

Regional Stratigraphic Architecture of the Spathian Deposits in Western Canada – Implications for the Montney Resource Play

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2 Western Canada – Implications for the Montney Resource Play

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ABSTRACT

11	Thick Spathian deposits of the Lower Triassic Montney formation are preserved in
12	northeastern British Columbia and west-central Alberta, where they hold massive
13	amounts of unconventional resources. Understanding the internal architecture of
14	these marine deposits at basin-scale can provide a framework to better predict the
15	distribution of source-rocks, reservoirs and seals within this petroleum system and to
16	investigate their control on hydrocarbon generation and migration pathways.
17	Ultimately, this high resolution stratigraphic framework can be used to investigate the
18	impact of geological heterogeneities on well performance at the regional scale.
19	In northeastern British Columbia, the Spathian deposits consist mainly of offshore and
20	offshore transition sediments forming a wedge prograding from northeast to
21	southwest. This wedge is punctuated by major marine flooding surfaces bounding
22	parasequence sets that can be correlated regionally owing to their characteristic
23	gamma ray logs signature and to the high density of well and core control. The
24	regional correlation of these parasequence sets, based on over 1,450 wells, reveals
25	well-defined clinoform morphologies characterized by topset, foreset and bottomset
26	geometries along a proximal-distal depositional profile. The facies analysis and the
27	characteristic dimensions of these morphologies are consistent with deposition in a
28	predominantly siliciclastic shoreface to shelf setting and marks a significant contrast
29	to the ramp setting of hybrid clastic-carbonate lithologies which prevailed during the
30	Griesbachian to Smithian. The stratigraphic architecture is analogous to "subaqueous
31	shelf-prism clinoforms" that have been described on numerous present-day and
32	ancient continental shelves. Subaqueous shelf-prism clinoforms typically display a

33	sigmoidal shape in the dip direction and along-shore-elongated depositional thick in
34	plan-view. This geometry results from the interaction of clastic sediment input with
35	shelf hydrodynamic processes such as storm generated waves and sediment gravity
36	flows as well as nearshore and offshore bottom currents. Consequently, the topset,
37	foreset and bottomset of these clinoforms are characterized by different depositional
38	facies that can be predicted and mapped at basin-scale, over hundreds of kilometers.
39	In the Spathian depositional system of western Canada, clinoform bottomset facies
40	are mainly a product of suspension deposition, hemipelagic sedimentation and
41	mineral precipitation. These facies form the main source-rock intervals within the
42	Montney Formation, due to anoxic conditions and lower sedimentation rates resulting
43	in better preservation of organic matter. Clinoform foresets result from traction
44	transport processes of coarser siliciclastics and higher sedimentation rates, forming
45	thick, mostly organic-lean intervals with better reservoir quality. Foreset deposits
46	form the thickest part of the Spathian parasequence sets and are the main targets of
47	horizontal drilling and multistage fracturing. Clinoform topsets mainly consist of
48	shoreface to offshore transition deposits and are poorly preserved due to the erosion
49	under the top Montney unconformity. The distribution of the depositional thick in
50	map view and along a strike-oriented regional cross-section suggest that these
51	deposits were influenced by major structural elements at basin scale. The regional
52	flooding surfaces bounding the parasequence sets might form extensive permeability
53	barriers that potentially control up-dip migration of hydrocarbons within the Montney
54	petroleum system.

INTRODUCTION

57	The Lower Triassic Montney Formation of western Canada forms a thick hybrid clastic-
58	carbonate sediment wedge prograding from northeast to the southwest, in Alberta
59	and British Columbia. This formation has been the target of oil and gas exploration
60	and production for over 60 years. Until the 1980's, oil was exploited from
61	conventional reservoirs in bioclastic and siliciclastic shoreline successions of the
62	eastern, proximal part of the depositional system. In the 1990's, natural gas and
63	liquids from turbiditic tight reservoirs were exploited further west into the Deep Basin
64	of west-central Alberta, using vertical wells and hydraulic fracturing. The stratigraphic
65	architecture and the paleogeographic reconstruction of the Montney Formation were
66	mostly developed based on the analysis of the Induan and Lower Olenekian aged
67	deposits containing these shallow marine and turbiditic facies (Davies et al., 1997;
68	Moslow and Davies, 1997; Embry, 1997; Zonneveld et al., 2011). With the recent
69	development of the unconventional reservoirs of the Montney Formation, through
70	horizontal drilling and multistage fracturing, a wealth of new data have been made
71	available in the Upper Olenekien (Spathian Substage) deposits of northeastern British
72	Columbia. The objective of this paper is to illustrate the high-resolution sequence
73	stratigraphy and internal architecture of the Spathian deposits of the Montney
74	Formation at basin scale.
75	The Montney Formation is subdivided into three third-order sequences which
76	correspond respectively to the Griesbachian-Dienerian, the Smithian and the Spathian
77	Triassic substages (Fig. 1; Embry and Gibson, 1995; Davies et al., 1997; Golding et al.,
78	2014; Crombez et al., 2016a and 2016b; Davies and Hume, 2016; Moslow et al., 2016,

