In the present work element
200 concentration (ppm or %) refers to weigh ratios.

201 In order to investigate the vertical and the lateral variations of metal trace elements (MTE), the
202 concentration of MTE was divided by the Aluminum content of the sample and normalized to the
203 upper continental crusts (UCC) by computing an enrichment factors (EF) (Taylor and McLennan,
204 1985; McLennan, 2001):

205
$$EF_E = \frac{[E]_{sample}}{[Al]_{sample}} \bigg/ \frac{[E]_{UCC}}{[Al]_{UCC}} \quad (\text{Equation 2})$$

206 With EF_E the enrichment factor of E; [E] the atomic concentration of E (ppm) and [Al] the
207 concentration of aluminum (ppm).

208 **3.2.5. Mineralogical analyses**

209 In addition to core and outcrop descriptions, cuttings from one well were sampled in order to
 210 quantify the mineralogy of the Triassic strata. QEMSCAN analyses (Gottlieb *et al.*, 2000) were
 211 performed by SGS Canada Inc. on 72 samples. QEMSCAN automated mineralogical analysis is based
 212 on backscattered-electron imaging and energy dispersive X-ray spectroscopy techniques.

213 **3.2.6. Weathering index of Parker (WIP) and chemical index of alteration (CIA)**

214 Based on elemental major element concentrations, the weathering index of Parker (WIP, Parker,
 215 1970) and the chemical index of alteration (CIA, Nesbitt and Young, 1982) provide information on the
 216 maturity of siliciclastic sediments:

$$217 \quad WIP = \left(\frac{[Na]^*}{0.35} + \frac{[Mg]^*}{0.9} + \frac{[K]^*}{0.25} + \frac{[Ca]^*}{0.7} \right) \times 100 \quad \text{(Equation 3)}$$

$$218 \quad CIA = \left(\frac{[Al_2O_3]}{[Al_2O_3] + [Na_2O] + [K_2O] + [CaO]} \right) \quad \text{(Equation 4)}$$

219 Where [E] is the atomic concentration of E (ppm) and [E]* represent the atomic concentration of an
 220 element divided by its atomic weight. In order to reflect chemical variations associated with climatic
 221 changes and the weathering of siliciclastic minerals, the [Ca] and [CaO] values used in the **equation 3**
 222 **and 4** were corrected for each samples to remove the effect of carbonate minerals using QEMSCAN
 223 analysis. WIP and CIA indexes were only calculated on one well where both elemental analysis and
 224 QEMSCAN data were available on the same samples (0/14-14-76-12W6). Furthermore, the sodium
 225 (Na) concentration was not measured on this well, but the impact of Na on these indexes is likely
 226 negligible based on its low concentration in other wells of this study (average of 0.8% in well 0/16-
 227 17-83-25W6).

228 **4. RESULTS**

229 **4.1. Characterization of the organic content**

230 **4.1.1. Rock-Eval analyses**

231 Most of the studied samples have Rock Eval TOC values ranging between 0.25 and 1.75 wt%, with a
232 mean TOC of 1.28 wt% (see **figure 7**). However locally, organic-rich intervals present TOC higher than
233 4 wt% in the Montney Fm. and can reach up to 13 wt% in the Doig phosphate zone (TST4). The wide
234 range of Tmax (from 397 to 479 °C) of our dataset is globally consistent with published vitrinite
235 reflectance data (Rokosh *et al.* 2012; Romero *et al.*, 2016) and suggests NE-SW increasing maturity
236 trend from immature to overmature. The wide range of maturity may induce an under or over
237 estimation of the *in-situ* TOC. Indeed, the dysmigration of the generated HC will lead to the
238 underestimation of the TOC whereas the contamination by migrated HC will lead to the
239 overestimation of the TOC. Rock-Eval pyrolysis results of the low maturity samples show that most of
240 the HI values fall between 150 and 450 mgHC/gC. This observation suggests that the OM found in the
241 Montney and Doig Formations is mainly of Type II and Type III (**figure 3**).

242 Detailed analysis of Rock-Eval pyrograms shows that the S2 peak often presents a shoulder during
243 the beginning of the temperature increasing (between 300 °C and 450 °C, **figure 4**). This shoulder can
244 be interpreted in two different ways: there are two types of kerogen in the sample, or there is a
245 presence of heavy hydrocarbons (Grundman *et al.*, 2012). **Figure 4** presents the pyrogram of both
246 bulk-rock (BR) and extracted bulk-rock (eBR) samples. The analysis of both bulk-rock and extracted
247 sample shows that the S2 is composed of both soluble and non-soluble OM, likely representing
248 respectively heavy hydrocarbons and primary kerogen (**figure 4**). According to the work of Behar *et*
249 *al.* (2008) and considering the low maturity of this sample (Tmax = 439 °C), those heavy
250 hydrocarbons may come from the early cracking of the kerogen.

251 **4.1.2. Palynofacies studies**

252 The investigated samples contain mainly AOM (**figure 5**). In the analyzed samples, only a small
253 proportion of the OM derives from woody and terrestrial debris, regardless of the sedimentary facies
254 (SP and PM on **figure 5 B, C and I**). The absence of damaged terrestrial OM showing a transformation

255 from undamaged particles to AOM suggests that the AOM was more likely derived from marine
256 rather than terrestrial sources (Tyson, 1995).

257 **4.2. Distribution of the organic content in the stratigraphic framework**

258 **4.2.1. TOC and TOC_{ini} in the stratigraphic framework**

259 The Rock-Eval results show that the two samples with the lowest maturity present high to moderate
260 HI (respectively 549 and 373 mgHc/gTOC). This is consistent with of a good Type II marine kerogen
261 and a fair Type II/III kerogen. The palynofacies analyses paired with the Rock-Eval measurements
262 suggest that regardless of the sedimentary facies, the AOM mainly derives from marine sources,
263 typically having an initial HI (HI_{ini}) between 350 and 600 mgHC/gTOC. These two values were used to
264 compute a maximum and a minimum value of TOC_{ini} . In low maturity areas ($T_{max} < 450^{\circ}C$), the
265 computed TOC_{ini} values likely reflect the initial organic content of the sediment. On the other hand,
266 in more mature areas ($T_{max} > 450^{\circ}C$), TOC_{ini} computation can be affected by the secondary cracking
267 of migrated oil. **Figure 6 and 7** illustrate that sequence 3 and TST4 are the two main organic-rich
268 intervals of this succession based on TOC_{ini} computation. In low maturity areas TOC_{ini} is close to
269 present day TOC, whereas in more mature areas, TOC_{ini} can be up to twice as high as present day
270 TOC (with $HI_{ini} = 600$).

271 The vertical distribution of TOC values within the stratigraphic framework highlight major differences
272 between sequences (**figure 6 and 7**). Sequences 1 and 2 have low background present day TOC
273 (respectively 1.3 and 0.9 wt% on average), with localized organic-rich intervals up to about 3 wt%
274 (**figure 7**). Sequence 3 has higher background TOC (average of 2.2 wt%) and fewer low TOC values (<1
275 wt%) than sequence 1 and 2. TOC_{ini} values can reach up to 9 wt% in LST3. The base of Sequence 4 is
276 the richest interval in OM, with TOC_{ini} up to 14% (TST4=phosphate zone), but the rest of sequence 4
277 is organic-lean (average of 1.1wt%). The two main organic-rich intervals LST3 and TST4 show
278 contrasting spatial distributions of the OM:

279 In LST3, the organic content increase in the deeper central part of the basin at that time
280 (offshore environment).

281 In TST4, TOC increase towards both margins of the basin (well 0/16-17-83-25W6 and 07-14-
282 74-06W6 on **figure 6**) while lower values are observed toward the axis of the basin (well
283 0/14-14-76-12W6 on **figure 6**).

284 **4.2.2. Sedimentology of organic rich intervals**

285 In this section, we illustrate the sedimentological features of the organic-rich intervals of sequence 3
286 and 4. **Figure 8** presents a synthetic sedimentary section from the sequence boundary 3 (SB3) up the
287 maximum flooding surface 4 (MFS4). This interval dominantly consists of wave-dominated deposits,
288 from offshore (bathymetry \approx 200 m) to shoreface depositional environments (**figure 8**, Crombez,
289 2016). In both sequences, organic-rich intervals correspond to offshore depositional environments.
290 Sequence 3 presents a thick continuous interval of prograding deposits from offshore to lower
291 shoreface (e.g. from 2380 to 2260 m on **figure 8**) whereas TST4 consists of thinly interbedded
292 offshore and offshore transition deposits (e.g. from 2255 to 2240 m on **figure 8**). In sequence 3, the
293 high TOC intervals are associated with pyrite and phosphate grains, but with only rare bioturbations
294 (from 2380 to 2320 m on **figure 8**). In contrast, organic-rich layers in TST4 are associated with erosive
295 lags, shell debris as well as pyrite and phosphate grains whereas bioturbations are present in the
296 coarse-grained interbedded shallower deposits (from 2255 to 2240 m on **figure 8**). These differences
297 suggest that the organic rich offshore deposits of TST4 are shallower than the offshore deposits of
298 sequence 3

299 **4.2.3. Vertical and lateral variation of the sediment rates**

300 Sequence stratigraphic surfaces provide time lines across the basin (Crombez, 2016) and allowed for
301 the computation of average sedimentation rates (SR) in the studied intervals. The sequence A was
302 deposited during the lower Triassic (approximately 5 My) and the sequence B during the Middle
303 Triassic (approximately 8 My).

304 The **figure 9** presents a cross-plot of the distribution of TOC_{ini} versus the SR in the third order
305 sequences along 8 sections. It shows that sequence B presents lower sedimentation rates ($\text{SR} < 6$
306 cm/ka) than sequence A ($\text{SR} < 16 \text{ cm/ka}$). More precisely it shows that sequences 1 to 3 present
307 increasing average sedimentation rates (average SR from 4 cm/ka to 12 cm/ka) whereas HST4
308 present lower sedimentation rates than TST4 (respectively average SR: 2 cm/ka and 3 cm/ka). On
309 **figure 9**, the sequences 1 and 2 present decreasing TOC_{ini} concentration (from 3 to 0.2 wt%) with
310 increasing SR (from 16 to 4 cm/ka). The sequence 3 presents a similar evolution but with a steepest
311 trend (TOC_{ini} from 7 to 3 wt% and SR from 12 to 16 cm/ka). The TST4 does not present a clear
312 relation between TOC_{ini} accumulation and SR. On one side, the **figure 9** presents high TOC_{ini} (up to 15
313 wt%) associated with the highest SR of the TST4 (4 cm/ka) and on the other side it shows decreasing
314 TOC_{ini} (from 2.5 to 0 wt%) with increasing SR (from 1 to 2 cm/ka). Lastly HST4 presents an increasing
315 then decreasing TOC_{ini} (from 1 to 2.5 wt% then from 2.5 to 0 wt%) with increasing SR (from 0.3 to 4
316 cm/ka).

317 Tyson (2001) highlighted the impact of SR on OM accumulation. On one side, this study showed that,
318 in oxic environments, a range of SR (from 2 to 20 cm/ka) is increasing OM preservation. In oxic
319 intervals, the impact of the SR results in an increasing then decreasing TOC concentration with a
320 maximum accumulation above 5 cm/ka . The cross-plots of sequences 1, 2 and of the HST4 highlight
321 the direct impact of organic particles dilution: sequences 1 and 2 only present the decreasing TOC_{ini}
322 whereas the HST4 presents both the increasing and decreasing trends linked to the ideal
323 sedimentation rates interval. On the other side, in anoxic environments the preservation of the
324 organic matter is assured and an increasing SR will only decrease the TOC (Tyson, 2001). The rapid
325 increase of the TOC_{ini} in the Seq 3 and the complex relation between TOC_{ini} and SR in TST4 suggest
326 that organic matter accumulation in TST4 and sequence 3 is not solely controlled by the dilution but
327 by a complex combination of primary productivity, preservation and dilution.

