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► **To cite this version:**

Tristan Euzen, Thomas F. Moslow, Vincent Crombez, Sébastien Rohais. Regional Stratigraphic Architecture of the Spathian Deposits in Western Canada – Implications for the Montney Resource Play. Bulletin of Canadian Petroleum Geology, 2018, 66 (1), pp.175-192. hal-02196715

HAL Id: hal-02196715

<https://ifp.hal.science/hal-02196715>

Submitted on 29 Jul 2019

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1 **Regional Stratigraphic Architecture of the Spathian Deposits in**

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.

55

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 Olenekian (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,

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.

100

DATA AND METHOD

101

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 Elsworth
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

141 The Spathian deposits correspond to the third and youngest 3rd-order sequence of the
142 Montney Formation. This sequence is bounded below by a sequence boundary
143 corresponding to the Smithian-Spathian unconformity and above by a coplanar
144 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 et 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

241 hemipelagite deposits, form 5 to 30 cm thick inversely graded beds and are observed
242 within the bottomset and foreset areas of the clinoforms, throughout the Spathian
243 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**

283 **Figure 10** shows the isopach maps of the parasequence sets M3-1 through M3-4 at
284 regional scale. These four lower Spathian units were selected to illustrate the
285 depositional morphology of the clinoforms, because they were well preserved as
286 opposed to the overlying units M3-5 to M3-7, that were extensively eroded under the
287 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).

314 A compensation effect between units 3-1 and 3-2 due to depositional paleorelief is
315 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).

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

334 clinofrom analogues, suggests a distance between the shoreline and the clinoform
335 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 wedge
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
354 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
383 deposition. Alternatively, it might be interpreted as resulting from uplift and erosion
384 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
392 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,
395 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.

399 The foreset of the clinoforms up-dip from the offshore region are characterized by
400 thicker offshore transition facies of burrowed, crypto-bioturbated, parallel laminated
401 to lenticular bedded fine- to coarse-grained bituminous siltstone. The macro-scale
402 burrowing and crypto-bioturbation in these foreset siltstones preserve intergranular
403 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 clinofolds 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.

423

424 **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 into
448 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 clinofolds 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.

462

ACKNOWLEDGEMENTS

463 The authors would like to acknowledge Progress Energy Canada Ltd. for authorizing
464 the use and publication of the core descriptions used in this manuscript. We also
465 thank Brad Hayes, Graham Davies and Mark Caplan for their constructive comments
466 and suggestions that helped improve the manuscript.

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679

680

FIGURE CAPTIONS

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 Bergaueria 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 clinofolds 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.

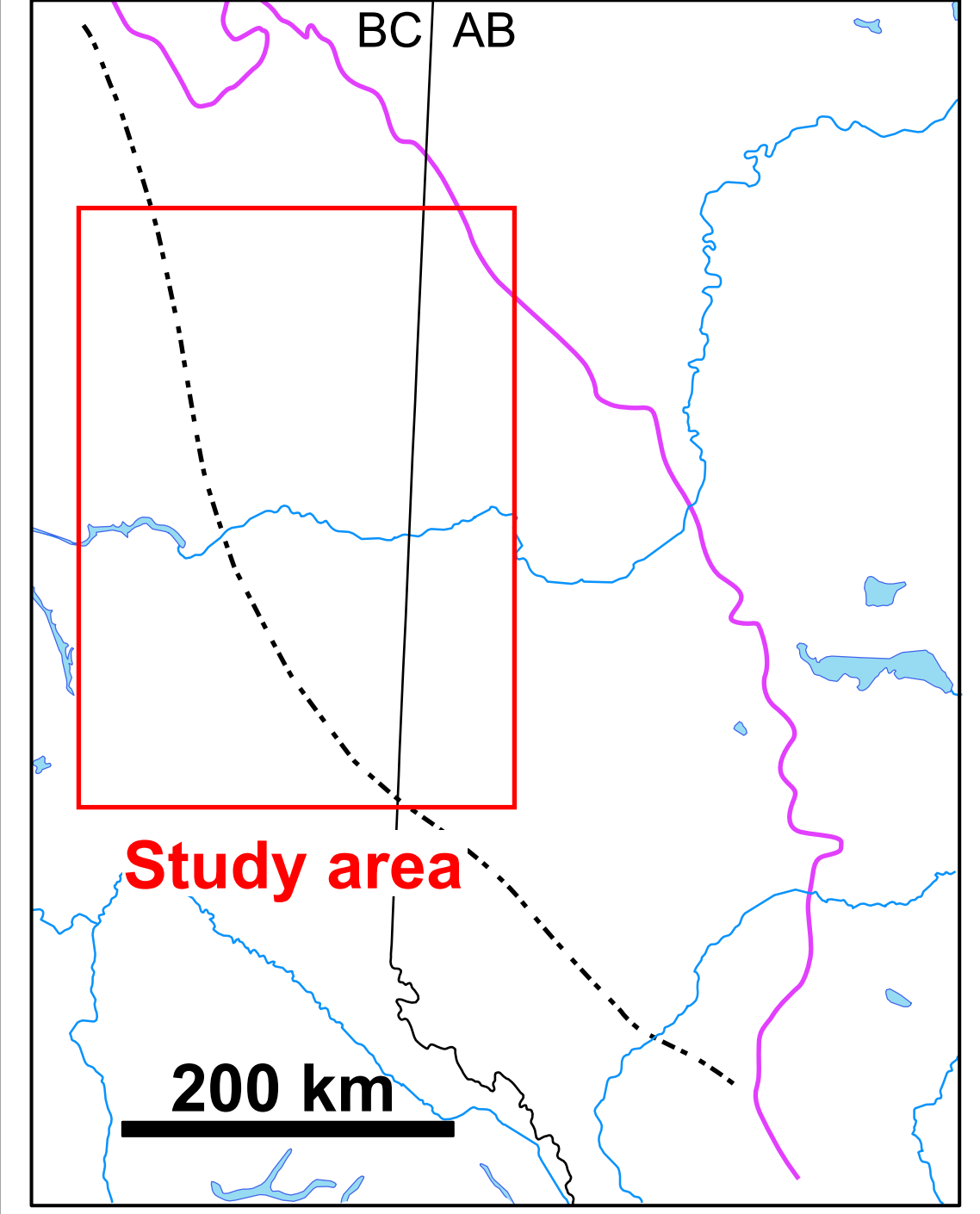
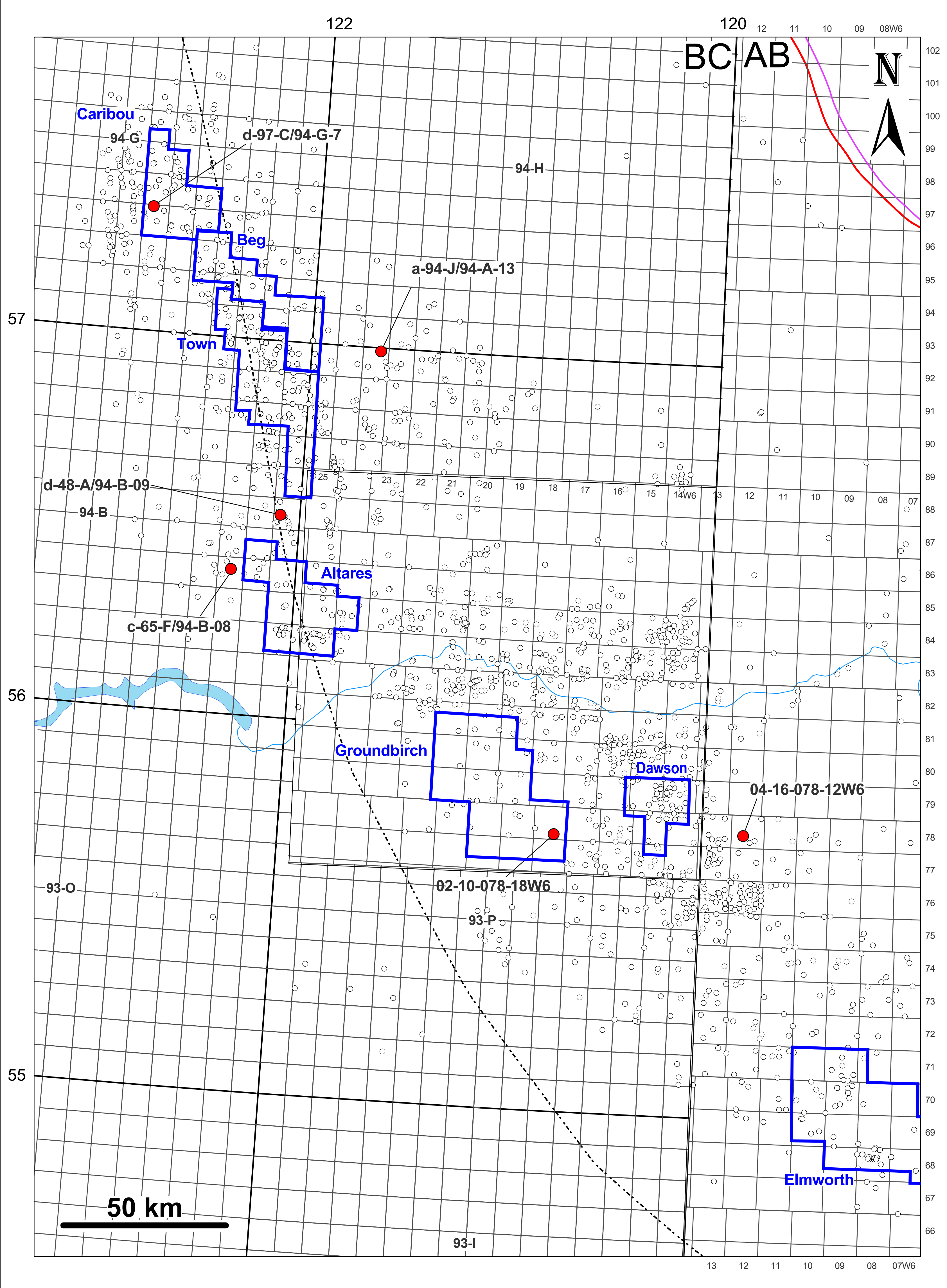
736 **Figure 11:** Regional strike-oriented 330 km-long cross-section of the Montney
737 Formation, with Spathian internal units. Wireline logs are are Gamma Ray curves.
738 Insert map shows major structural elements from Berger et al. (2008).