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79	Henderson and Schoepfer, 2017). Although several conodont zones were identified
80	within these third-order sequences, published biostratigraphic data do not allow for
81	defining higher resolution units at a regional scale (Gibson and Barclay, 1989; Orchard
82	and Tozer, 1997; Davies et al., 1997; Orchard and Zonneveld, 2009; Golding et al.,
83	2011; Golding et al., 2014; Henderson and Schoepfer, 2017). However, based on well
84	log correlations, internal clinoform morphologies have long been recognized within
85	the Griesbachian-Dienerian and Smithian sequences (Davies et al. 1997, Wilson et al.
86	2012, Davies and Hume 2016), and more recently within the Spathian sequence
87	(Dixon, 2009; Lynch and Stasiuk, 2011; Wilson et al., 2012; Wood, 2013, Euzen et al
88	2017). In the Spathian deposits, these clinoforms form internal packages separated by
89	extensive flooding surfaces that can be correlated regionally, owing to their
90	characteristic gamma ray log signature and to the very high density of well control.
91	However, to our knowledge, basin-scale correlation and mapping of these internal
92	units have not been published. This paper aims at filling this gap by presenting the
93	results of basin-scale correlation and mapping of the Spathian internal architecture,
94	based on over 1,450 wells. The implications of this work on the paleogeographic
95	reconstruction and sequence stratigraphic interpretation of the Spathian deposits are
96	discussed. The cross-sectional morphology and plan-view geometry of the Spathian
97	internal units, as well as the facies partitioning within them, have a direct impact on
98	the distribution of source rocks, reservoirs and seals within the unconventional
99	Montney play.

DATA AND METHOD

102	The interpretation presented in this work is based on the correlation of over 1,450
103	wells using the gamma ray logs and detailed sedimentologic descriptions of 6 full -
104	diameter cores through the entire Spathian succession (Fig. 2).
105	Our well database contains over 1,450 wells with a gamma ray log over the complete
106	Spathian section and covers an area of about 50,000 square kms, from the Elmworth
107	Field of Alberta in the southeast to the Caribou Field of British Columbia in the
108	northwest. The study area extends from the erosional pinchout of the Spathian
109	deposits to the east and south, to the Cordillera deformation front or slightly beyond
110	to the west and southwest (Fig. 2). Well to well correlation was performed by
111	constructing tens of dip-oriented cross-sections throughout the study area from the
112	updip topset to the downdip bottomset of clinoforms where preserved. Due to
113	variations in calibration and vintage of gamma ray logs, the API scale was set
114	individually for each well, to maximize the variability and magnify high frequency
115	patterns of cyclicity. The unconformable surface at the base of the Spathian substage
116	and the Montney-Doig boundary (base of the Doig 'Phosphatic Member') were both
117	used alternatively as a datum to verify the consistency of correlations.
118	The sedimentological expression of major flooding surfaces, the lateral facies
119	variations along the depositional profile and the vertical facies evolution of the
120	Spathian succession were investigated using selected core descriptions from 6 wells
121	(400 m of cumulative thickness). The thickness of the parasequence sets bounded by
122	the flooding surfaces was mapped throughout the basin and discussed in terms of
123	reservoir and source-rock distribution, as well as structural controls on sedimentation.

124 CORE-LOG CALIBRATION OF MAJOR FLOODING SURFACES

125	In the Spathian sequence, the gamma ray log signature is strongly influenced by the
126	uranium concentration, as observed in spectral gamma ray data (Fig. 3). Uranium
127	precipitation in sediments is influenced by redox conditions as well as by the
128	abundance of reactive organic matter (Tribovillard et al., 2006). Uranium is also
129	concentrated in phosphate enriched layers, often associated with condensed intervals
130	with multiple reworking/winnowing episodes (Li and Schieber 2015). As observed in
131	full-diameter cores within the Spathian interval, flooding surfaces are associated with
132	massive-appearing bituminous siltstone with higher organic content and occasionally
133	with pebbly siltstone phosphatic lags (Fig. 3 and 4). These flooding events have a
134	regional extent and can therefore be correlated across the basin over several
135	hundreds of km, based on the gamma ray log signature. However, correlating these
136	flooding surfaces with a good level of confidence requires a high density of well
137	control especially where the Spathian units become more condensed in the downdip
138	(bottomset) and updip (topset) directions. In those areas, the distance between wells
139	used for the correlation was kept between 1 and 3 km where possible.