328 **4.3. Trace metal element variations**

329 **4.3.1. Copper (Cu) and Nickel (Ni) variations**

330 Organic productivity can be studied through several proxies, including Cu and Ni which are micro-
331 nutrients assimilated by the micro and macro-organisms (Calvert and Price, 1983; Calvert and
332 Pedersen, 1993; Whitfield, 2001; Brumsack, 2006; Tribovillard *et al.*, 2006; Schoepfer *et al.*, 2014). In
333 the present study, the vertical evolution of Ni/Al and Cu/Al are chosen to reflect the variations of
334 nutrients input in the basin which may be associated with primary organic productivity variations
335 (Whitfield, 2001; Brumsack, 2006; Tribovillard *et al.*, 2006)

336 The **figure 10** presents a cross-plot of the EF of Cu vs Ni at four different locations in the basin. In this
337 figure, most of EF of Cu and Ni are higher than 1. In comparison to black shale (Cretaceous and
338 present day, Brumsack, 2006) the EF of Cu and Ni remain low in the Montney and Doig Formations.
339 TST4 shows the highest EF in sections 0/16-17-83-25W6 section ($3 < EF(Ni) < 10$; $2 < EF(Cu) < 30$) and
340 0/14-14-76-12W6 ($EF(Ni) \approx 10$; $EF(Cu) \approx 2.5$). In these wells, samples with High TOC always have high
341 EF, however high EF does not automatically imply high TOC. No simple linear relation exists between
342 $EF(Ni)$ or $EF(Cu)$ and TOC.

343 The **figure 11** presents the vertical evolution of Cu/Al and Ni/Al along the four sections. In these
344 sections, Cu/Al ranges from $3 \cdot 10^{-4}$ to more than $30 \cdot 10^{-4}$ whereas Ni/Al ranges from $5 \cdot 10^{-4}$ to $55 \cdot 10^{-4}$.

345 *0/16-17-83-25W6:*

346 In sequences 1 and 2, both ratios show little variations and stay low ($Cu/Al \approx 5 \cdot 10^{-4}$ and $Ni/Al \approx$
347 $7.5 \cdot 10^{-4}$), slightly higher than the Upper crust average ($Cu/Al = 3.1 \cdot 10^{-4}$ and $Ni/Al = 5.5 \cdot 10^{-4}$).
348 Sequence 3 records a small increase in Cu/Al (from $5 \cdot 10^{-4}$ to $6 \cdot 10^{-4}$) and in Ni/Al (from $7.5 \cdot 10^{-4}$ to
349 $11 \cdot 10^{-4}$). In contrast, sequence 4 shows high Ni/Al and Cu/Al ratios ($Cu/Al > 20 \cdot 10^{-4}$ and $Ni/Al >$
350 $25 \cdot 10^{-4}$). These higher concentrations of Cu and Ni in TST4 are associated with high TOC value.

351 *0/14-14-76-12W6:*

352 In this section, TST4 shows a strong increase of Ni/Al ratio from $7.5 \cdot 10^{-4}$ to $50 \cdot 10^{-4}$ and a slight
353 increase of Cu/Al ratio from $5 \cdot 10^{-4}$ to $9 \cdot 10^{-4}$. No other significant variations are present along this
354 section (Cu/Al $\approx 5 \cdot 10^{-4}$ and Ni/Al $\approx 7.5 \cdot 10^{-4}$).

355 *0/06-33-72-25W5:*

356 This section shows low values for both ratios (Cu/Al $\approx 5 \cdot 10^{-4}$ and Ni/Al $\approx 7.5 \cdot 10^{-4}$), consistent with a
357 more proximal depositional setting dominated by detrital inputs.

358 *Brown Hill:*

359 In sequences 1 and 2, the low Cu/Al and Ni/Al (respectively $6 \cdot 10^{-4}$ and $8 \cdot 10^{-4}$) are punctuated by
360 peaks of higher Cu/Al (up to $22 \cdot 10^{-4}$). Along this section, the highest peaks of both ratios are not
361 linked to an important concentration of Ni and Cu but to a very low concentration of Al, it is
362 therefore an artifact of normalization.

363 *Interpretation:*

364 On the four sections, the only significant increase in Cu/Al and Ni/Al ratios occurs during TST4,
365 suggesting a strong increase in organic paleoproductivity during this interval. High amplitude
366 variations of both ratios in this interval also highlight cyclic fluctuations of paleoproductivity during
367 TST4. It is important to note that the increase of the authigenic Ni and Cu occurred after a sharp drop
368 of the sedimentation rates across the boundary between sequence A and B. Even though HST4
369 present low Ni/Al and Cu/Al ratios, the influence of low sedimentation rates on TST4 enrichment
370 cannot be ruled out. However, it is also worth noting that both Cu and Ni concentrations are
371 positively correlated to Al during sequence A, whereas no such relations were observed in TST4. This
372 evidence supports the hypothesis of a change of nutrient source between sequence A and B, with an
373 increase of primary productivity during TST4. In sequence 3, the small increase of Ni and Cu
374 concentration can be either linked to a small increase of the primary productivity or to a better
375 preservation of the OM (confirmed by U/Th and Mo/Al proxies) at the water sediment interface that
376 will induce a lower recycling of the nutrients included in the OM (Riquier *et al.*, 2005).

377 **4.3.2. Uranium (U), Molybdenum (Mo) and Vanadium (V) variations**

378 Some trace elements present in the water are sensitive to redox condition (e.g. U, Mo, V and Ce) and
379 provide information on the oxygen and sulfur content in the water at the time of the deposition
380 (Emerson and Husted, 1991; Calvert and Pedersen, 1993; Crusius *et al.*, 1996; Brumsack, 2006;
381 Algeo and Lyons, 2006; Tribovillard *et al.*, 2006; Algeo and Tribovillard, 2009).

382 The **figure 12** presents a cross-plot of the U/Th and V/Cr ratios from four different sections across the
383 basin. In these ratios, the redox-sensitive elements (U and V) are normalized to Th and Cr which are
384 both assumed to be linked to detrital inputs. These ratios therefore present the authigenic variation
385 of U and V that are linked to anoxic episodes. These cross-plots show a link between the ratios and
386 the TOC content along wells 0/16-17-83-25W6 and 0/14-14-76-12W6: samples with high ratios
387 present the highest TOC. These cross-plot also show that sequence 1 and 2 present higher oxygen
388 content (U/Th < 0.75 and V/Cr < 2) than sequence 3 and part of sequence 4 (most of U/Th > 0.75 and
389 V/Cr > 2).

390 The **figure 13** Error! Reference source not found. presents the vertical evolution of U/Th and Mo/Al
391 along four sections. In the four sections, U/Th ranges from 0.3 to 4.5 whereas the Mo/Al ranges from
392 1.10^{-4} to 24.10^{-4} .

393 *0/16-17-83-25W6:*

394 From SB1 up to MFS2, both ratios stay low (U/Th \approx 0.3 and Mo/Al \approx 1.10^{-4}). The interval between
395 MFS2 and SB3 shows an increase, then a decrease of U/Th and Mo/Al ratios (U/Th: from 0.3 up to
396 1.25 down to 0.3 and Mo/Al: from 1.10^{-4} up to $7.5.10^{-4}$ down to 1.10^{-4}). In sequence 3 the interval
397 presents moderate U/Th (> 0.75) and high Mo/Al (> 5.10^{-4}) that seems to oscillate with no correlation
398 with the transgressive and regressive trends of the sedimentary system. Lastly in the TST4, U/Th and
399 Mo/Al both show significant increases (U/Th: from 0.3 up to 4.5; Mo/Al: from 2.10^{-4} up to 25.10^{-4}).

400 *0/14-14-76-12W6:*

401 Along this section, U/Th and Mo/Al mainly present low values (U/Th < 0.75 and Mo/Al < $5 \cdot 10^{-4}$)
402 except in the TST4 where both ratios increase significantly (up to U/Th ≈ 2.25 and Mo/Al < $15 \cdot 10^{-4}$).

403 *0/06-33-72-25W5:*

404 On this section no significant increase of both ratios are present (U/Th < 0.75 and Mo/Al < $5 \cdot 10^{-4}$)

405 *Brown Hill:*

406 As for the 0/06-33-72-25W5, both proxies along Brown Hill section show very low values. The only
407 high values of both ratios are linked to very low concentration of Al or Th.

408 *Interpretation:*

409 **Figures 12 and 13** present sedimentary records of redox sensitive elements. These figures suggest
410 that the water column was oxic to dysoxic during sequence 1 and 2. In sequence 2, the small increase
411 then decrease of the U/Th and Mo/Al ratios is interpreted as the development of small anoxic puddle
412 in the deepest part of the basin. Above SB3, redox sensitive trace elements suggest variations of O₂
413 concentrations in the water column and the occurrence of dysoxic to anoxic layers in the deepest
414 part of the basin (located near the well 0/16-17-83-25W6 at that time). In this sequence, the high
415 concentration of Mo suggests that water/sediment interface may contain H₂S (Jones and Manning,
416 1994). In sequence 4, due to the geodynamic evolution and the changes in the basin physiography,
417 the well 0/16-17-83-25W6 present more proximal deposits. In the TST4, the high U/Th and Mo/Al
418 ratios show the occurrence of anoxic to euxinic conditions. In this interval, O₂-depleted and possible
419 H₂S enriched conditions took place along the more proximal areas. As already mentioned for Ni/Al
420 and Cu/Al ratios, the drop of sedimentary fluxes across the boundary between sequence A and B may
421 influence the dilution of authigenic molybdenum and uranium. However, when corrected from
422 dilution effect based on computed sedimentation rates (dilution 4 times lower in sequence B
423 compared to sequence A), U/Th and Mo/Al ratios are still characteristic of anoxia (respectively 1 and
424 $5 \cdot 10^{-4}$).

425 **4.3.3. Molybdenum (Mo) and TOC variations**

426 Changes in basin restriction can be investigated thanks to molybdenum and TOC covariations. **Figure**
427 **14** presents molybdenum versus TOC cross-plot along four sections. On these cross plots, TOC values
428 range from 0 to 15.2 wt%, with the maximums located in the sequence 4 and, the molybdenum
429 concentration ranges from 0 to 101.6 ppm with the maximums located in the sequence 3. The TOC
430 and Mo concentrations from wells 0/14-14-76-12W6 and 0/06-33-72-25W5 and from Brown Hill
431 outcrop stay very low (TOC < 3wt% and Mo < 25) except for two cutting samples located near SB3
432 and SB4. Mo and TOC covariations in different restricted basins (the Saanich inlet, the Cariaco basin,
433 the Framvaren fjord and the Black sea, respectively SI, CB, FF and BS on **figure 14**) are presented by
434 Algeo and Lyons (2006). All the low TOC and Mo samples of the present cannot be related to one of
435 these case studies. The samples of well 16-17-83-25W6 present more significant results with
436 moderate to high TOC and molybdenum concentration ($1.5 < \text{TOC} < 15.2 \text{ wt\%}$ and $0 < \text{Mo} < 101.6$
437 ppm). Along this well, values for sequences 1 to 3 fall between the Cariaco basin trend and the Black
438 sea trend, whereas sequence 4 values clearly fall along the Black sea trend.

439 In restricted basin, due to low water and molybdenum reservoir renewal, the Mo/TOC ratio generally
440 stays low (< 15) whereas in open marine settings, due to the water circulation, the Mo/TOC ratio is
441 relatively high (> 60). The cross-plots of **figure 14** show that regardless of the well and the sequence,
442 samples always presents relatively low Mo/TOC ratios (< 35) which tend to highlight a moderately to
443 highly restricted basin (Algeo and Lyons, 2006). The cross-plots of 0/14-14-76-12W6, 0/06-33-72-
444 25W5 and Brown Hill sections are consistent with **figure 13**: anoxia proxies (U/Th, V/Cr and Mo/Al)
445 do not highlight major anoxic event along those three sections excepted in the early sequence 4 of
446 the 0/14-14-76-12W6 well which induced a low concentration of Mo. Along the well 0/16-17-83-
447 25W6, the interpretation of the basin restriction evolution between sequence A and sequence B
448 must be done with caution: firstly only some intervals of sequence 3 and the TST 4 present anoxia.
449 Secondly, the significant drop of the sedimentary supply across the boundary between sequence 3
450 and 4 (see **figure 9**) may also impact the concentration of Mo and the TOC. In order to remove this
451 impact, Mo and TOC values from sequence 4 were divided by 4. (which represents the average

452 sedimentary supply decrease between sequence A and B, Crombez, 2016). This correction puts the
453 sequence 4 samples in the lower left side (with sequences 1 and 2) of the cross plot in an area where
454 a restriction is uncertain. All these observation tends to show that both sequence A and B were
455 deposited in a restricted basin, that may be more restricted in sequence 3 that in the other
456 sequences.