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)
Middle Triassic	Anisian	Doig	Sequence 4
Lower Triassic	Olenekian	Montney	Sequence 3 (M3)
			Smithian
	Induan		Sequence 1 (M1)
Permian	Changhsingian	Belloy	

D.P.
A.W.



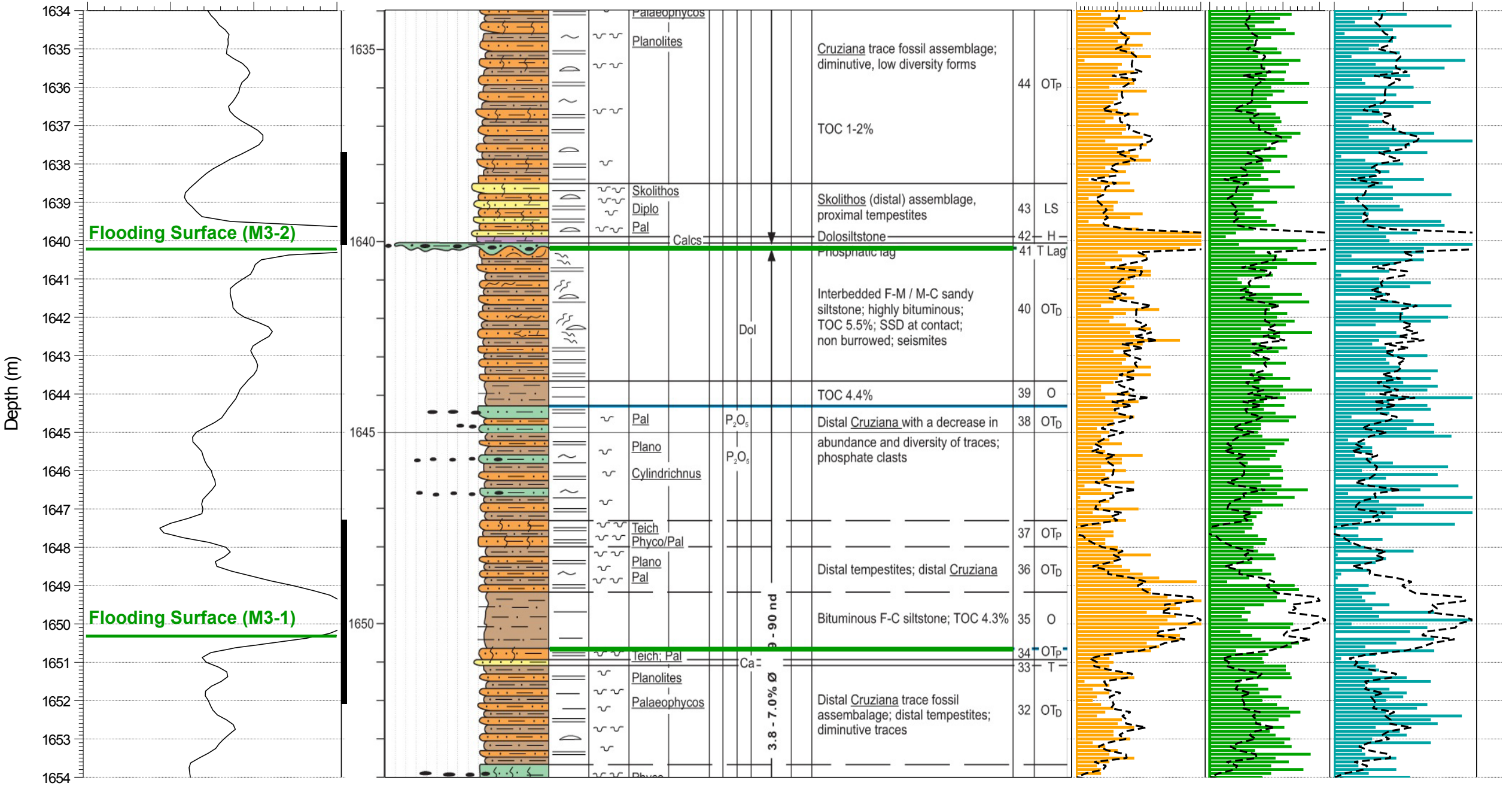
- Montney subcrop edge
- - - Cordillera deformation front
- Well data
- Core data
- Fields cited in this study

----- Core Gamma Ray (UG)

U-Core (ppm) K-Core (%) Th-Core (ppm)

Wireline Gamma Ray (API)

Core description



Bituminous siltstone (TOC=4.3%)