140 INTERNAL ARCHITECTURE OF THE SPATHIAN SUBSTAGE



- 142 Montney Formation. This sequence is bounded below by a sequence boundary
- 143 corresponding to the Smithian-Spathian unconformity and above by a coplanar
- sequence boundary and transgressive surface of erosion separating the Montney
- 145 Formation from the overlying Doig 'Phosphatic Member' of the Doig Formation
- 146 (Golding et al., 2015; Crombez, 2016). Recent work demonstrates that an

147 unconformity-bounded Early Anisian unit thickening downdip to the west, informally

148 named 'Anisian Wedge', is present between the Montney and Doig Formations

149 (Zonneveld et al., 2016; Furlong et al., 2017; Furlong et al. a and b, this volume).

150 PARASEQUENCE SETS AND MORPHOLOGY OF THE CLINOFORMS

151 Clinoforms are seaward dipping stratal surfaces commonly observed on seismic data 152 in present-day and ancient coastal, shelf and continental margin depositional systems 153 (Nittrouer et al. 1996; Hampson 2010, Helland-Hansen el al, 2012; Patruno et al. 154 2015). The proximal-distal cross-sectional morphology of a clinoform typically consists 155 of gently basinward-dipping topset and bottomset separated by a steeper foreset, 156 with slope changes occurring through upper and lower rollover points respectively up-157 dip and down-dip of the foreset. Patruno et al. (2015) analyzed a large morphological 158 dataset of present-day and ancient clinoform systems, and defined four main type of 159 clinoforms associated with different scales and controlling processes. In subaerial 160 delta clinoforms, the upper rollover point corresponds to the shoreline, whereas in 161 subaqueous delta or shelf-prism clinoforms the transition between the topset and the 162 foreset occurs at 10's to 100's of meters in water depth. At an even larger scale, 163 continental margin clinoforms are associated with the continental slope, with water 164 depth of the upper rollover point typically occurring at depths greater than 1000 165 meters (Patruno et al., 2015). Analyzing the characteristic dimensions of the Spathian 166 clinoform morphologies observed in the Montney Formation and the depositional 167 facies associated with them, can help to better understand the physiography of the 168 basin at the time of deposition.

169	Figure 5 illustrates the internal architecture of Spathian deposits along six dip-
170	oriented regional cross-sections, from the Dawson area to the south to the Caribou
171	area to the north. The datum for these cross-section was set at the base of the Doig
172	Formation 'Phosphatic Member'. Seven regionally correlatable internal units were
173	defined within the Spathian sequence (Fig. 5). These units are interpreted as
174	parasequence sets because they contain several smaller-scale parasequences,
175	bounded by major marine flooding surfaces and are themselves contained within
176	depositional sequence systems tracts (Catuneanu et al., 2009). They have been
177	numbered M3-1 through M3-7, the first number corresponding to the sequence
178	(third-order sequence 3 of the Montney Formation sensu Crombez, 2016) and the
179	second number corresponding to the parasequence set from oldest to youngest
180	(bottom to top). Some of the uppermost deposits of the top unit (M3-7) have been
181	identified as part of the 'Anisian Wedge' from core data (Furlong et al 2017) and are
182	therefore of Anisian age (see Fig. 1). The 'Anisian Wedge' was not mapped in this
183	study, but it is the focus of two papers within the present volume (Furlong et al. a and
184	b, this volume).
185	The flooding surfaces bounding the Spathian parasequence sets clearly define
186	sigmoidal clinoform morphologies (Euzen et al., 2017) along dip-oriented cross-
187	sections (see Fig. 5C, 5E and 5F). These morphologies are only fully preserved in the
188	lower part of the Spathian succession (units M3-1 to M3-4), as the proximal part of
189	the overlying units (M3-5 to M3-7) have been eroded beneath the basal Doig

- 190 unconformity. The geometry of the lower Spathian clinoforms can be observed from
- 191 the low angle topset in the northeast, through the paleo-seaward dipping foreset
- 192 where the parasequence sets thicken, down to the subparallel bottomset. The

193 bottomset interval is characterized by a spiky gamma ray log signature interpreted to 194 be due to the condensation of multiple cycles in a starved offshore setting. This high 195 cyclicity may have resulted from changes in the relative balance between bottom 196 water oxygenation and sedimentation rate. As observed in core, bottomset facies are 197 highly bituminous to kerogenous, phosphatic siltstones (high gamma ray values) 198 interbedded with calcareous dolosiltstones of hemipelagic origin (low gamma ray 199 values). The foreset region is characterized by a steeper slope and a depositional thick 200 of parasequence sets that thin basinward and landward. In many places, the thinning 201 of individual parasequences is clearly associated with a vertical contraction of the GR 202 log pattern, suggesting that the change of thickness results from variations of the 203 sedimentation rate along the depositional profile (see the lateral variation of gamma 204 ray signature in unit M3-2 along the cross-section C of Fig. 5).