457 **4.3.4. Weathering index of Parker (WIP) and chemical alteration index (CIA) variations**

458 **Figure 15** presents a cross-plot of the WIP and CIA along the 0/14-14-76-12W6. On this figure, the
459 WIP ranges from, 20 to 80 but most of the samples are comprised between 35 and 50 whereas the
460 CIA ranges from 45 to 85. This figure does not show any maturity trend along the four sequences.
461 Sediment maturity trend are likely to reveal climatic evolution of an area (Parker, 1970; Nesbitt and
462 Young, 1982; Bahlburg and Dobrzinski, 2011), the cross plot presented in **figure 15** suggests that no
463 major climatic changes took place over the western Canada sedimentary basin during the Lower and
464 Middle Triassic.

465 **5. DISCUSSIONS**

466 In the following section, we discuss the source of OM in the Montney and Doig Formations, the
467 spatial and temporal variations of controlling factors on the accumulation and preservation of this
468 OM and finally, their relationship with relative sea level variations and the basin physiography.

469 **5.1. Organic matter in the Montney and Doig Formations**

470 Rock-Eval analyses show that the OM in the Montney and Doig Formation represents Type II/III
471 source rocks (**figure 3**), which is consistent with the studies of Riediger *et al.* (1990) and Riediger
472 (1997). In the Montney and Doig Formations, two intervals present significant enrichment in OM: the
473 sequence 3 (Upper Montney) and the TST4 (Doig phosphate) which is also consistent with previous
474 studies (Ibrahimbas and Riediger, 2004).

475 Our Rock-Eval analyses data on extracted, low maturity samples, confirm the presence of kerogen in
476 the studied samples (**figure 4**) whereas palynomorphs analyses (**figure 5**), show that this primary OM
477 derives from planktonic sources. Lastly, the analysis of trace elements shows the occurrence of Cu,
478 Ni, U and Mo enrichments in the Montney and Doig Formations. In the present work, these
479 enrichments are interpreted to be linked to redox conditions and/or primary productivity variations
480 (Tribovillard *et al.*, 2006). As crude oil contains important concentration of trace metal elements
481 (Lord, 1991; Duyck *et al.*, 2002), the enrichments that are highlighted in sequence 3 could also be
482 linked to bitumen associated with secondary cracking of migrated oil. In the present study, we were
483 unable to establish a clear relation between TOC concentration and the trace metal element
484 concentrations, or the Al-normalized concentration of those elements and the TOC. It is therefore
485 unlikely that all the organic content in the Montney Formation comes from migrated hydrocarbons.

486 In the present work, the study of Rock-Eval S1 values does not allow for the recognition of good
487 conventional reservoir intervals. In the Montney and Doig Formations, average S1 value is low (< 0.4
488 mgHC/gRock) and high S1 values within low maturity areas, which correspond to good conventional
489 reservoir, are absent. Recent works of Sanei *et al.* (2015) and Wood *et al.* (2015) concluded that most
490 of the organic content in the Montney Formation derives from migrated hydrocarbons. In their
491 studies, the most part of the organic content in the Montney Formation is considered to be
492 pyrobitumen, resulting from the secondary cracking of migrated oil. Regarding the low maturity
493 ($T_{max} < 450$) of the primary organic matter in some part of the basin and the very low permeability
494 of the Montney and Doig Formation (< 0.01 mD, Chalmers and Bustin, 2012), it is unlikely that the
495 organic matter is coming from the secondary cracking of a migrated bitumen (due to the low
496 permeability) or from the secondary cracking of a light oil (due to the low thermic maturity). Our
497 study does not question the presence of pyrobitumen in the Montney-Doig Formations, but it also
498 emphasizes the occurrence of primary kerogen in this interval. Analysis of the elementary proxies
499 shows that the sequence 3 and part of sequence 4 present propitious redox conditions and primary
500 productivity for source rocks development, whereas sequences 1 and 2 present less conductive

501 conditions to organic rich sediment accumulation (**figure 10 to 13**). Estimating the relative proportion
502 of migrated versus in place hydrocarbons in the Montney Formation is beyond the scope of the
503 present study and would necessitate a quantitative basin analysis.

504 **5.2. Spatial variations and temporal evolution of primary productivity, anoxia and dilution** 505 **and their impacts on organic matter distribution**

506 Recent works (Sageman *et al.*, 2003; Bohacs *et al.*, 2005; Katz, 2005) showed that the organic
507 richness of sedimentary rocks is controlled by a combination of three main factors: (1) the primary
508 organic production by flora and fauna, (2) its dilution by non-hydrogenated particles and (3) its
509 preservation. Bohacs *et al.* (2005) showed that a high productivity combined with a low dilution rates
510 is not the most efficient way to produce and preserve an organic rich rock. Indeed, an extremely high
511 planktonic productivity will dilute the organic content in the tests of the micro-organisms and a low
512 SR will minimize the burial efficiency and will allow a higher bacterial degradation and oxidation at
513 the water sediment interface and therefore lead to weak preservation.

514 In the present study, the palynofacies analyses mostly revealed AOM coming from marine planktonic
515 faunas. In a sedimentary basin, the OM can be degraded or destructed by various processes
516 occurring in the water column and in the first centimeters below the water-sediment interface
517 (Demaison and Moore, 1980; Southam *et al.*, 1982; Einsele, 1992; Calvert *et al.*, 1996): (1) In the
518 production areas, the OM produced by micro-organisms can be consumed and recycled by macro-
519 organisms (Eppley and Peterson, 1979). However assuming that the macro organisms also produce
520 OM, this phenomenon only has a small impact on the total OM production. (2) While settling through
521 the water column, the OM can be oxidized and therefore degraded by the oxygen present in the
522 water (Karl *et al.*, 1988; Wakeham and Lee, 1993). Therefore, at a constant production rate, the OM
523 is better preserved in anoxic or dysoxic water (Cowie and Hedges, 1992; Canfield, 1993). However, if
524 production is high enough, sinking OM consume all the oxygen leading to the creation of Oxygen
525 Minimum Zone (OMZ) and the preservation of the remaining OM (Southam *et al.*, 1982; Einsele,

526 1992; Paulmier and Ruiz-Pino, 2009). (3) In the first centimeter below the water/sediments interface,
527 rapid degradation of the OM takes place as long as oxygen is present. The occurrence of macro-
528 organism in oxic sediments results in bio-degradation of the OM present in the sediments (Ingall *et*
529 *al.*, 1993). Most of OM degradation will stop a few centimeters below the water/sediments interface
530 due the depletion in oxygen in the buried layers (Wenzhofer and Glud, 2002). Globally, the
531 preservation of OM is highly linked to the oxygen content in the water and sediments.

532 **5.2.1. Basin scale variations of primary productivity, anoxia and dilution**

533 The relative contribution of the three main factors (production-dilution-preservation) controlling
534 initial TOC of sediment can be estimated by integrating sequence stratigraphy interpretation with
535 trace element analysis. Based on trace elements analyses from wells 0/16-17-83-25W6; 0/14-14-76-
536 12W6 and 0/06-33-72-25W5 and based on the Rock-Eval analyses of five additional wells, the **figure**
537 **16** presents an interpretation of the vertical and the lateral variations of the factors that drive
538 organic richness in sedimentary rocks. It confirms that there is no simple relation between SR
539 (dilution) and the organic content in the studied interval. Tyson (2001) concluded that SR close to 5
540 cm/ka may enhance the concentration of the OM which is observable in sequence 1, 2 and the HST4
541 (**figure 9**).

542 On the **figure 16**, it is apparent that local OM enrichment occurs near MFS or parasequence flooding
543 surfaces, similar to trends observed by Creaney and Passey (1993). However, a low SR alone cannot
544 explain the organic enrichment of condensed layer, indeed low burial efficiency resulting from a low
545 SR will promote the degradation of OM (Tyson, 2001; Bohacs, 2005; Katz, 2005). In the studied
546 interval, small increases of anoxia proxies are commonly associated with organic rich intervals,
547 suggesting occurrence of small anoxic puddles, most likely linked to basin floor physiography. Local
548 and punctual enrichment would therefore be linked to a combination of starved intervals and local
549 anoxic layers (Algeo and Rowe, 2012).

550 **Figure 16** illustrates that low to moderate organic productivity, mainly oxic water (85% of the U/Th
551 ratio < 0.75, Jones and Manning, 1994) and high sedimentation rates prevailed during sequence 1
552 and 2, regardless of the position along the depositional profile. In this interval, rare TOC peaks are
553 present and are interpreted to be associated with either local dysoxic to anoxic episodes (U/Th ratio
554 increase) or punctual decrease SR (e.g. near MFS). Above sequence 1 and 2, **figure 16** shows a major
555 change in the paleo-redox conditions. At that time the oxic to dysoxic water of sequence 2 turns into
556 dysoxic to anoxic water marked by an increase of U/Th and Mo/Al ratios (Emerson and Husteded,
557 1991; Tribovillard *et al.*, 2004; Brumsack, 2006). These anoxic conditions are clearly present in the
558 deepest part of the basin, in offshore facies and are weaker in the shoreface facies on the edges on
559 the basin (**figure 16**). This major change of the water's oxygen content is not interpreted to be
560 associated with an important variation of primary productivity. Indeed, the small increases in Cu/Al
561 ratio observed on the 0/16-17-83-25W6 are interpreted to be linked to the better preservation of the
562 OM (Riquier *et al.*, 2005). In sequence 3, the organic-rich deposits are located in the central part of
563 the basin where oxygen content is minimum (**figure 16**). In this interval, the fluctuation of anoxic
564 conditions are associated with the progradation and backstep of the depositional system.

565 Above this anoxic episode, the **figure 16** shows for the first time an important increase of primary
566 productivity associated with anoxic water marked by important increase of Cu/Al, Ni/Al, U/Th and
567 Mo/Al ratios (Tribovillard *et al.*, 2004; Algeo and Lyons, 2006; Tribovillard *et al.*, 2006). In this
568 interval, organic rich deposits are located in periphery of the basin. Unlike in sequence 3, anoxia is
569 strongest at the edges of the basin and alternate with dysoxic periods, suggesting the onset of an
570 OMZ, triggered by the high primary productivity at sea surface. Above the MFS4, the basin returns to
571 similar conditions as in sequence 1 and 2: low to moderate productivity and high oxygen content in
572 the water, leading to low production and poor preservation of OM (**figure 16**).

573 **5.2.2. Models for organic-rich rocks deposition**

574 In this study, we highlight four main stages characterized by contrasted depositional dynamics that
575 result in different temporal and spatial distributions of OM in the basin:

- 576 - Sequence 1 and 2: oxic water and low paleoproductivity.
- 577 - Sequence 3: dysoxia/anoxia takes place in the deepest part of the basin.
- 578 - TST4: the anoxia is associated with an increase of paleoproductivity on the basin margins.
- 579 - Above MSF4, the basin returned to its initial condition: oxic water associated with a low
580 productivity.

581 Based on these observations we propose a model for the deposition of the organic-rich layer in the
582 Montney and Doig Formations (**figure 17**). These models split the investigated interval in 3
583 conceptual basin types: Type 1: an oxic basin, that prevailed during sequence 1 and 2 and HST4. Type
584 2: a restricted basin that is representative of the sequence 3. Type 3: a high primary productivity
585 basin that is diagnostic of the TST4.

586 During sequence 1, 2 as well as HST4, the low primary productivity along the coast, the high oxygen
587 content in the water lead to limited organic accumulation in the basin (**figure 16 and 17 A**).

588 In sequence 3, a restriction of the connection between the open marine settings and the basin due to
589 low relative sea level induced a decrease of water circulation and therefore a stratification of the
590 water column that to the development of anoxia in the deepest part of the basin (**figure 16 and 17 B**,
591 Demaison and Moore, 1980; Huc, 1988; Arthur and Sageman, 1994; Brumsack, 2006; Algeo *et al.*,
592 2008; Algeo and Rowe, 2012). The stratification is supposed to take place below the storm weather
593 wave base (SWWB) where water mixing is limited. This stratification associated with a primary
594 productivity similar to sequence 1 and 2 allows for the preservation of produced OM transported in
595 the deepest part of the basin. On the edges of the basin, where the bathymetry does not go below
596 the SWWB, OM is poorly preserved (**figure 16**).