1647.30

Distal tempestites →



1652.10

50 cm

Proximal tempestites →

Dolosiltstone →

Phosphatic lag (M3-2) →

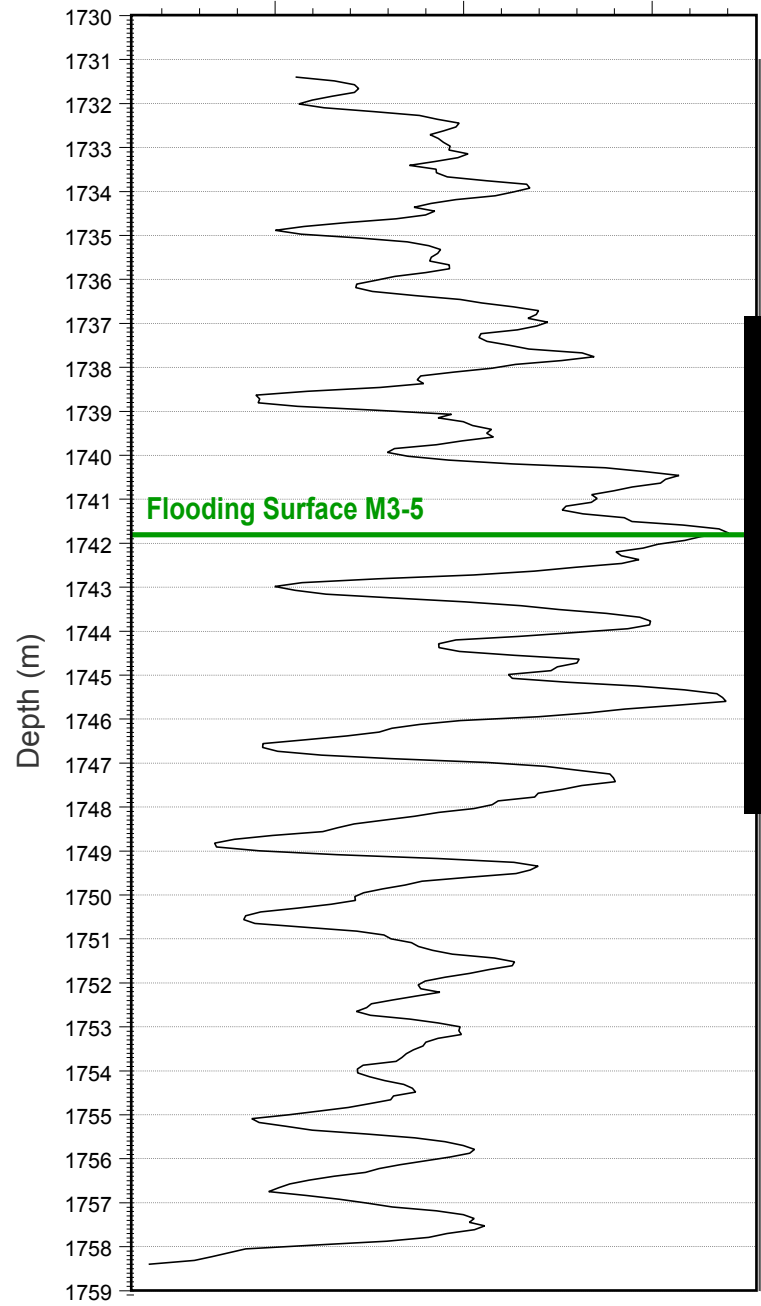


1640.10

Core Gamma Ray