205 VERTICAL AND LATERAL FACIES EVOLUTION

206 The sedimentological description and depositional interpretation of a set of selected 207 cores were used to investigate the vertical and lateral facies variability within the 208 Spathian parasequence sets and along the depositional profile from the topset to the 209 bottomset of clinoforms. There are four principal facies recognized from the Spathian 210 interval of the study area. Their principal sedimentary characteristics and interpreted 211 environments of deposition are illustrated in Fig. 6 and 7. Observed lithologies vary 212 from siliciclastic to phosphatic in composition. Based primarily on physical and 213 biogenic sedimentary structures, processes of deposition are inferred for each facies 214 providing the basis for environmental interpretation. All four facies are interpreted to 215 have been the product of storm, wave and/or suspension settling processes of 216 deposition in lower shoreface through offshore environments of deposition as part of

217	an inner continental shelf, as opposed to ramp, profile (Moslow et al, 2016) (Fig. 8).
218	Siliciclastic facies are predominantly bituminous siltstone to silty very-fine grained
219	sandstone with the former lithology being far more common. In more distal
220	environmental settings, bituminous matrix increases and grain size decreases.
221	Conversely, sedimentary facies deposited in a more proximal position on the
222	shoreface-shelf profile have a less bituminous matrix, coarser grain size and higher
223	net to gross of coarse siltstone and very- fine grained sandstone to total bulk volume
224	textural composition.
225	Lower shoreface facies are observed in core as sparsely to moderately burrowed,
226	occasionally cryptobioturbated, planar laminated, wavy bedded fine to coarse-grained
227	siltstone, interbedded with very fine-grained silty sandstone. Macro-scale burrow
228	traces include diminutive forms of Bergaueria, Palaeophycus, Lingulichnus and
229	Skolithos. Normally-graded, sharp-based planar-laminated silty sandstone beds with
230	burrowed tops and varying in thickness from 3-5cm are interpreted as tempestites
231	(Fig. 6A). Offshore transition facies are observed as parallel-laminated to lenticular-
232	bedded, burrowed to cryptobioturbated fine to coarse-grained siltstone (Fig. 6B).
233	Trace fossils occur either as diminutive forms within a distal Cruziana assemblage with
234	low to moderate diversity, interpreted as part of the proximal offshore transition
235	environment, or as cryptobioturbation, interpreted as being characteristic of the
236	distal offshore transition environment. Offshore facies are highly bituminous to
237	occasionally kerogenous, massive-appearing to faintly parallel-laminated, fine to
238	coarse-grained siltstone with frequent phosphatic lenses and laminae (Fig. 6C).
239	Phosphatic clasts or nodules are sporadically observed in proximal and distal offshore
240	transition deposits as well. Calcareous, calcispheric dolosiltstones, interpreted as

hemipelagite deposits, form 5 to 30 cm thick inversely graded beds and are observed
within the bottomset and foreset areas of the clinoforms, throughout the Spathian
succession (Fig. 6D).

244 The topset clinoform setting is dominated by proximal offshore transition to lower 245 shoreface deposits, whereas the foreset setting is dominated by distal offshore 246 transition facies (Fig. 7). The bottomset clinoform setting dominantly consists of 247 bituminous to kerogenous fine to coarse-grained siltstone with phosphatic lenses and 248 laminae deposited in an offshore environment of deposition, and interbedded with 249 hemipelagites. The lateral distribution of sedimentary facies and inferred depositional 250 environments suggest that the upper rollover point of the clinoforms corresponds 251 approximately to the limits between proximal and distal offshore transition 252 (corresponding to the mean storm wave base), whereas the lower rollover point 253 would mark the change from offshore transition to offshore (basinward influence of 254 storm waves: Fig. 8). These observations support the interpretation of Montney 255 Spathian deposition on a shoreface to inner shelf setting comparable to the 256 morphology of muddy subaqueous deltas or shelf-prism clinoforms (Patruno et al, 257 2015). In this setting and with respect to the Montney, the transition between the 258 topset and the foreset of clinoforms does not correspond to a shoreline break but is 259 instead associated with pre-existing (Smithian) subaqueous topography and a change 260 in hydrodynamic processes of deposition and concomitant increase in sedimentation 261 rate. 262 In the foreset area, the vertical stacking pattern of sedimentary facies reflects an

263 overall progradation throughout the Spathian, with an upward increasing proportion

264 of proximal offshore transition or lower shoreface deposits, depending on location in