597 This study highlighted an increase in primary productivity and the occurrence of anoxic water along
598 the margin of the basin In the TST4 (**figure 16 and 17 C**, Demaison and Moore, 1980; Calvert and
599 Price, 1983; Emeis *et al.*, 1991; Wignall and Newtown, 2001; Brumsack, 2006; Algeo *et al.*, 2008). This

600 productivity, associated with the anoxia controlled the preservation of very rich organic layers on the
601 edges of the basin. In this systems tract, anoxic condition and increased productivity were also
602 highlighted in the central part of the basin, but with a lower intensity than on the edges of the basin.

603 The integration of geochemical analyses in the stratigraphic framework highlighted three different
604 types of basin in the studied interval. Those three types of basin present drastically different
605 distribution of OM due to differences in dynamic of anoxia and primary productivity.

606 Sequence stratigraphy study shows that the deposition of the Montney and Doig Formations most
607 likely took place in an oval shaped basin between the proto-cordillera and the western margin of
608 Pangea (Crombez, 2016; Rohais *et al.*, 2016). In these settings, OM is poorly preserved in type 1 basin
609 (**figure 17 A**). In a type 2 basin (**figure 17 B**), organic rich deposits are located in the central part of
610 the basin where the oxygen content is minimum. This type of basin is very similar to the present-day
611 Black Sea where the production of the OM takes place along the margin of the basin and OM is
612 accumulated in the central part of the basin (Huc, 1988; Wilkin *et al.*, 1997; Arthur and Dean, 1998;
613 Algeo and Lyons, 2006; Algeo *et al.*, 2008). In this type of basin, the organic rich area will likely be
614 round-shaped in the deep basin. Lastly, in a type 3 basin (**figure 17 C**), the organic-rich layers are
615 located below the production areas, where the oxygen content is minimum due to the development
616 of OMZ. As the production areas can be considered a function of the distance to the shore (Calvert,
617 1987; Baudin *et al.*, 2007), the organic rich areas resulting from this type of basin are likely to be
618 halo-shaped parallel to the shoreline.

619 **5.3. Controls on primary productivity and anoxia**

620 Our analysis suggest that during the Lower and Middle Triassic in Western Canada, the evolution of
621 primary productivity and anoxia through time was associated with major stratigraphic surfaces
622 (**figure 16**). In particular, physiographic changes of the basin across the boundary between third-
623 order sequence 2 and 3 as well as between second-order sequence A and B (Crombez, 2016) appear

624 to have a major impact on the distribution of organic matter. These changes likely reflect the early
625 geodynamic evolution of the Canadian Cordillera.

626 **5.3.1. Primary productivity**

627 A strong increase of primary productivity occurred during TST4, above a major erosional
628 unconformity that modified the physiography of the basin. Several models explain the increase of
629 organic productivity by an augmentation of nutrients inputs from the continent due to climate
630 enhanced continental weathering (Algeo et al., 2008) or associated with a marine transgression
631 (Wignall and Newton, 2001). Other studies explain the increase of primary productivity by the input
632 of deep marine nutrients associated with upwelling cells (Heckel, 1977; Demaison and Moore, 1980;
633 Calvert and Price, 1983; Emeis et al., 1991).

634 During sequence A, the positive correlation of detrital supply proxies (Al) with organic productivity
635 proxies (Ni, Cu) suggests that nutrients were supplied by the continent and their low concentration
636 resulted in low to moderate organic productivity in the Montney Formation. During TST4, such a
637 relation between detrital input and organic productivity was not observed, suggesting another
638 source of nutrients. A recent study (Krajewski, 2013) on Triassic strata from Svalbard archipelago,
639 shows that the increase of primary productivity in the basin is mainly controlled by the stratigraphic
640 evolution that establish the connection between upwelling cells and a moderately restricted basin
641 (**figure 14**). A major change of basin physiography across the boundary between sequence A and B,
642 associated with the early geodynamic evolution of the foreland basin might have resulted in the
643 connection with upwelling cells present during the Triassic along the NW margin of Pangea (Parrish
644 and Curtis, 1982). Accordingly, the increase of nutrients delivery during TST4 is probably linked to a
645 combination of the transgressive trend and the regional geodynamic evolution that connect the
646 basin with upwelling cells.

647 **5.3.2. Anoxia**

648 Anoxia in sedimentary basin is mainly driven by two processes: the basin restriction (e.g. the Black
649 Sea, Demaison and Moore, 1980; Huc, 1988; Arthur and Sageman, 1994; Brumsack, 2006; Algeo and
650 Rowe, 2012) and the primary productivity (e.g. the Peruvian Margin, Demaison and Moore, 1980;
651 Arthur and Sageman, 1994; Emeis *et al.*, 1991; Calvert and Price 1983; Arthur and Dean, 1998;
652 Brumsack, 2006; Paulmier and Ruiz-Pino, 2009).

653 The Montney and Doig Formations present two intervals of anoxia during sequence 3 and TST4. The
654 anoxia in sequence 3 is associated with a moderate to low productivity and a major falling stage of
655 relative sea level whereas TST4 is a second order transgressive period associated with increased
656 primary productivity.

657 During sequence 3, the lowstand relative sea level lead to restricted connections between the basin
658 and the open marine settings and resulted in reduced water exchange between the two domains and
659 a stratification of the water column. In this setting, the anoxia in the basin is controlled by both the
660 physiography of the basin and the stratigraphic settings that allow for the occurrence of a threshold
661 area.

662 In the TST4, the high primary productivity triggered the development of an oxygen minimum zone
663 directly below the production area. Unlike in sequence 3, the anoxia in TST4 was controlled by the
664 primary productivity, although the additional impact of basin restriction on anoxia is difficult to
665 estimate.

666 In the Montney and Doig Formations, the two anoxic episodes present different extension and
667 dynamic. (1) The anoxic episode at the upper part of the Montney Formation was mainly linked to
668 the physiography of the basin and to its stratigraphic evolution. (2) The anoxic areas in TST4 were
669 likely controlled by organic productivity and therefore were not located in the center of the basin but
670 instead in halo-shaped belts associated with up-welling cells. Further work involving forward
671 stratigraphic modeling would help addressing the relative impact of primary productivity versus basin
672 restriction on the resulting anoxia.

673 **6. CONCLUSIONS**

674 The work presented in this paper is based on well and outcrop data. It integrates geochemical
675 analyses in a stratigraphic framework in order to understand the distribution of organic-rich layers in
676 a sedimentary basin and the dynamic of the key controlling factors: primary productivity, dilution and
677 preservation of OM at basin scale. This multidisciplinary study shows:

- 678 - The occurrence of primary OM in the Montney and Doig Formations. The palynofacies
679 analyses reveal the occurrence of planktonic OM (**figure 5**).
- 680 - The need for a large scale sequence stratigraphic framework to understand local
681 variation of OM accumulation. In the studied interval, the time lines provided the
682 opportunity to understand the major spatial and temporal changes of organic primary
683 productivity and redox conditions.
- 684 - The impact of these variations of redox conditions and productivity on the vertical
685 distribution of OM in the Montney and Doig Formations. Sequences 1 and 2 present low
686 TOC content, whereas sequence 3 and TST4 present some organic-rich accumulations.
687 This complex distribution is linked to the development of a “Restricted basin” in
688 sequence 3 and a “High primary productivity basin” in the TST4.
- 689 - The lateral variation of OM content due to different rates of productivity and different
690 types of anoxia. In a “High primary productivity basin”, the organic rich layers are located
691 along the coast below the production areas whereas, in a “Restricted basin”, the organic
692 rich layers is deposited in the center basin.
- 693 - The occurrence of two different types of anoxia. In the Montney Formation, sequence 1
694 and 2 may show small episodic “Restricted basins” (ponds) in the basin center and the
695 sequence 3 can be considered as a large “Restricted basin” (**figure 17 B**). In the TST4, the
696 anoxia is located along the basin margin (“High primary productivity basin”, **figure 17 C**).
697 In the Montney Formation, the anoxia is induced by the physiography of the basin and by

698 the sea level falling stage whereas in the Doig phosphate unit, the anoxia is linked to
699 organic primary productivity associated with a second order transgressive trend induced
700 by major geodynamical changes.

701 - The primary controls of the basin physiography and stratigraphic settings on anoxia. In
702 the studied interval, the “Restricted basin” is the result of a major sea level falling stage
703 in a threshold basin whereas the “High primary productivity basin” is linked to a major
704 transgressive interval. In the present study, the threshold is linked to the proto-Canadian
705 Cordillera accretion and induces strong restriction.

706 - The second order transgressive periods do not always present high organic accumulation.

707 - In our case study anoxia and primary productivity are the two main controls on organic
708 richness, while dilution as only a marginal impact.

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978 Pedigree-Ring/Border-Kahntah River Area, Northwestern Alberta and Northeastern
979 British Columbia. *Bulletin of Canadian Petroleum Geology* 58, 115–140.

980 FIGURES CAPTIONS

981 **Figure 1:** Location map of the data available for this study. The names 0/06-33, 0/14-14 and 0/16-17,
982 respectively stand for wells: 0/06-33-72-25W5, 0/14-14-76-12W6 and 0/16-17-83-25W6. The map on
983 the upper right side indicates the location of the study area within the Western Canada sedimentary
984 basin and the Montney Formation subcrop area. BC – British Columbia; AB – Alberta; CC – Canadian
985 Cordillera; WCSB – Western Canada Sedimentary Basin; CS – Canadian Shield; UC – Ursula Creek
986 outcrop; BH – Brown Hill outcrop.

987 **Figure 2:** Simplified sedimentary architecture of the Lower and Middle Triassic strata of the Western
988 Canada sedimentary basin (modified from Crombez, 2016). On this sketch, the Brown Hill outcrop
989 (BH) located near to Williston Lake in the fold and thrust belt of the Canadian Cordillera, was moved
990 to its estimated original position at the time of deposition. TST – Transgressive systems tract; HST –
991 Highstand systems tract; FSST – Falling stage systems tract; LST – Lowstand systems tract.

992 **Figure 3:** A. HI vs Tmax cross-plots for core samples with TOC values. B. HI vs Tmax cross-plots for
993 cuttings samples with TOC values. These figures show that most of the OM in the Montney and Doig
994 Fm is Type II and Type III. Here, the increase of the TOC with the maturity is biased by the data
995 sampling: in the basin the most mature areas contain the richest samples. HI – Hydrogen index.

996 **Figure 4:** FID curves from the Basic Rock–Eval pyrolysis of an early mature cutting sample before and

997 after hydrocarbons (HC) extraction with organic solvent. HC extraction highlighted the presence of
998 heavy HC in the S2 peak. FID - Flame Ionization Detector; BR – Bulk Rock; eBR – Extracted Bulk Rock.

999 **Figure 5:** Palynofacies view of the Montney and Doig Fm. showing that most of the primary OM of
1000 the studied interval is amorphous. On these pictures only few terrestrial particles (spores, pollen
1001 grains or woody debris) are present and no damaged terrestrial particles can be observed. PM –
1002 Palynomaceral = Terrestrial organic matter; SP – Spore/Pollen; AOM – Amorphous organic matter; Py
1003 – Pyrite.

1004 **Figure 6:** Well section across the Montney and Doig Fm with TOC measurements and estimations of
1005 the TOC_{ini} for two initial Hydrogen index ($IH_{ini} = 350$ and $IH_{ini} = 600$) in a stratigraphic framework. This
1006 **figure** shows that the organic content of sequence 3 and 4 is higher than in sequence 1 and 2.

1007 **Figure 7:** Distribution of the TOC and computed TOC_{ini} in the studied interval and in the four
1008 sequences. Solid bars represent actual TOC and hatched bars represent TOC_{in} . It shows that the mean
1009 TOC in the studied interval is 1.28 wt% and present heterogeneities: the TOC content of sequence 3
1010 and TST4 is higher than the content of sequence 1 and 2.