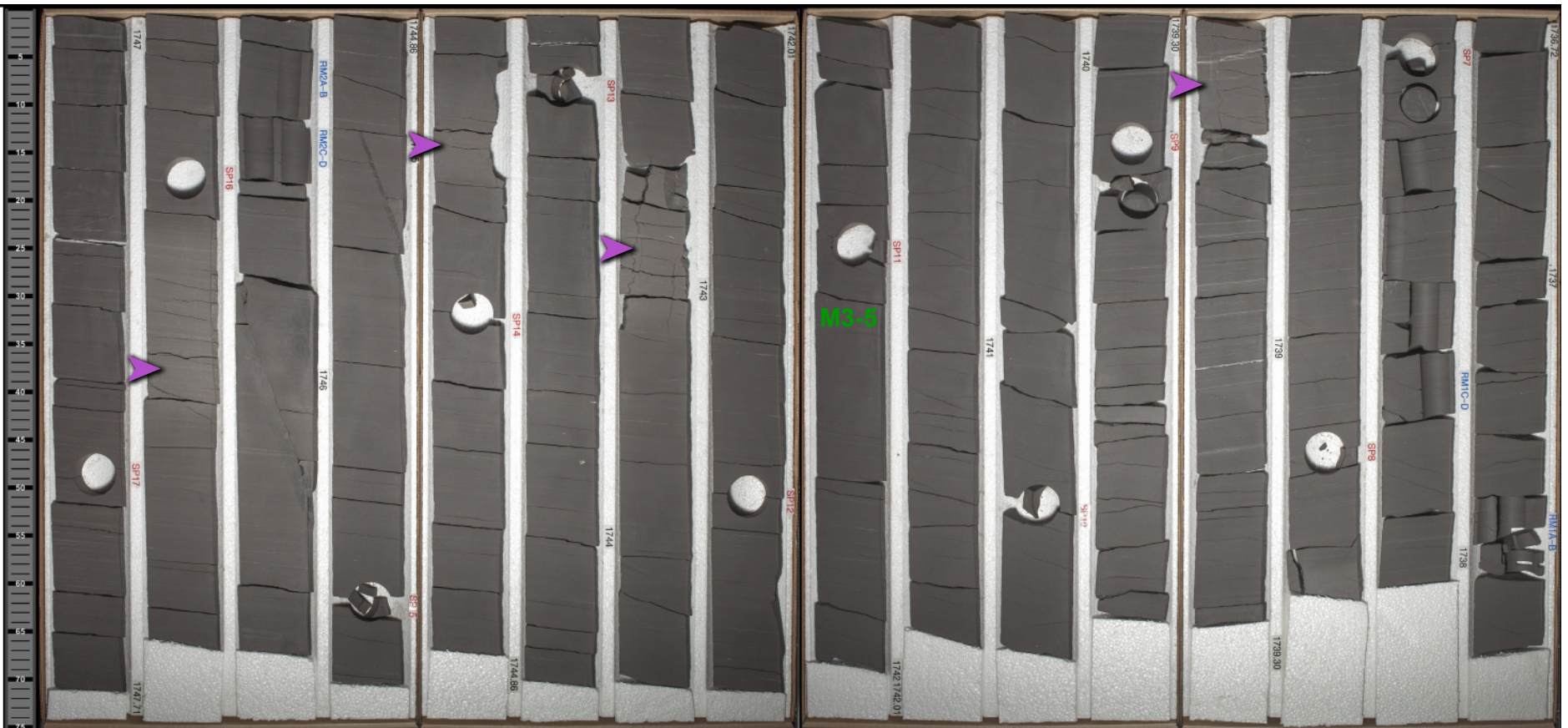
100 150 200

Core Description

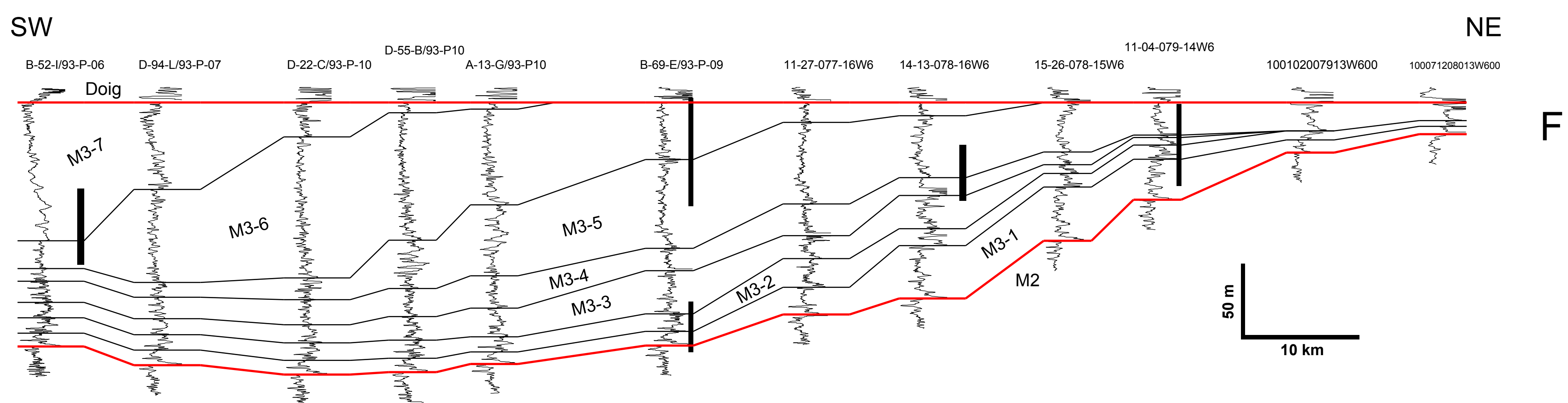
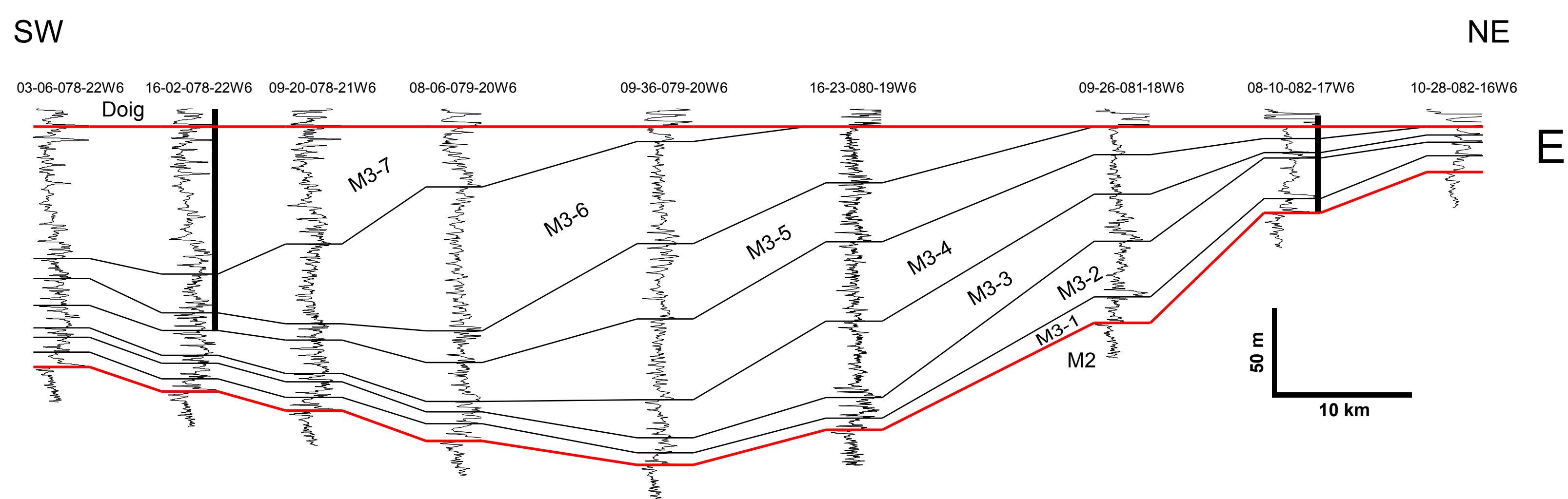
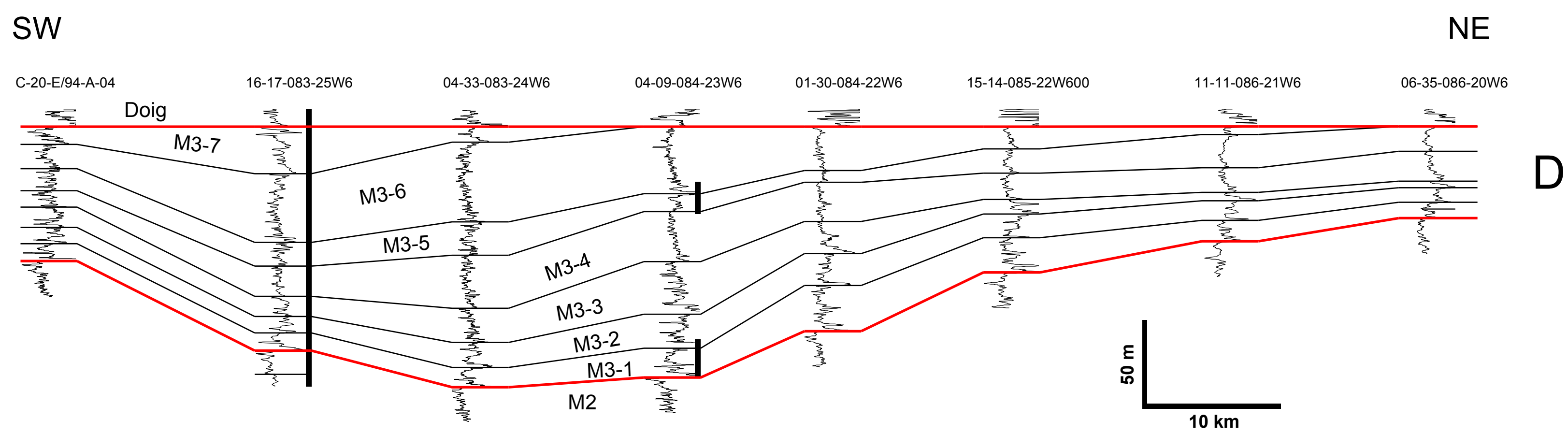