265	the basin (Figure 9). This progradation is punctuated by flooding surfaces demarcated
266	by a rapid and sustained shift in water deepening as observed in core by an
267	immediately overlying facies change to a relatively thick occurrence of offshore facies
268	composed of massive-appearing bituminous siltstones, occasionally associated with
269	calcispheric dolosiltstone of hemipelagic origin. However, calcispheric dolosiltstone
270	intervals are observed throughout the Spathian succession (see Fig. 4) and are not
271	necessarily associated with the flooding surfaces bounding parasequence sets
272	(highlighted by purple arrows on Fig. 9). Calcispheres in the Montney formation may
273	be the product of deposition associated with algal blooms (Chau and Henderson,
274	2010) or possibly dinoflagellate blooms (G. Davies, 2015, pers. comm.; Moslow et al,
275	2016). Given the frequency of these dolosiltstone beds (46 throughout the Spathian
276	succession in well c-65-F/94-B-08 for example) and the duration of the Spathian
277	interval (ca. 1.5 My; Henderson and Schoepfer, 2017), these intervals might reflect
278	obliquity and/or precession Milankovitch cycles (Henderson and Schoepfer, 2017).
279	In the topset area of the proximal part of the basin, the vertical stacking of offshore
280	sediments on top of shoreface deposits suggests a downlap surface (see well 04-16-
281	078-12W6, Fig. 9).

282 MAPPING OF THE PARASEQUENCE SETS

Figure 10 shows the isopach maps of the parasequence sets M3-1 through M3-4 at regional scale. These four lower Spathian units were selected to illustrate the depositional morphology of the clinoforms, because they were well preserved as opposed to the overlying units M3-5 to M3-7, that were extensively eroded under the top Montney unconformity, in the eastern proximal part of the study area. These

288	maps display the depositional thick of each unit (thickness>10m), that corresponds to
289	the foreset area of the clinoforms. The thickness of the parasequence sets in the
290	topset and bottomset areas typically is around 10m or less and increases up to over
291	60m in foreset areas. The width of the foreset area corresponds to the distance
292	between the upper and lower rollover points, and varies between 30 and 50km in the
293	dip direction. The thickness and the orientation of the foreset depositional thicks also
294	vary along strike as illustrated by the isopach maps (Fig. 10). Each unit presents two or
295	three depositional thick separated by thinner areas. A 330 km-long strike-oriented
296	NW-SE cross-section of the Montney Formation (Fig. 11), suggests that major
297	structural elements may have influenced these thickness variations (Berger et al.,
298	2008). The thinning of the Montney Formation over the Fort St. John Graben might
299	indicate that this structure was inverted during the deposition of the Montney
300	Formation. Another thinning of the Montney Formation occurs across a major fault
301	bounding the Laurier Embayment (Berger et al., 2008). Thinner areas generally
302	correspond to transition zones where the orientation of the clinoform changes. These
303	changes of orientation and thickness along strike suggest a regional structural control
304	on sedimentation and possibly the occurrence of tectonically-controlled localized
305	sediment sources.
306	These regional structural discontinuities may have influenced subsidence variations
307	across the basin and potentially controlled the location of sedimentary entry points

308 into the basin. Differential subsidence across the basin may be due to tectonic

309 movements and/or to differential compaction due to variable thickness of the pre-

310 Triassic sediment cover on top the basement (Rohais et al., this volume). Such a

311 structural control on sediment sources and transport directions have previously been

- 312 suggested in the Montney Formation (Davies et al., 1997; Moslow and Davies, 1997;
- 313 Zonneveld and Moslow, 2014; Davies and Hume, 2016).
- A compensation effect between units 3-1 and 3-2 due to depositional paleorelief is
- also suggested by a switch in the position of the thick areas (Fig. 10).

316 PALEOGEOGRAPHIC RECONSTRUCTION

317 Reconstructing the paleogeography of the Montney Formation during Spathian time is 318 impeded by the non-preservation of the coeval shoreline and nearshore deposits that 319 were eroded under the top Montney/base Doig unconformities, in the eastern 320 proximal part of the basin. However, analyzing the dimensions and depositional 321 environment of the Spathian clinoforms and comparing them to ancient or recent 322 analogues, can provide useful information to better understand the physiography of 323 the basin at the time of deposition. The facies analysis of the Spathian clinoforms 324 suggests that the upper rollover point between the topset and the foreset occurs 325 within or close to the mean storm-weather wave base, typically at 15 to 40 m of 326 water depth (Coe et al 2006).

The non-preservation of Spathian coastal deposits implies that the coastline was located eastward from the present-day subcrop edge of the Spathian. Based on a comparative analysis of morphological parameters from over a hundred clinoform systems, Partuno et al (2015) highlighted a strong correlation between the distance from the shoreline to the clinoform toe point (Hd) and the width of the foreset (Fd) (see Fig. 5 and Fig. 14D in Patruno et al., 2015). The comparison of the width of the foreset mapped in the Spathian deposits (30 to 50 km, see **figure 10**) with subaqueous

clinofrom analogues, suggests a distance between the shoreline and the clinoform
toeset (Hd) in the range of 90 to 150 km.

336	Based on the above considerations, Figure 12 illustrates a schematic paleogeographic
337	reconstruction of the lower Spathian depositional system. On this map, the bottomset
338	offshore region in dark blue represents an organic-rich area during the deposition of
339	the lower units of the Spathian (Crombez et al., 2016b). The foreset, offshore
340	transition to offshore region in medium blue corresponds to the area where thick
341	bioturbated siltstone reservoirs were deposited during the Lower Spathian (Moslow
342	et al., 2016). The topset, offshore transition to lower shoreface region corresponds to
343	the area where the Spathian deposits thin both depositionally and erosionally,
344	preventing the development of thick Spathian reservoirs.