1011 **Figure 8:** Sedimentary section of sequences 3 and 4 from the core description of the 0/16-17-83-
1012 25W6. This figure shows that low energy facies were dominant in the LST3 whereas during the TST4
1013 high energy facies are dominant.

1014 **Figure 9:** Cross-plots of the TOC_{ini} and the SR. Here, SR are based on undecomposed sediments.
1015 White symbols show intervals where SR may be underestimated due to an erosional top. These
1016 cross-plots, present two types of relation between TOC_{ini} and SR. In sequence 1, 2 and HST4 a linear
1017 relation exists between TOC_{ini} and SR that reflect organic dilution by non-organic sediments. In
1018 sequence 3 and TST4, this relation is not evident which suggests others controls on organic
1019 accumulation and preservation.

1020 **Figure 10:** Cross-plots of the enrichment factors (EF) of Ni and Cu. The EF are computed based on the
1021 UCC (McLennan, 2001). Red lines in the cross-plots represent the Upper Continental Crust. This figure

1022 shows that paleoproductivity increased significantly in the TST4 whereas it remains stable in the rest
1023 of the studied interval.

1024 **Figure 11:** Vertical evolution of paleoproductivity proxies (Cu/Al and Ni/Al) in relation to TOC and
1025 TOC_{ini}. This figure shows that paleoproductivity increased significantly in the TST4 and that along
1026 Brown Hill, small increases of Ni/Al often occur in sequence 2, but no increases in TOC can be related
1027 to these peaks.

1028 **Figure 12:** Cross-plots of paleoredox proxies (U/Th and V/Cr). Limit values between
1029 oxic/dysoxic/anoxic domains are from Jones and Manning (1994). This figure shows the occurrence
1030 of anoxic layers in sequence 3 and 4.

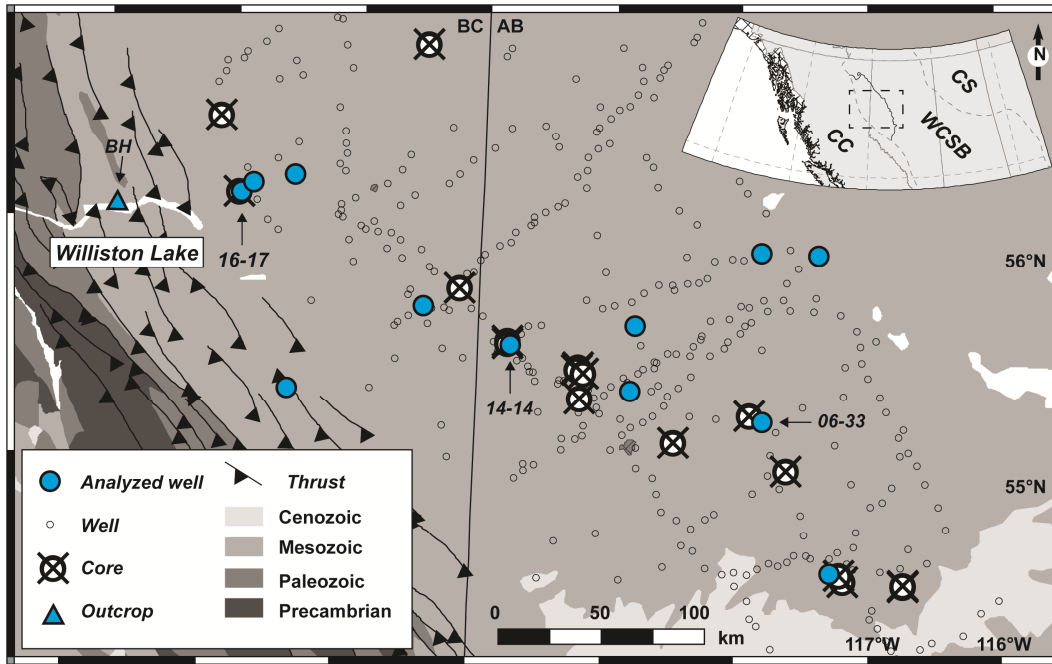
1031 **Figure 13:** Vertical evolution of paleoredox proxies (U/Th and Mo/Al) in relation to TOC and TOC_{ini} in
1032 the stratigraphic framework. This figure shows a major change above the SB3 and above the
1033 TS4/SB4. During sequence 3, the basin seems to be anoxic in its deepest parts whereas in the TST4,
1034 the basin presents anoxia to euxinia along its margin.

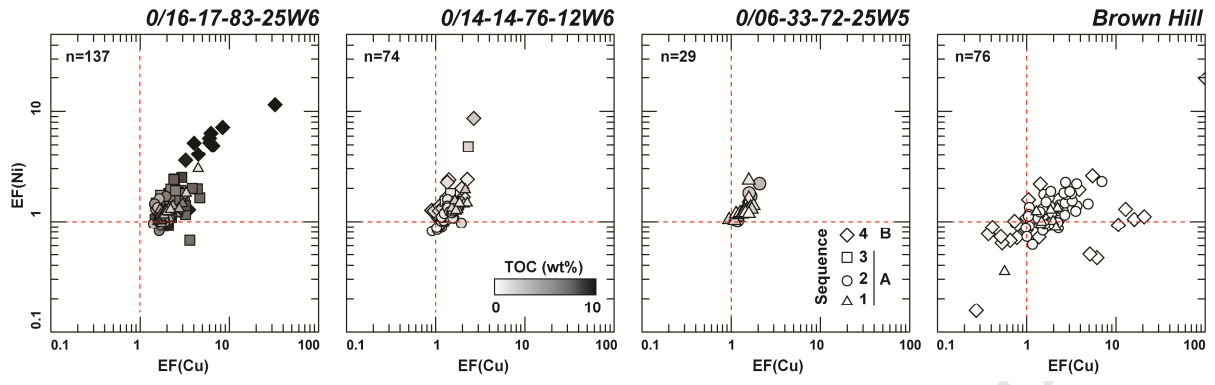
1035 **Figure 14:** Cross-plot of the molybdenum versus the TOC in the stratigraphic framework. This figure
1036 shows that in the Lower and Middle Triassic strata of the western Canada sedimentary basin, the
1037 Mo/TOC ratio is low ($< 30 \cdot 10^{-4}$) which suggests a basin restriction. SA: Saanich inlet; CB: Cariaco
1038 basin; FF: Framvaren fjord; BS: Black sea. Grey arrows highlight the potential effect of maturity on
1039 TOC values.

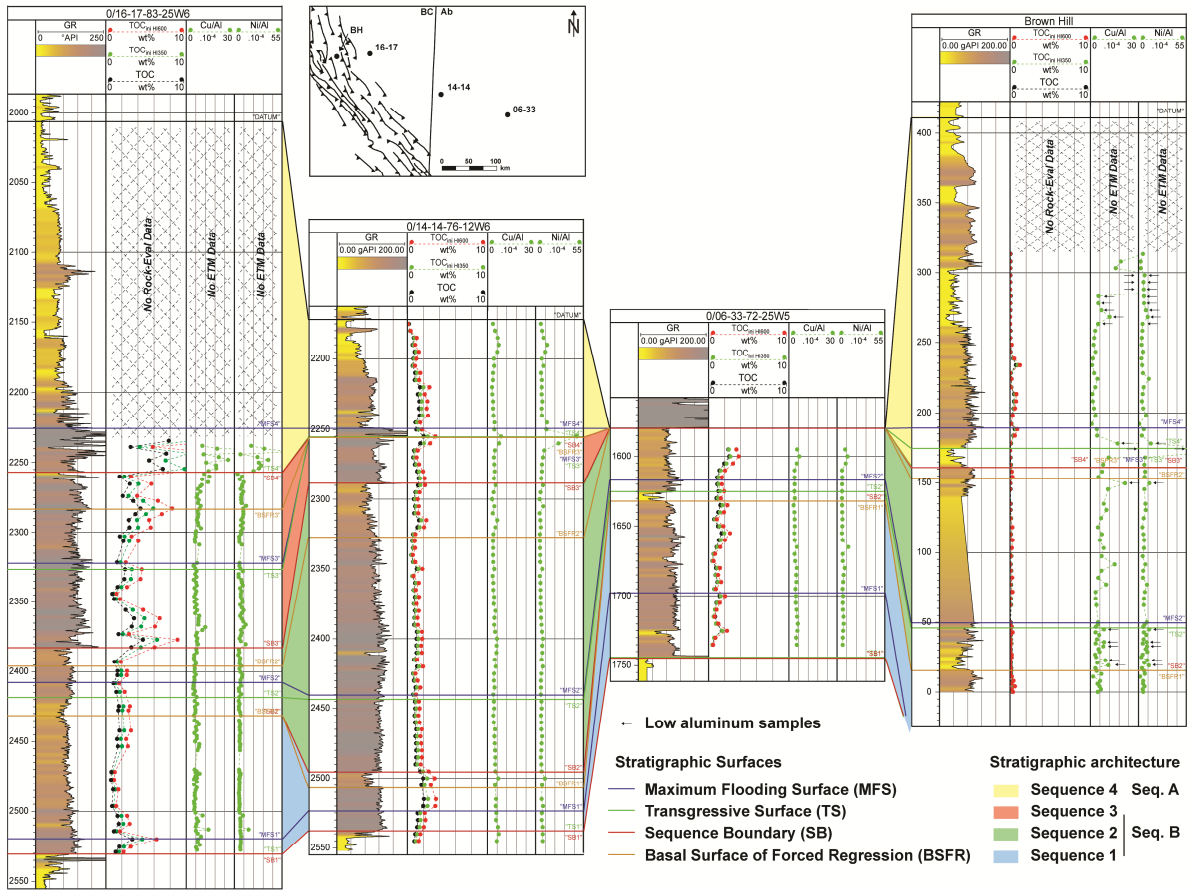
1040 **Figure 15:** Cross-plot of the weathering index of Parker (WIP) and the chemical index of alteration
1041 (CIA) in the stratigraphic framework. This cross-plot suggests that no major change of sediment
1042 maturity occurred during the Lower and Middle Triassic strata of the western Canada sedimentary
1043 basin.

1044 **Figure 16:** TOC distribution and its controlling factors. This figure shows that high TOC values may
1045 result from different combinations of controlling factors

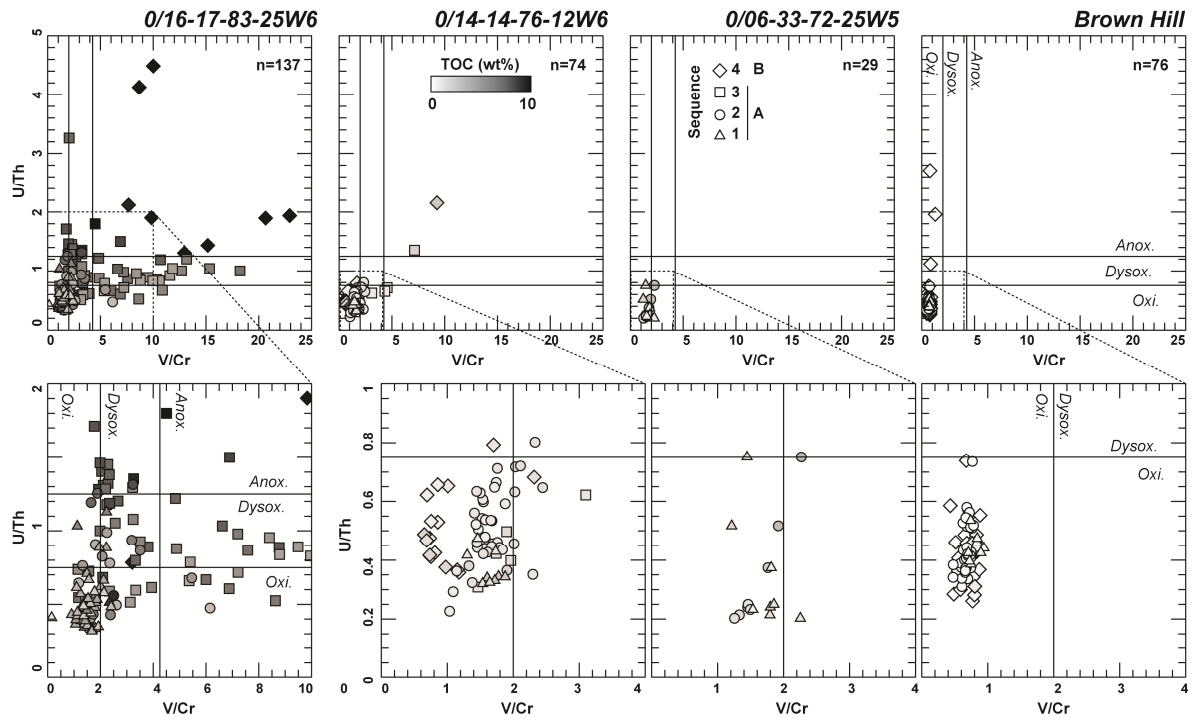
1046 **Figure 17:** Conceptual models of basin types proposed for the controls of organic matter
1047 accumulations in the Lower and Middle Triassic of Western Canada. A. Type1: Oxic basin, with low
1048 OM accumulation. B. Type 2: Restricted basin, with the occurrence of organic rich layer in the central
1049 part of the basin due to stratified water. C. Type 3: High primary productivity basin, with the
1050 occurrence of organic rich intervals along the proximal parts of the basin due to high productivity.