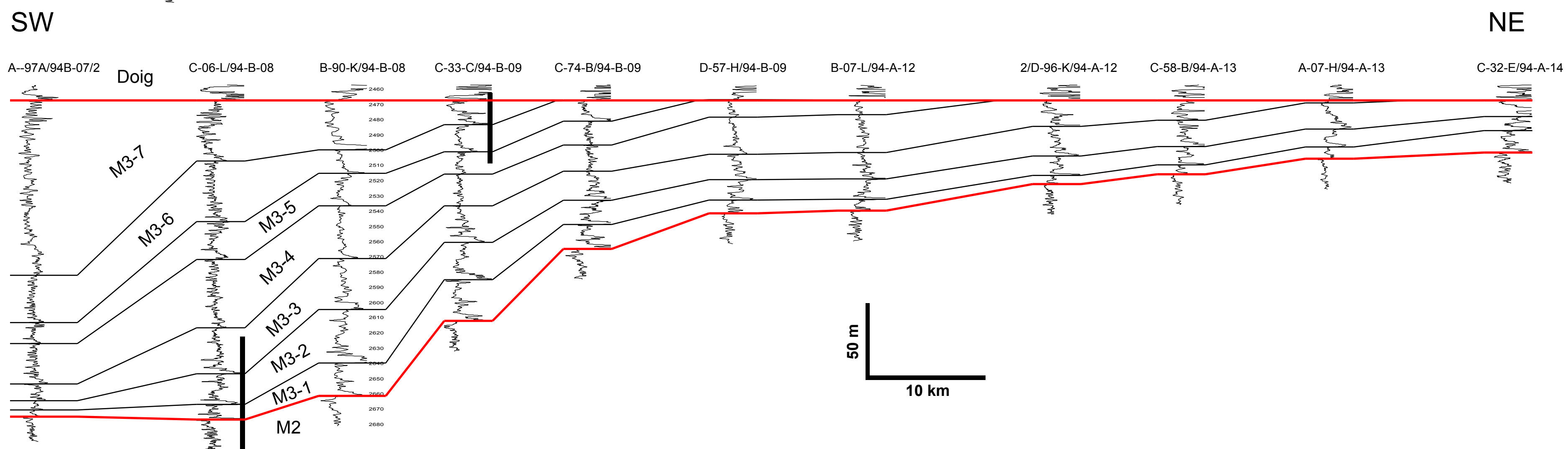
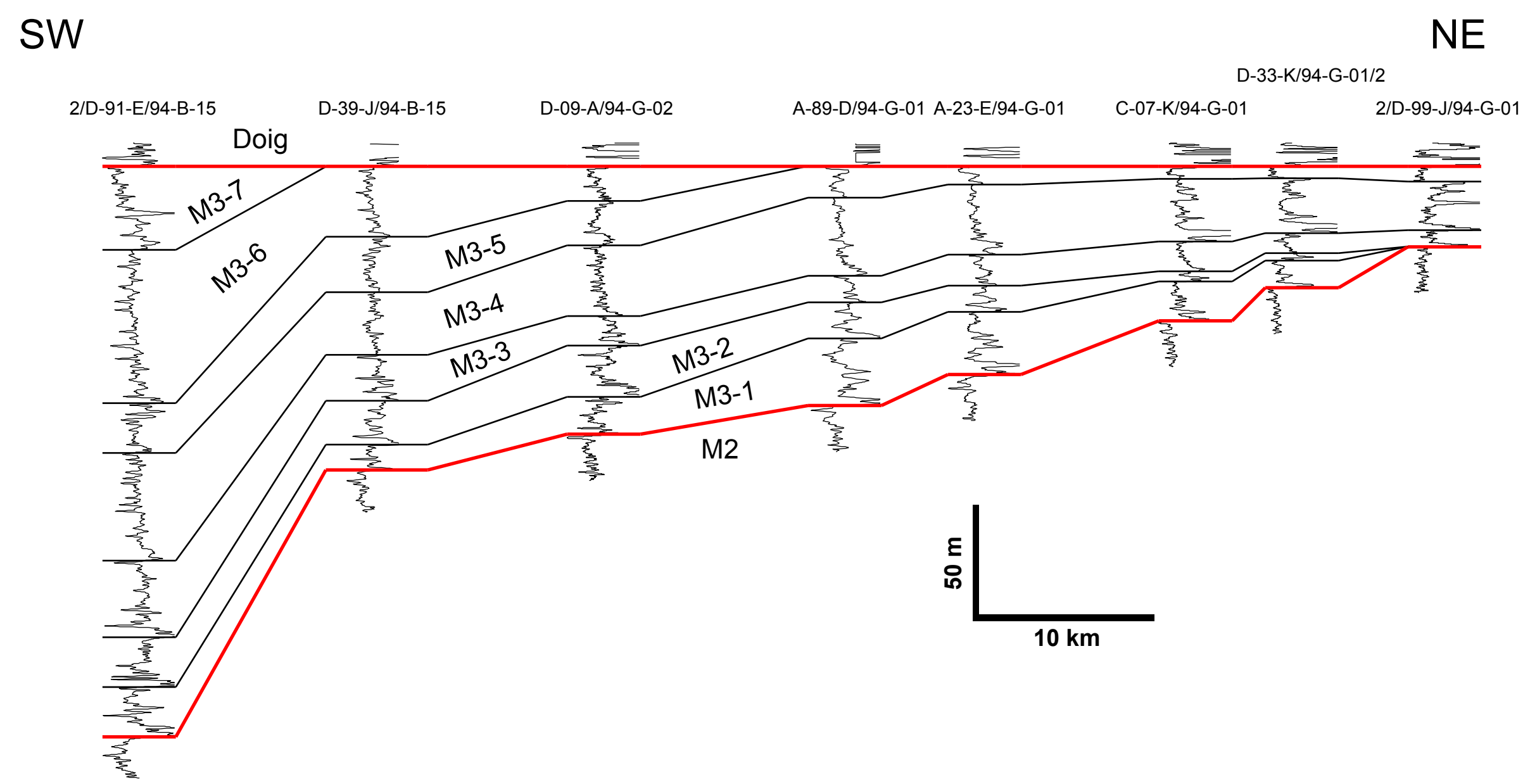
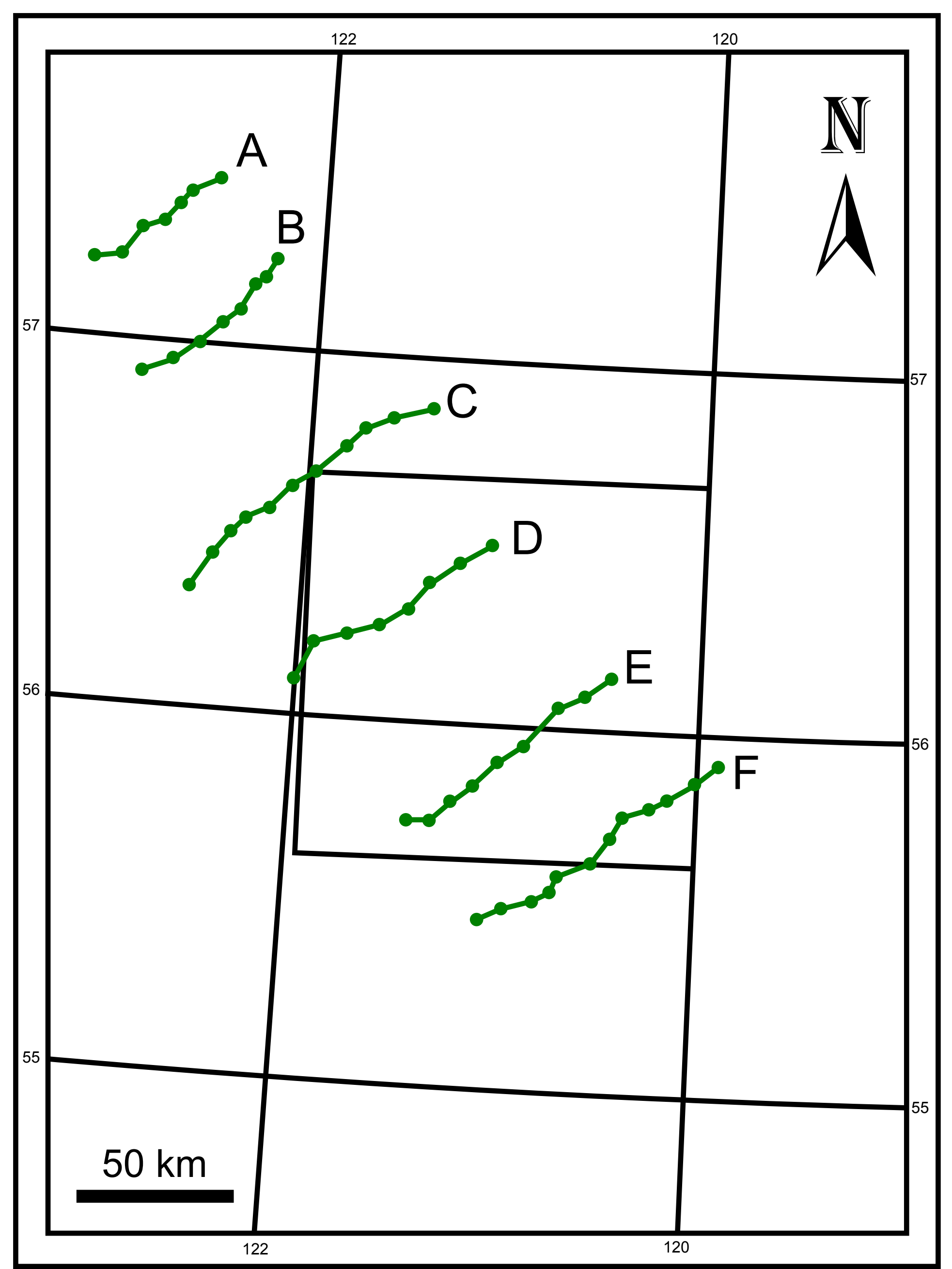
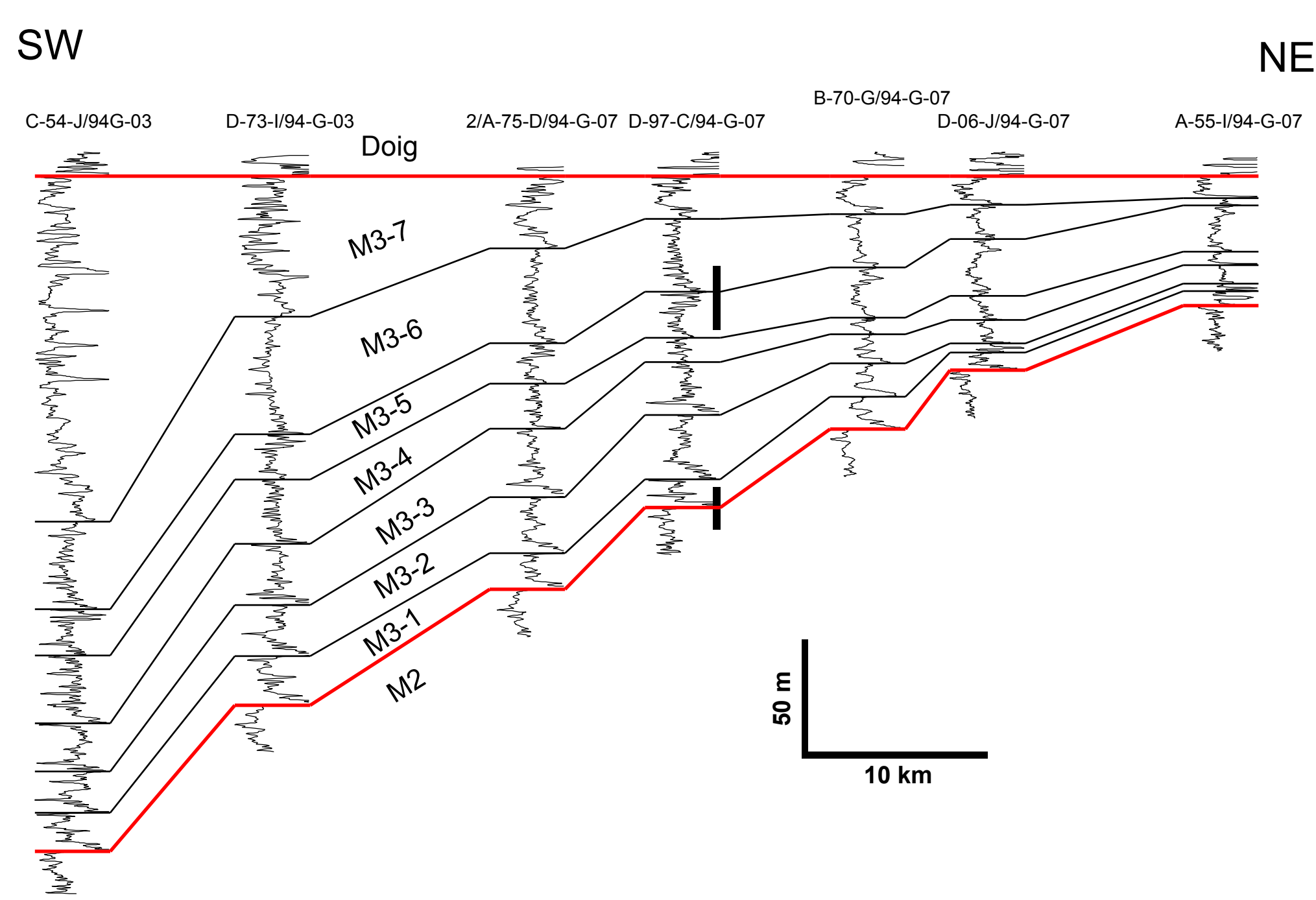