345 STRATIGRAPHIC ARCHITECTURE OF THE SPATHIAN DEPOSITS

346 A sequence stratigraphic interpretation of the Montney Spathian succession was

- 347 proposed by Davies and Hume (2016), where a lowstand wedge onlaps on the basal
- 348 sequence boundary just eastward of the Alberta-BC border, and a highstand systems
- 349 tract (HST), corresponding to the "Lower Doig Siltstone" in Alberta, progrades
- 350 westward and downlaps onto the lowstand systems tract (LST). The lowstand wegde
- 351 thickens to the west, but their schematic cross-section does not extend beyond Range
- 352 17W6 (see Fig. 2 in Davies and Hume, 2016).
- 353 The correlation and mapping of the present study extends over about a hundred
- kilometer further downdip into the basin and shows that the lower Spathian
- 355 parasequence sets becomes thinner and organic-rich westwards in the bottomsets of
- 356 the clinoforms. Figure 13 illustrates the stratigraphic architecture of the Spathian

357	parasequence sets within the broader context of the Montney Formation, along five
358	dip-oriented schematic regional cross-sections throughout the basin, from Dawson to
359	Beg areas (datum at the base of the Doig Fm.). These cross-sections highlight the
360	onlap of the lower Spathian units to the west on the Smithian-Spathian sequence
361	boundary (Montney Sequence 3). The facies stacking patterns from core descriptions
362	(Moslow, 2016) and the overall aggradation of units M3-1 and M3-2 suggest that the
363	top of unit M3-2 might correspond to a 3rd order maximum flooding surface.
364	Alternatively, the apparent truncation of the units M3-3 and M3-4 to the west along
365	the Dawson cross-section (see Fig. 13) could tentatively be interpreted as associated
366	with a co-planar transgressive and maximum flooding surfaces, with internal downlap
367	onto this surface within the overlying unit M3-5. The vertical stacking of the of
368	offshore deposits on top of shoreface deposits in the proximal well 04-16-078-12W6
369	(see Fig. 9) might correspond to this downlap surface.
370	However, identifying this surface recording the maximum landward migration of the
371	shoreline, remains challenging because the coastal deposits to the east were not
372	preserved due to erosion under the basal Doig unconformity. A more detailed analysis
373	with additional core control along dip-oriented regional cross-sections would be
374	required to clearly identify at basin-scale the downlap surface corresponding to the
375	third-order maximum flooding surface of Montney sequence3.
376	Clinoform morphologies are well developed along the Dawson and Groundbirch cross-
377	section of Fig 13, but tend to be less well defined in the north, especially along the
378	northernmost cross-section in the Beg area. This may be related to the influence of an
379	additional sediment source to the north or northwest, perpendicular to this cross-
380	section. Another striking feature of the northern cross-sections on Fig. 13 is the

381 overall thinning of the Spathian succession to the far west. This may be an artefact

382 created by the use a datum that was a basinward dipping surface at the time of

deposition. Alternatively, it might be interpreted as resulting from uplift and erosion

- to the west, below the base Doig unconformity (Rohais et al., 2017; this volume).
- 385 IMPLICATIONS FOR THE MONTNEY PLAY
- 386 The reconstruction of the internal architecture of the Spathian succession and the

387 mapping of parasequence sets provide a framework to better predict the distribution

388 of source-rock and reservoir intervals at regional scale in the upper part of the

389 Montney play in northeastern British Columbia and west-central Alberta.

390 The bottomsets of the clinoforms identified in the lower part of the Spathian

391 succession correspond to condensed intervals with present day TOC values typically

up to 4-7 wt% (Crombez et al., 2016b). The bottomset region (Fig. 12) is in the deep

393 overmature part of the basin, preventing the characterization of this source-rock in its

394 early stage of maturation. Assuming an initial hydrogen index of 450 mg HC/g TOC,

the initial TOC of these organic-rich deposits would have been in the range of 5-10

396 wt% (Crombez et al., 2016b). Together with the Doig 'Phosphatic Member', these

397 offshore Spathian deposits are potentially a significant source of hydrocarbons for the

398 distal Montney play.