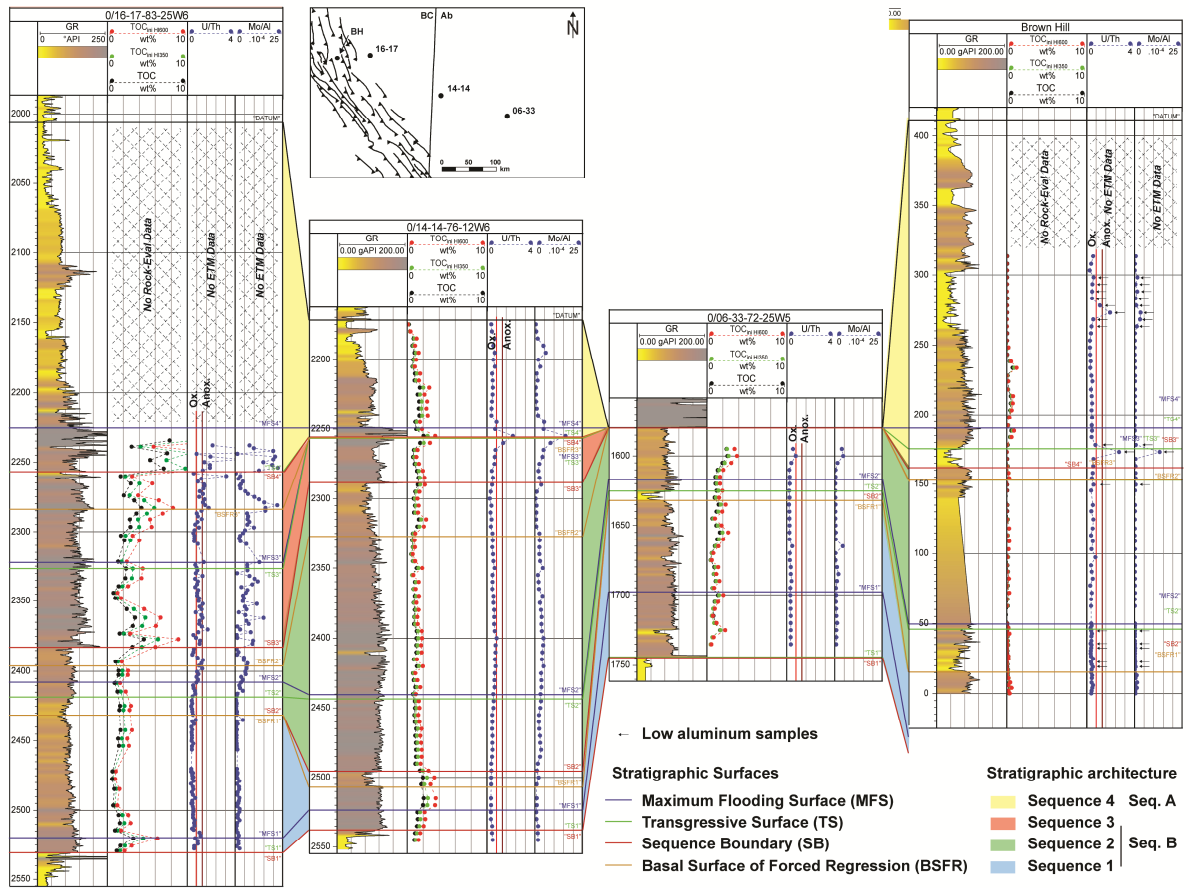




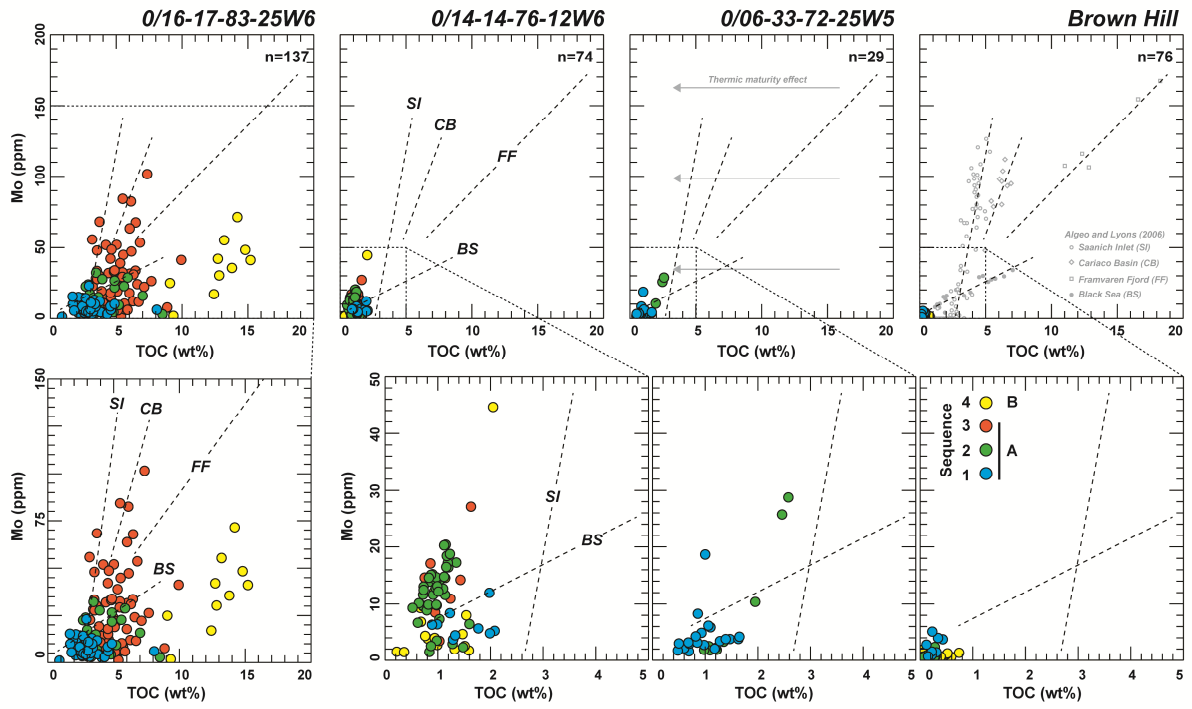


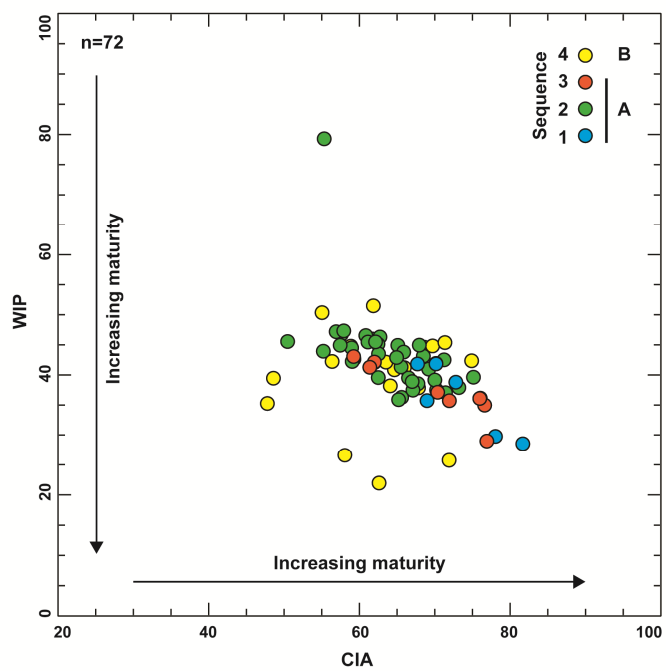
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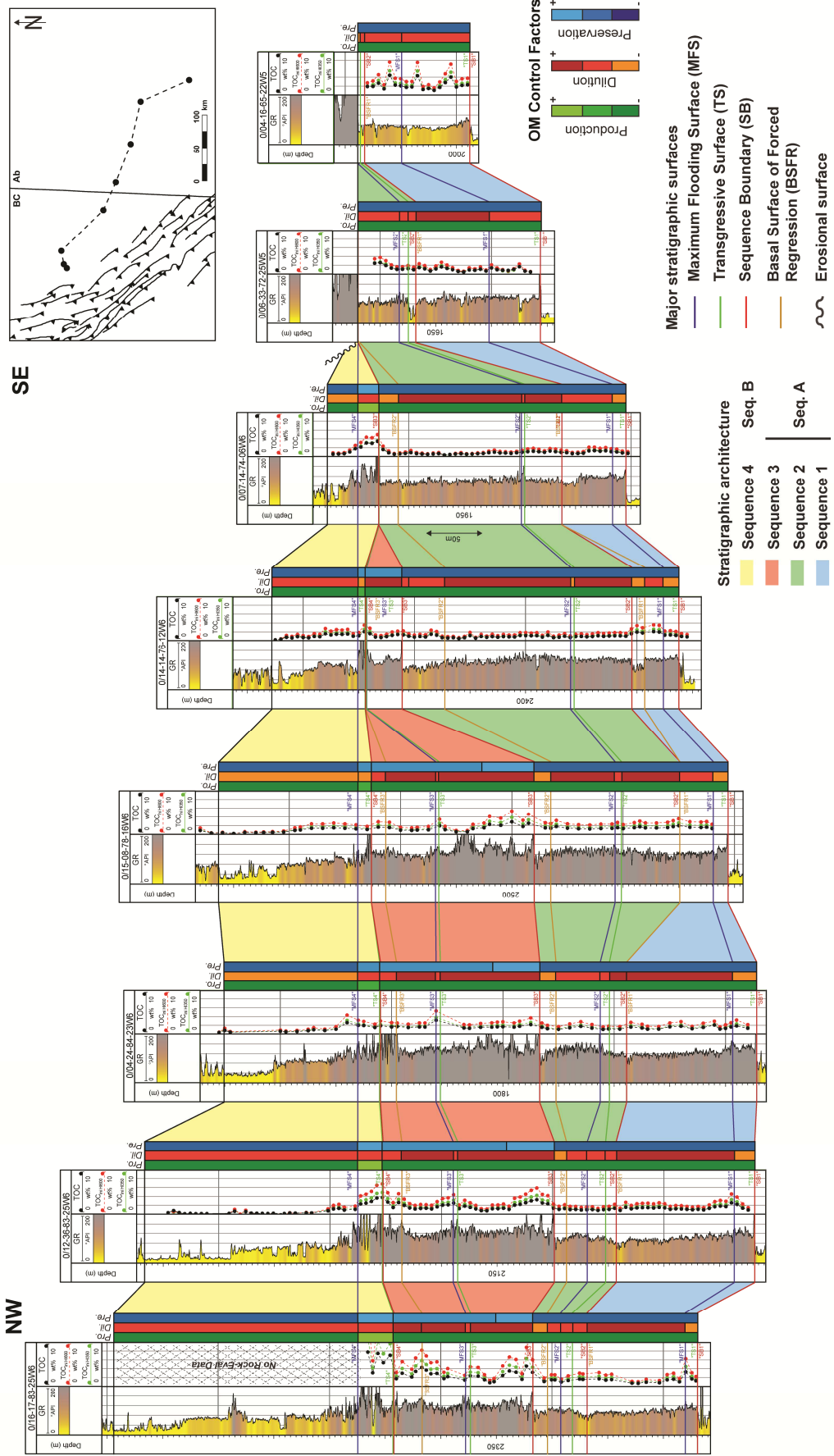