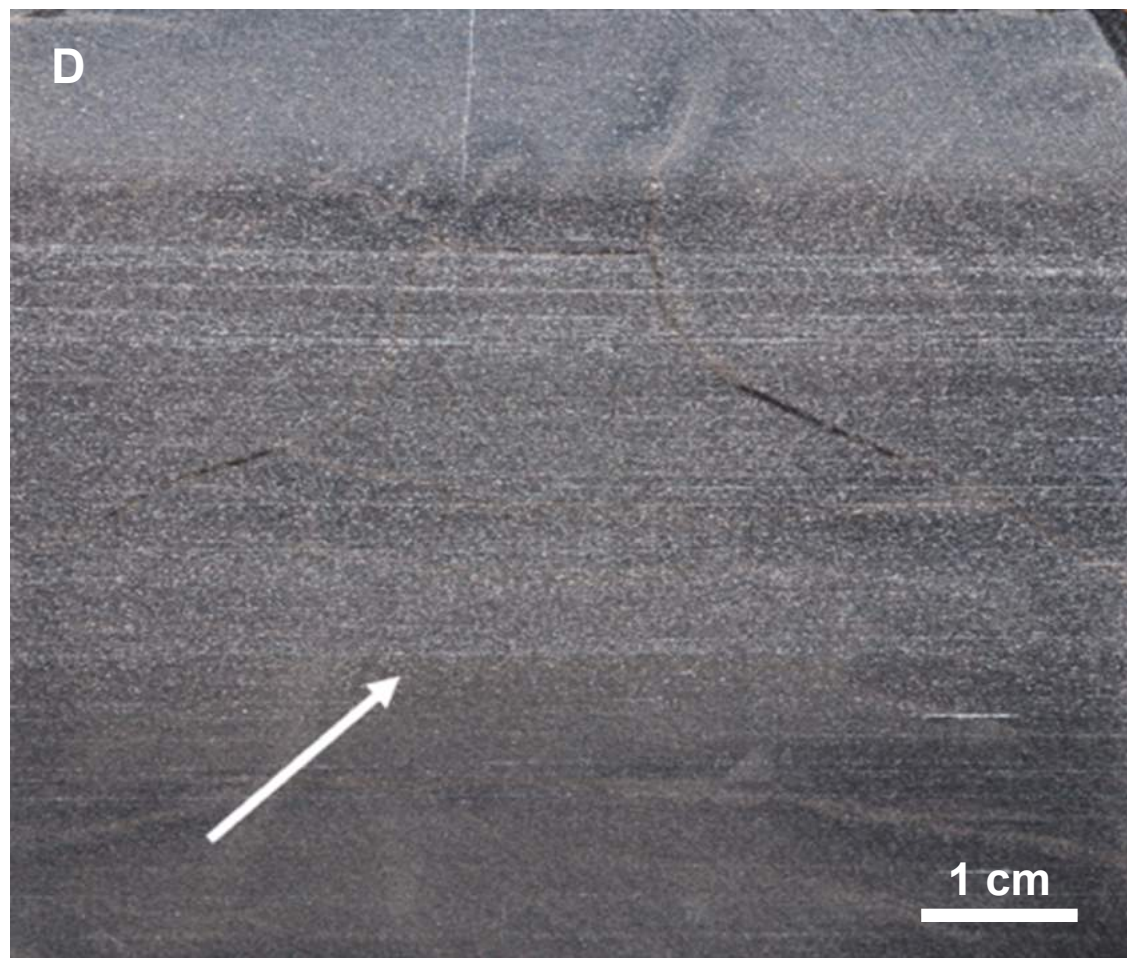
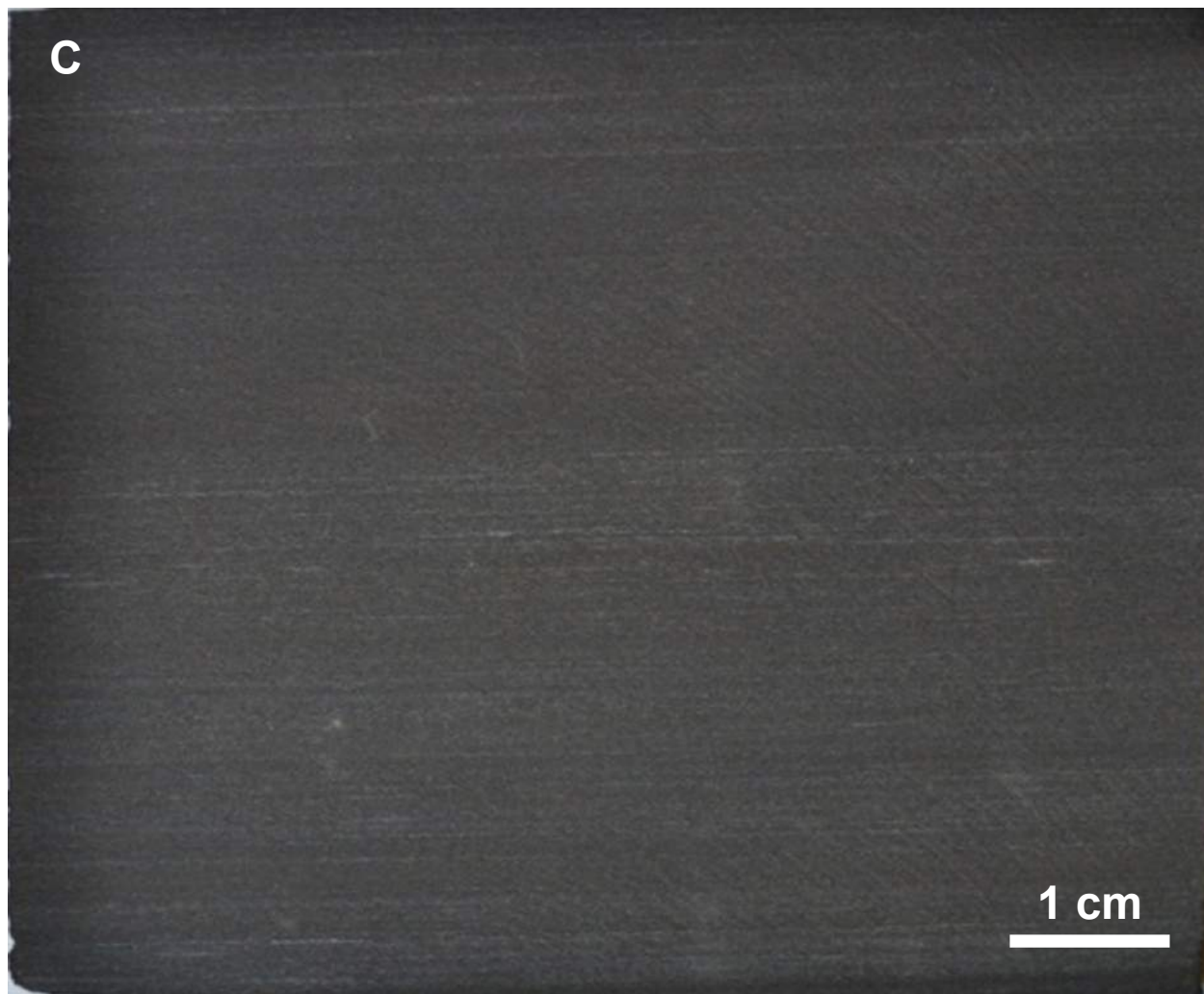
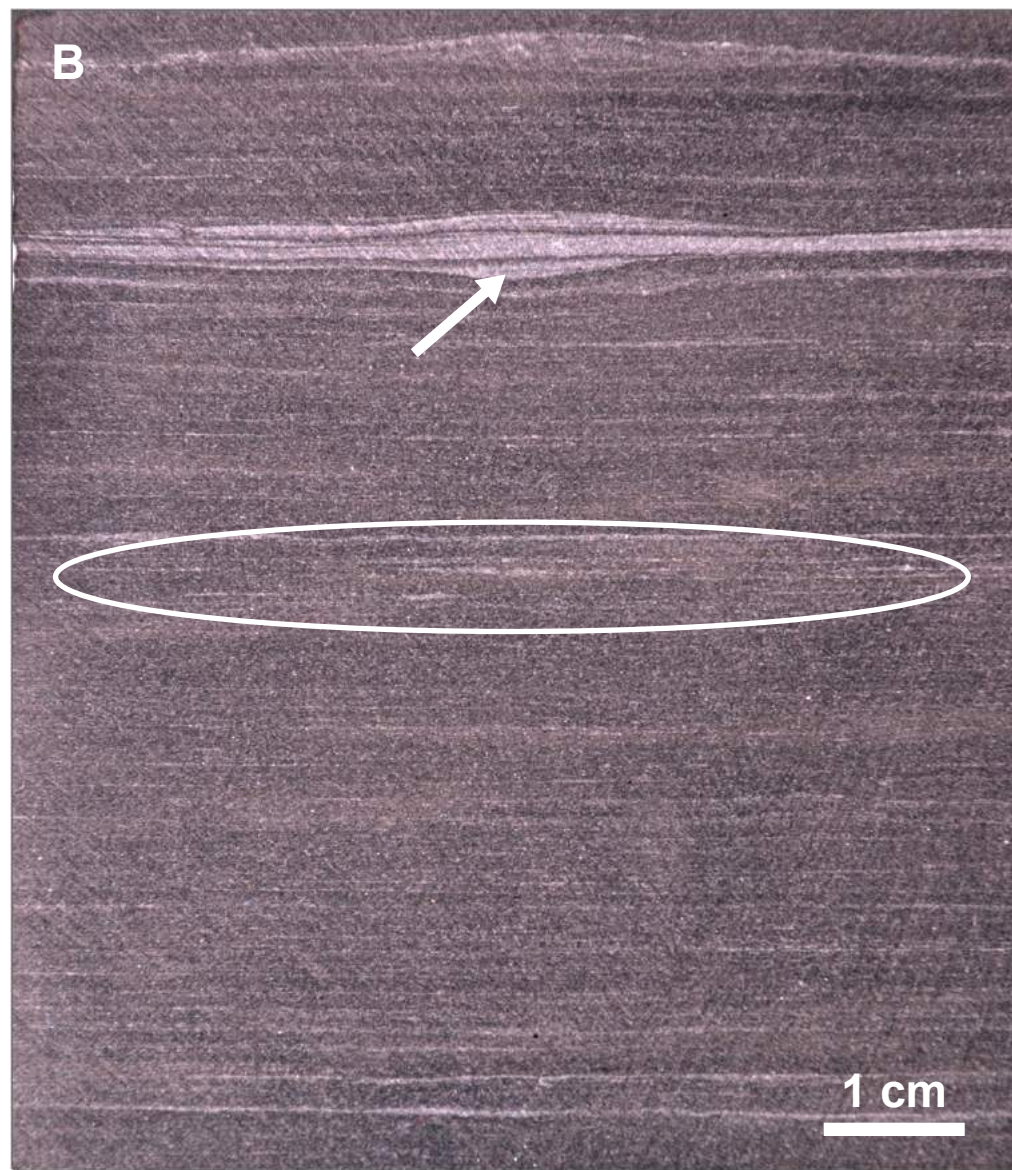
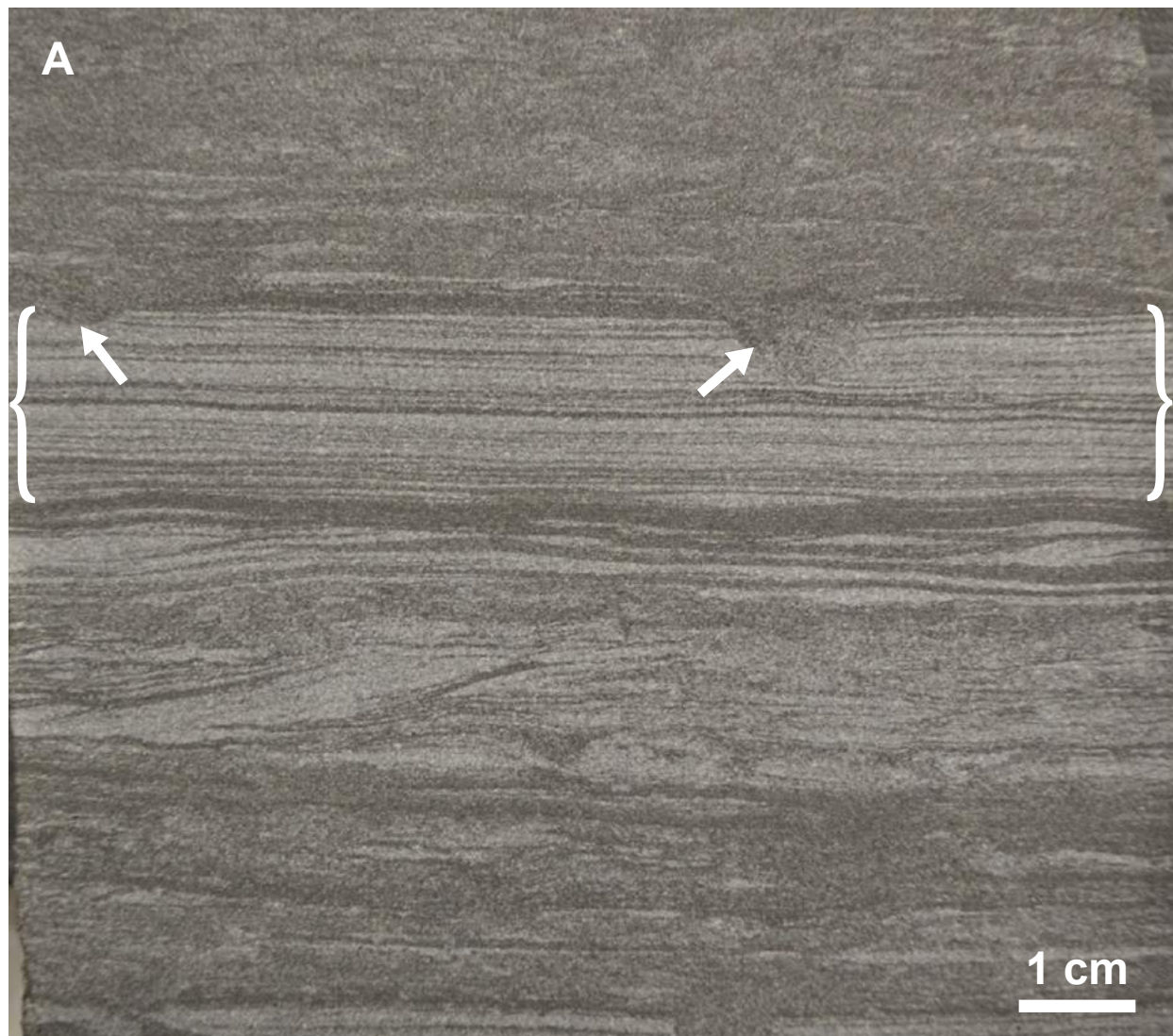
1731	Crypto	Ca	Horizontal fractures	28	OT _D
1732	Crypto	Ca		27	H
1733	Crypto/ Planolites?		Horizontal fractures (Ca)	25	OT _P
1734	Crypto			24	OT _D
1735	Calcs		Ca / bitumen fractures	23	H
1736	Crypto		Crypto coarse laminae	22	OT _D
1737					
1738					
1739	Crypto		Bitumen, Ca fractures	21	H
1740	Crypto			20	OT _P
1741			F-C bituminous siltstone	18	O
1742	Crypto		Coarse siltstone laminae crypto	17	OT _D
1743	Crypto	Ca	Ca, bitumen vertical fractures	16	H
1744	Crypto	Py/Ca	Pyrite replacement of clasts	15	OT _D
1745	Crypto	Ca	Dolosiltstone; bitumen free	14	H
1746		Ca	Two 20cm long Ca lined vertical fractures; 0-5cm offset in laminae	13	OT _D
1747	Calcs	Ca	Vertical Ca fracture	12	H
1748	Crypto	Ca	Crypto coarse siltstone laminae; horizontal fractures	11	OT _D
1749	Calcs	Ca	Bitumen fracture	10	H
1750	Calcs	Ca	Dolomitic F-C siltstone; coarse crypto laminae	9	OT _D
1751			Vertical fractures (bitumen) FD 3 and 4	8	H
1752	Crypto		Coarse siltstone laminae Crypto	7	OT _D
1753	Crypto	Ca*	Horizontal fracture breccia @ 1751.7m and 1751.3m (1-2cm)	6	OT _D
1754	Crypto		High angle fracture offset	5	OT _D
1755	Calcs		Cryptobioturbated coarse siltstone laminae	4	H
1756		Ca*	Bitumen vertical fractures	3	OT _D
1757	Crypto	Ca*	Horizontal fault breccia @ 1756.1m and 1755.5m (vuggy Ø)	2	OT _D
1758	Crypto		Cryptobioturbated coarse siltstone laminae; dolomitic	1	H
1759	Crypto	Calcspheres	Dolosiltstone; bitumen filled fractures		