The foreset of the clinoforms up-dip from the offshore region are characterized by thicker offshore transition facies of burrowed, crypto-bioturbated, parallel laminated to lenticular bedded fine- to coarse-grained bituminous siltstone. The macro-scale burrowing and crypto-bioturbation in these foreset siltstones preserve intergranular porosity by inhibiting the precipitation of calcite cement and enhancing vertical

404	permeability (Moslow et al., 2014). The upper Spathian to lower Anisian units
405	prograde over the offshore region of the lower Spathian units, superimposing higher
406	net to gross offshore transition deposits on top of organic-rich lower Spathian
407	organic-rich siltstones. These thick reservoir intervals are stratigraphically located
408	between two source-rock intervals, with the Spathian bottomset offshore deposits
409	below and the Doig 'Phosphatic Member' above them. The bottomsets of these upper
410	Spathian clinoforms probably consisted of organic-rich sediments deposited further
411	west, but that are now part of the Canadian Cordillera.
412	The extensive flooding surfaces bounding the parasequence sets are associated
413	regionally continuous metric to plurimetric massive siltstone layers with lower
414	permeability (Euzen et al., 2015; 2017). These intervals may have hindered crossflow
415	between the Spathian parasequence sets and controlled up-dip fluid migration during
416	the burial history of the Montney Formation (Wood, 2013). The reservoir quality and
417	geomechanical properties of the foreset bioturbated siltstone may also vary from one
418	unit to the other, due to changes in sediment source dynamics and/or paleo-
419	ecological parameters through time. Chemostratigraphic differences between the
420	Spathian parasequence sets support this hypothesis (Chemostrat unpublished report,
421	2011). Consequently, each parasequence set may have unique production
422	characteristics associated with specific reservoir properties and migration history.

CONCLUSIONS

425	Thanks to a wealth of new well data resulting from the recent development of the
426	distal unconventional part of the Montney play, it is now possible to decipher the
427	internal stratigraphic architecture of the Spathian deposits at basin scale. Based on
428	over 1,450 wells, this paper presents the correlation of seven parasequence sets and
429	mapping of four of them that were preserved from the topset to the bottomset of the
430	clinoforms. The regional distribution of these internal units, combined with core
431	descriptions and facies analysis, provide the basis for the reconstruction of the
432	stratigraphic architecture and paleogeography of the Montney Formation during
433	Spathian time. Implications for the Montney play are discussed in terms of source-
434	rock, reservoir and seal distributions.
435	The parasequence sets of the Spathian succession are bounded by extensive flooding
436	surfaces that clearly define clinoform morphologies. The dimensions of these
437	depositional geometries compared with present day and ancient analogues, as well as
438	the facies analysis from core descriptions, suggest that they correspond to
439	subaqueous delta or shelf-prism clinoforms. The foreset of these clinoforms form
440	depositional thicks dominated by bioturbated siltstone deposited in offshore
441	transition settings. These foresets thin downdip to form organic-rich bottomsets
442	deposited in the offshore environment. The lateral, along-strike variations of
443	thickness and orientation of the depositional thick of parasequence sets suggest
444	differential subsidence across the basin, associated with syn-sedimentary tectonic
445	movements and/or differential compaction of the pre-Triassic sedimentary cover.
446	Major structural elements such as the Fort St. John Graben and the Laurier

447 Embayment may also have controlled the location of sedimentary entry points into448 the basin.

449	Our model provides a stratigraphic framework to better predict the distribution of
450	source-rocks and reservoirs in the Montney Spathian deposits. Bottomsets of the
451	Spathian clinoforms are good potential source rocks for hydrocarbons in the Montney
452	play and were deposited in the western deep and now overmature part of the basin.
453	Individual parasequence sets may have specific reservoir characteristics resulting from
454	variations in sediment source dynamics and/or paleo-ecological conditions.
455	Furthermore, the extensive flooding surfaces bounding the parasequence sets may
456	have acted as regional permeability barriers and influenced the distribution of fluids
457	within the Spathian deposits. These depositional heterogeneities can therefore result
458	in variable production characteristics between different parasequence sets. To
459	validate this model and better understand the depositional controls on Montney
460	productivity at basin-scale, a statistical analysis of normalized well production within
461	the stratigraphic framework developed in this work is now possible.

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681	Figure 1: Stratigraphic Chart of the Montney Formation (Embry and Gibson, 1995;
682	Davies et al., 1997; Golding et al., 2014; Crombez et al., 2016a and 2016b; Davies
683	and Hume, 2016; Moslow et al., 2016, Henderson and Schoepfer, 2017). A.W.:
684	'Anisian Wedge'; D.P.: Doig 'Phosphatic Member'; Wavy red line: angular
685	unconformity.
686	Figure 2: Location map of the database wells used in this study and selected cores
687	illustrated in figures 3, 4, 6, 7 and 9. Oil and gas fields cited in this paper are also
688	shown.
689	Figure 3: Core and log expression of Spathian flooding surfaces from well a-94-J/94-
690	A-13. Note the consistency between the total Gamma Ray curve and the Uranium
691	concentration measured from core. See Fig. 7 for legend of lithology and
692	depositional environments.
693	Figure 4: Core and log expression of Spathian flooding surfaces from well d-97-C/94-
694	G-7. Note that most of the low API value Gamma Ray log spikes correspond to
695	dolosiltstone intervals. See Fig. 7 for legend of lithology and depositional beds.
696	Figure 5: Internal stratigraphic architecture of the Spathian deposits along six
697	depositional dip-oriented regional cross-sections. Logs are Gamma Ray curves and
698	vertical bars indicate cored intervals.
699	Figure 6: Representative core photos of depositional facies. A - Lower shoreface:
700	sharp based, normally graded, planar laminated, silty very-fine grained sandstone
701	bed in middle of photograph (brackets) is inferred to be the product of upper flow