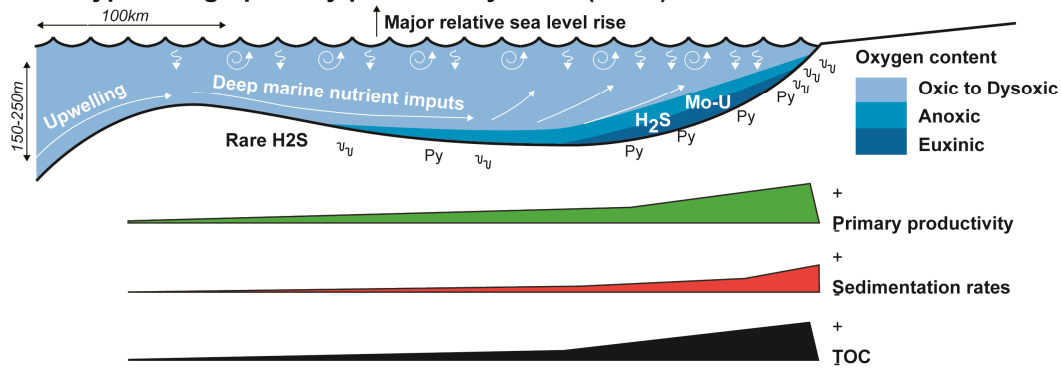
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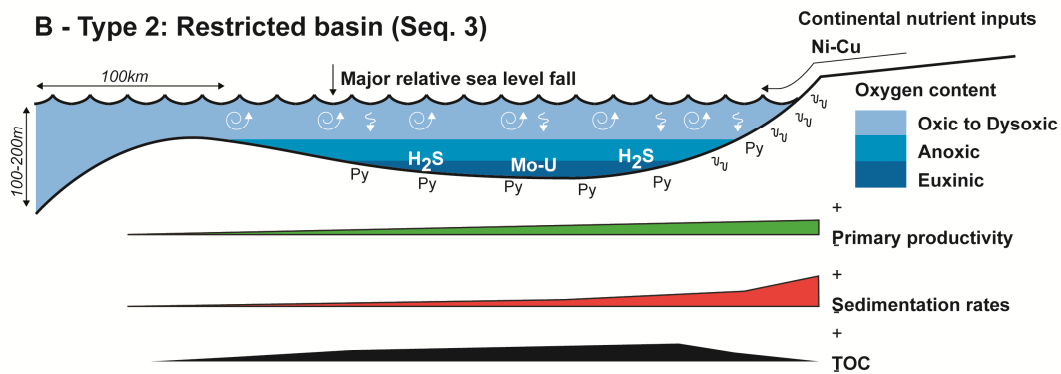




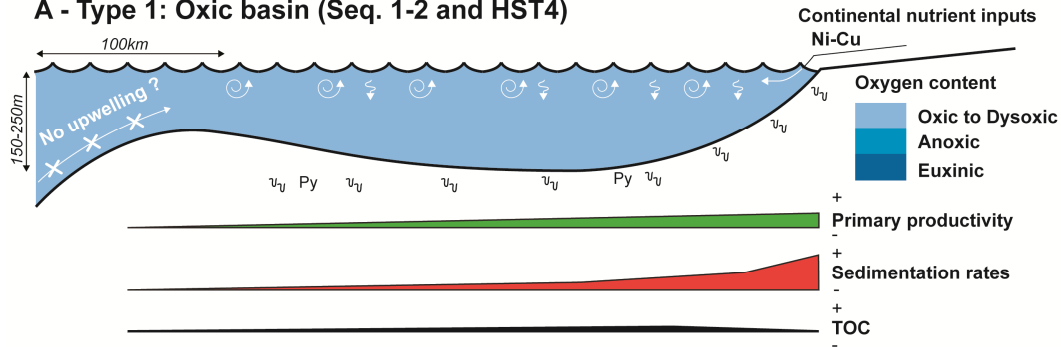
C - Type 3: High primary productivity basin (TST4)



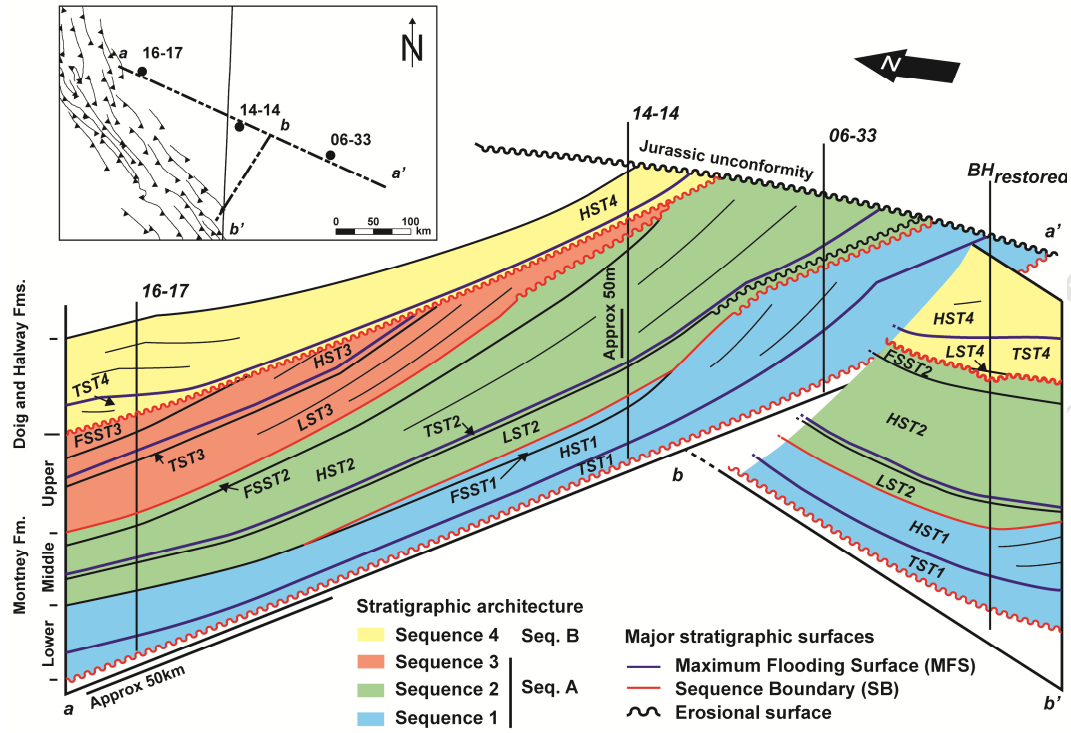
B - Type 2: Restricted basin (Seq. 3)

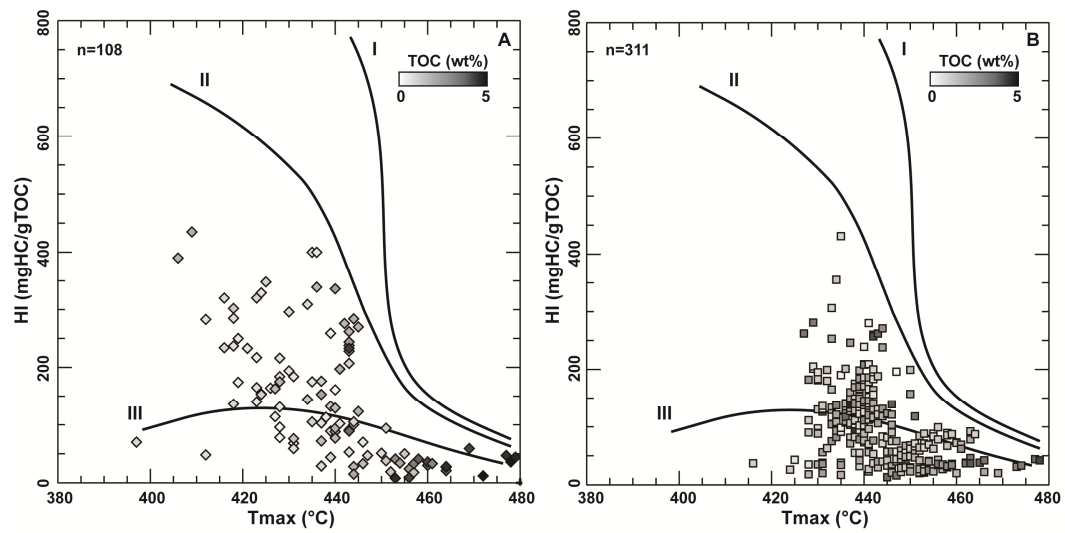


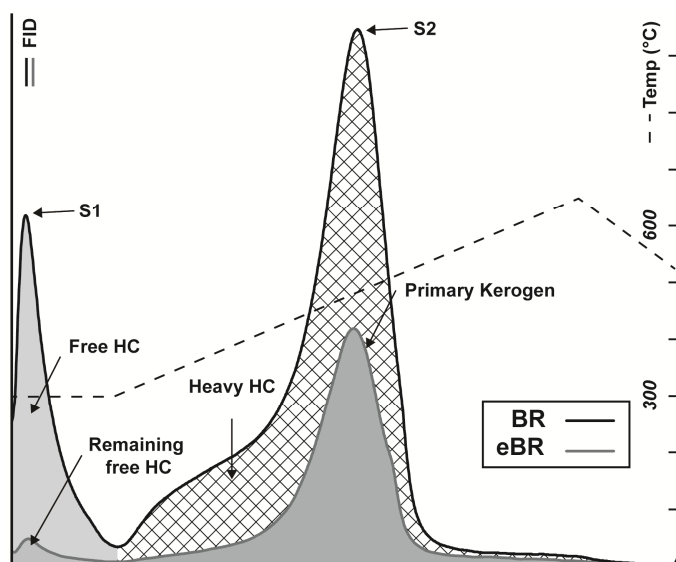
A - Type 1: Oxic basin (Seq. 1-2 and HST4)



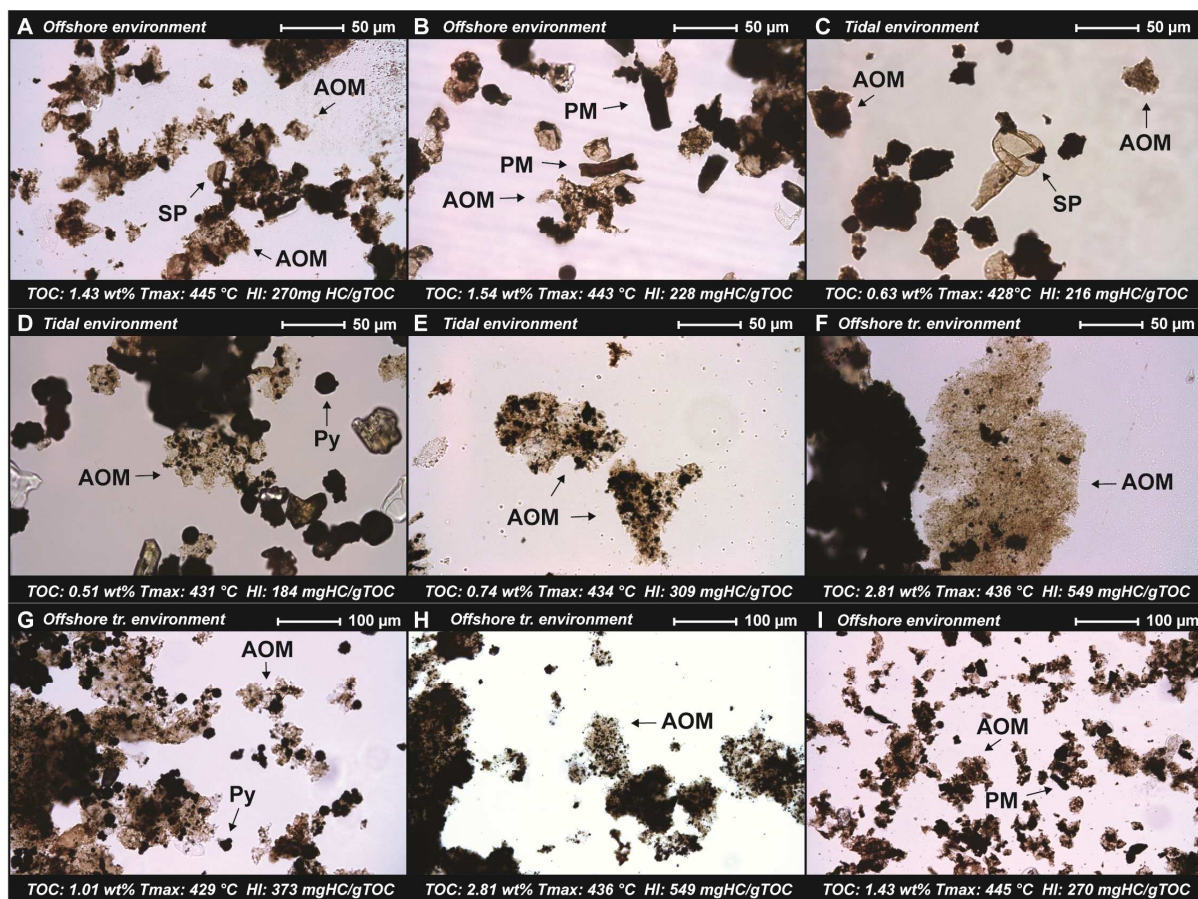
ν Bioturbations Py Pyrite \circlearrowright Wave action \downarrow Sinking O.M.

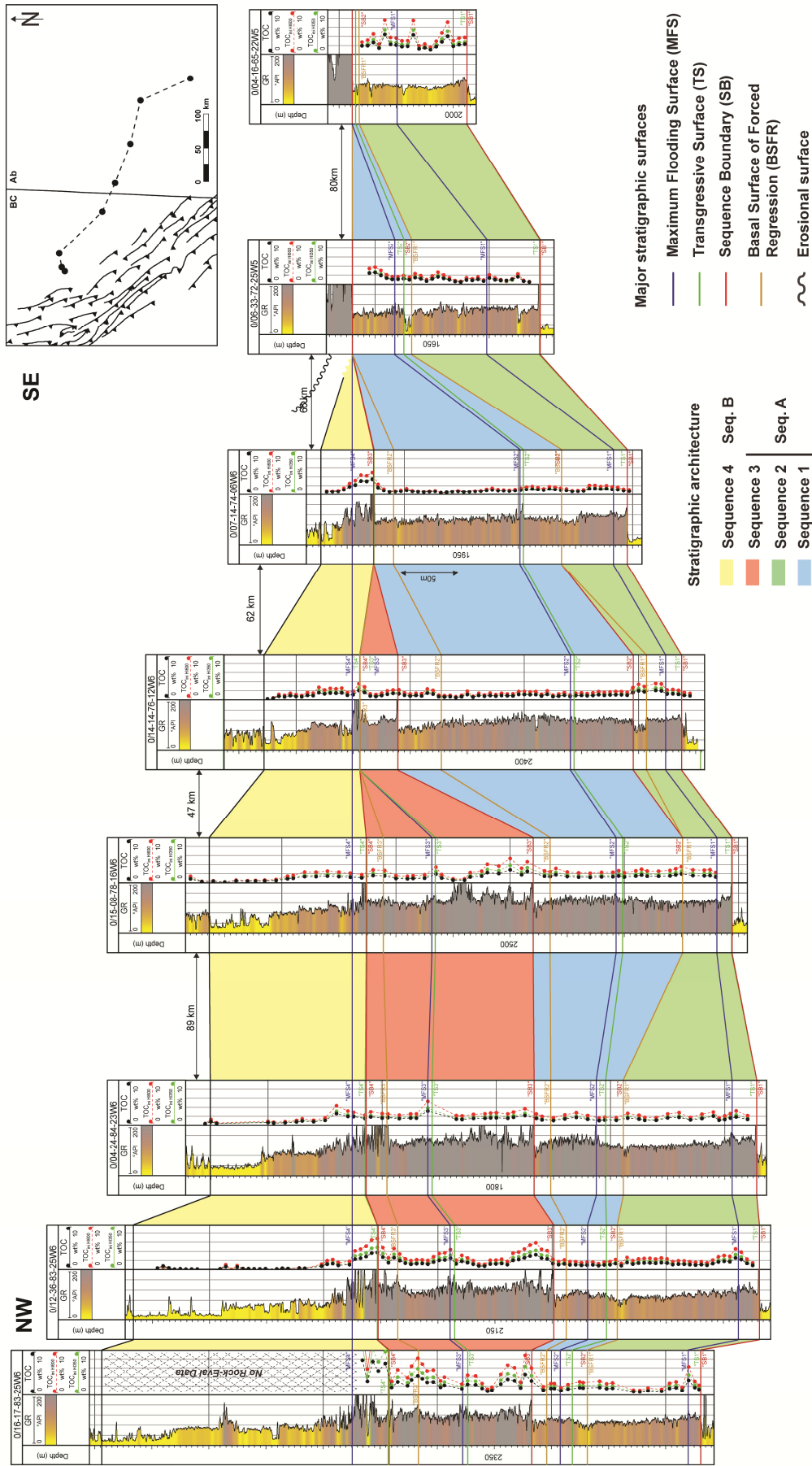


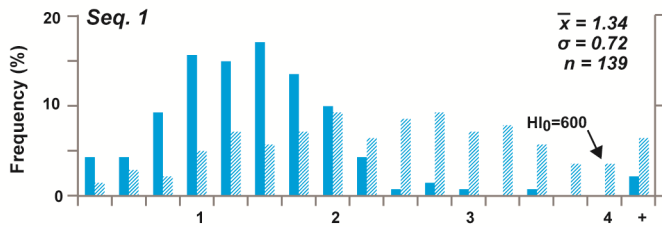
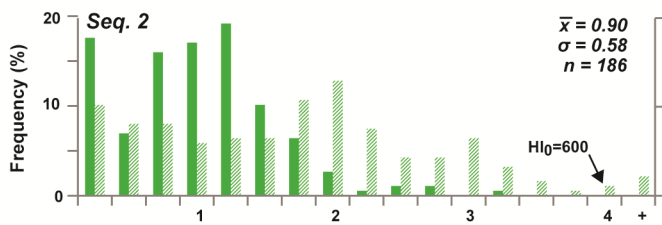
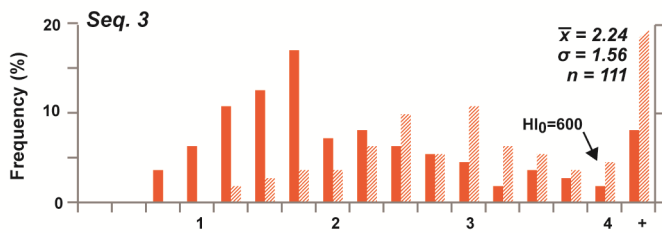
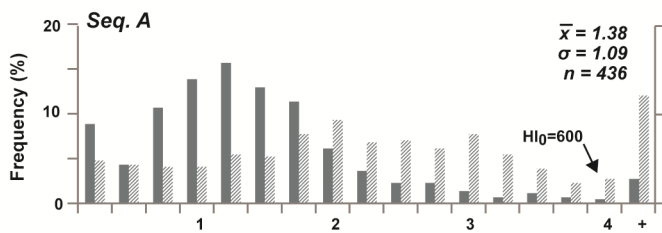
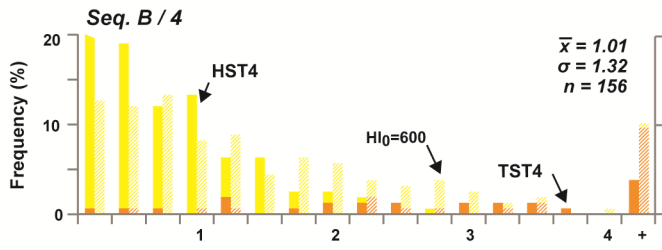
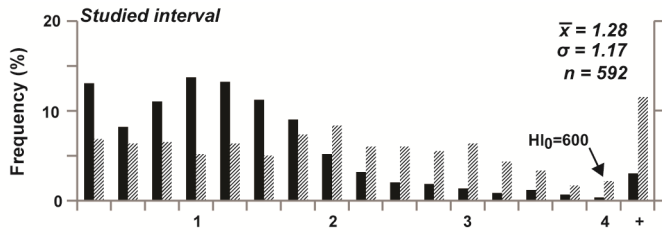


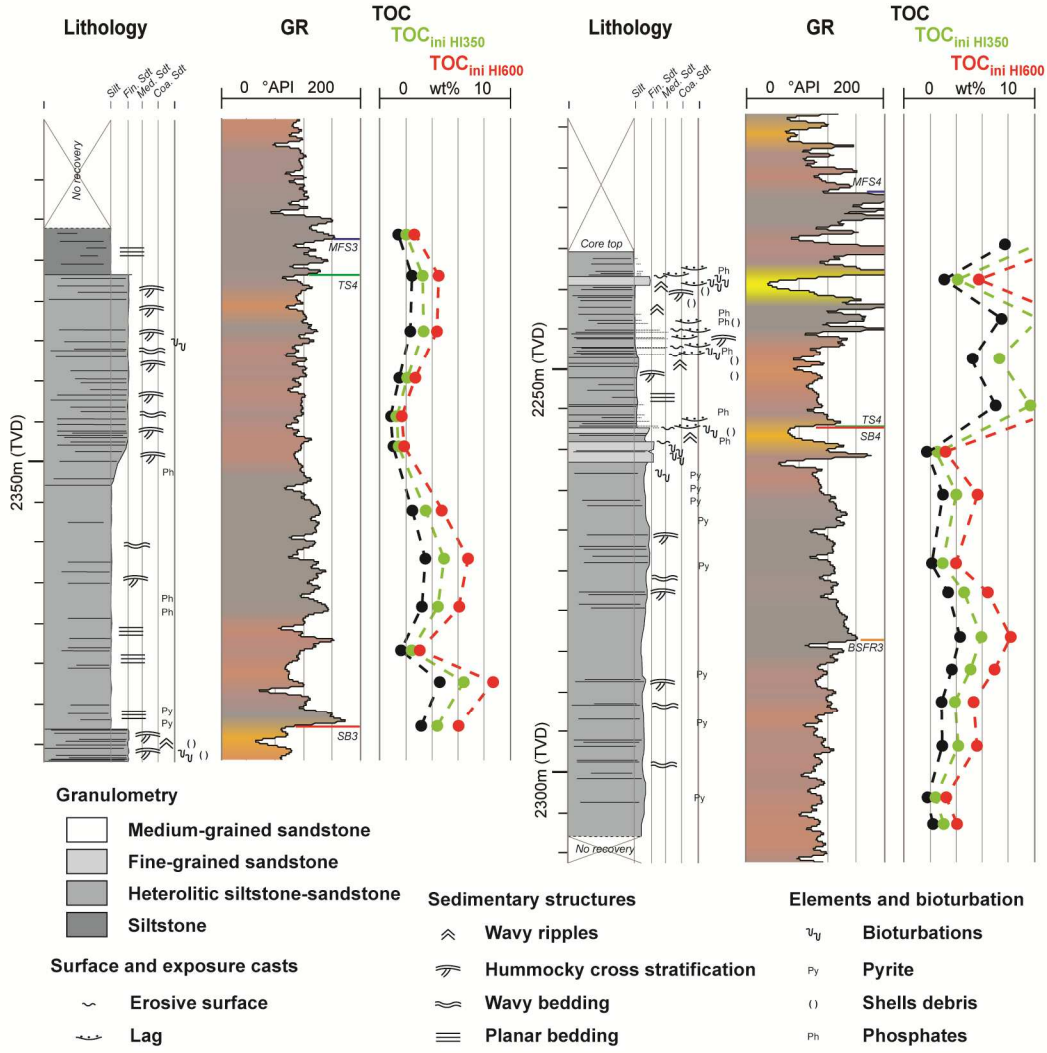


	(mgHC/gTOC)		(°C)	(%)
	S1	S2	Tmax	TOC
BR	0.46	1.96	443	1.05
eBR	0.07	1.40	439	0.92





TOC and TOC_{ini IH=600} (wt%)



ACCEPTED