702	regime transport and a waning of flow by a storm generated current, thus
703	interpreted to be a tempestite. Note <u>Bergaueria</u> burrow traces at top of the bed
704	(arrows). Tempestite bed is overlain and underlain by densely burrowed to
705	bioturbated coarse -grained siltstones. Core diameter is 10cm. B - Offshore
706	Transition: planar -to low relief ripple - laminated coarse-grained siltstone. Note
707	lateral discontinuity in planar laminations (ellipse) possibly due to crypto-
708	bioturbation; also note minor degree of load-casting at base of lenticular bed
709	(arrow). Core diameter is 7.5cm. C – Offshore: Massive - appearing to faintly parallel
710	laminated highly bituminous to kerogenous fine-to medium- grained siltstone.
711	Sedimentation is a product of suspension deposition seaward of mean storm-
712	weather wave base. Core diameter is 7.5cm. D – Hemipelagite: laminated calcite-
713	cemented bioclastic dolosiltstone; bioclasts occur as 0.5-1.0mm calcispheres
714	(dinoflagellates?); note inverse grading from base of bed (arrow) and increase in the
715	carbonate/clastic ratio upwards. Core diameter is 7.5cm.
716	Figure 7: Core descriptions and interpretation of the main sedimentary facies
717	associations observed in the Spathian deposits displaying the lateral facies
718	heterogeneity observed within individual parasequence sets (see Fig. 2 for the
719	location of wells). a) Topset setting (proximal offshore transition to lower
720	shoreface); b) Foreset setting (distal offshore transition to offshore); c) Bottomset
721	setting (Offshore).
722	Figure 8: Diagram illustrating the depositional environments and paleobathymetric

723 relief of clinoforms in the lower part of the Spathian.

724	Figure 9: Vertical stacking pattern of facies and depositional environments based on
725	sedimentologic description of full diameter core (Moslow et al., this volume) and
726	calibration to gamma ray log signature of the Spathian interval from three wells in
727	the study area. Wells are arranged in proximal to distal setting from right to left.
728	Purple arrows on the right side of each well highlight the occurrence of
729	hemipelagite dolosiltstone beds. Pie charts quantify the vertical and lateral
730	gradation of facies and depositional environments for individual parasequence sets.
731	Note volumetric increase in shallow water facies upwards inferring a progradational
732	trend in the Spathian.
733	Figure 10: Regional isopach maps of parasequence sets M3-1 to M3-4. The maps
734	only highlight the areas where thickness exceeds 10 m, which corresponds roughly
735	to the foreset area of each unit.
736	Figure 11: Regional strike-oriented 330 km-long cross-section of the Montney
737	Formation, with Spathian internal units. Wireline logs are are Gamma Ray curves.
738	Insert map shows major structural elements from Berger et al. (2008).
739	Figure 12: Paleogeographic reconstruction of the depositional environment during
740	lower Spathian times.
741	Figure 13: Five regional dip-oriented cross-sections in west-central Alberta and
742	northeastern British Columbia illustrating the internal stratigraphic architecture of
743	the Montney Formation and Spathian internal units at regional scale.

Series	Stages/Subsages		Formations	Third-order Sequences (Crombez et al 2016b)
iddle Triassic	Anisian		D.P.	Sequence 4
Σ			A.W.	$\sim\sim\sim\sim\sim\sim\sim$
	ekian	Spathian	lontney	Sequence 3 (M3)
er Triassic	Olen	Smithian		Sequence 2 (M2)
Lowe	Dienerian Dienerian Dienerian	Sequence 1 (M1)		
srmian			3elloy	~~~~~~
۲ A				



----- Core Gamma Ray (UG)



1652.10

1640.10





1747.71











SW

NE









a-94-J/94-A-13

Bottomset setting facies association

c-65-F/94-B-08 Foreset setting facies association

Topset setting facies association





Bituminous F-M Siltstone

(massive appearing to faintly parallel laminated)



Calcareous, Calcispheric Dolosiltstone



Sandy F-C Siltstone

(rippled, planar laminated, wavy bedded; macro-scale burrowing)

F-C Siltstone

(planar laminated, lenticular bedded, burrowed to cryptobioturbated)

- LS: Lower Shoreface
- OTP: Proximal Offshore Transition
- OT_D: Distal Offshore Transition
- O: Offshore
- H: Hemipelagite