1736.73



1747.71





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02-10-078-18W6

Bottomset setting facies association

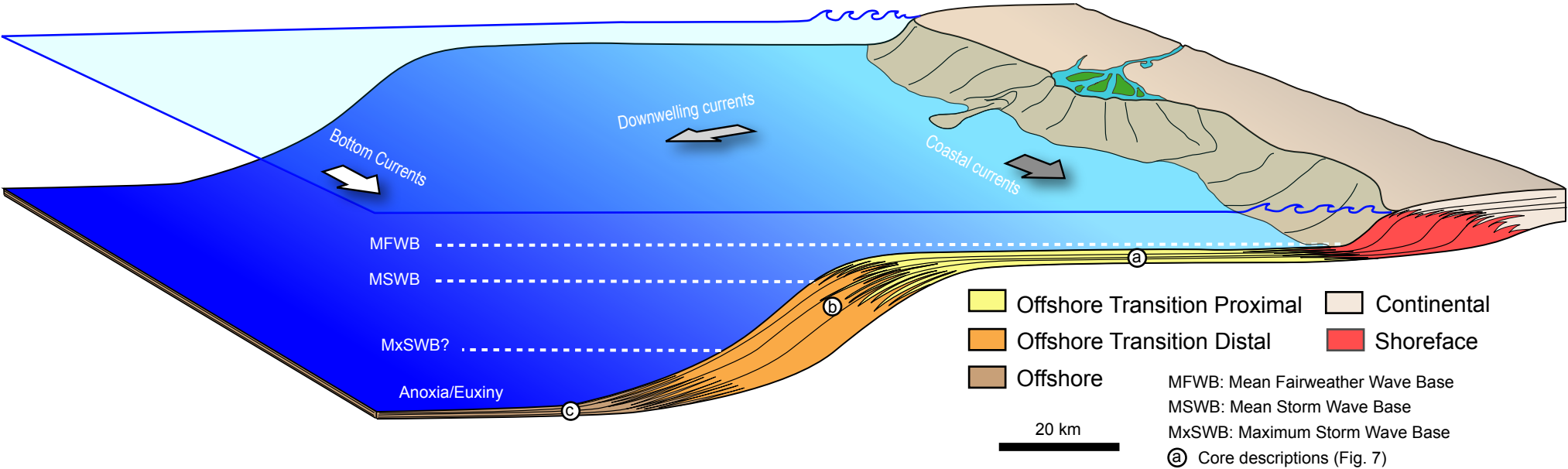
Depth (metres)	Lithology & Grain Size	Sed. Struct.		Burrow Traces	Organic Remains	Description	Sed. Unit	Environments
		Physical	Biogenic					
2730	Shale					Highly bituminous F-C siltstone; kerogenous laminae; pebble sized clasts of phosphate	O	
2725						Bituminous, parallel laminae to massive appearing	O	
2720						Highly bituminous F-C siltstone; kerogenous laminae; pebble sized clasts of phosphate	O	
2715						Dolosiltstone	H	
2710						Calcs	O	
2705						Calcs	H	
2700						Calcs	O	
2695						Calcs	H	
2690						Calcs	O	
2685						Calcs	H	
2680						Calcs	O	
2675						Calcs	H	
2670						Calcs	O	
2665						Calcs	H	
2660						Calcs	O	
2655						Calcs	H	
2650						Calcs	O	
2645						Calcs	H	
2640						Calcs	O	
2635						Calcs	H	
2630						Calcs	O	
2625						Calcs	H	
2620						Calcs	O	
2615						Calcs	H	
2610						Calcs	O	
2605						Calcs	H	
2600						Calcs	O	
2595						Calcs	H	
2590						Calcs	O	
2585						Calcs	H	
2580						Calcs	O	
2575						Calcs	H	
2570						Calcs	O	
2565						Calcs	H	
2560						Calcs	O	
2555						Calcs	H	
2550						Calcs	O	
2545						Calcs	H	
2540						Calcs	O	
2535						Calcs	H	
2530						Calcs	O	
2525						Calcs	H	
2520						Calcs	O	
2515						Calcs	H	
2510						Calcs	O	
2505						Calcs	H	
2500						Calcs	O	
2495						Calcs	H	
2490						Calcs	O	
2485						Calcs	H	
2480						Calcs	O	
2475						Calcs	H	
2470						Calcs	O	
2465						Calcs	H	
2460						Calcs	O	
2455						Calcs	H	
2450						Calcs	O	
2445						Calcs	H	
2440						Calcs	O	
2435						Calcs	H	
2430						Calcs	O	
2425						Calcs	H	
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2415						Calcs	H	
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2405						Calcs	H	
2400						Calcs	O	
2395						Calcs	H	
2390						Calcs	O	
2385						Calcs	H	
2380						Calcs	O	
2375						Calcs	H	
2370						Calcs	O	
2365						Calcs	H	
2360						Calcs	O	
2355						Calcs	H	
2350						Calcs	O	
2345						Calcs	H	
2340						Calcs	O	
2335						Calcs	H	
2330						Calcs	O	
2325						Calcs	H	
2320						Calcs	O	
2315						Calcs	H	
2310						Calcs	O	
2305						Calcs	H	

©

c-65-F/94-B-08

Foreset setting facies association

Depth (metres)	Lithology & Grain Size	Sed. Struct.		Burrow Traces	Organic Remains	Description	Sed. Unit	Environments
		Physical	Biogenic					
2305	Shale					Intensely, cryptobioturbated; F-C bituminous siltstone; conodonts @ 2305m	O _{T_D}	
2300						Crypto Calcs Dolosiltstone	O _{T_D}	
2295						Calcs Dolosiltstone	O _{T_D}	
2290						Calcs Dolosiltstone	O _{T_D}	
2285						Calcs Dolosiltstone	O _{T_D}	
2280						Calcs Dolosiltstone	O _{T_D}	
2275						Calcs Dolosiltstone	O _{T_D}	
2270						Calcs Dolosiltstone	O _{T_D}	
2265						Calcs Dolosiltstone	O _{T_D}	
2260						Calcs Dolosiltstone	O _{T_D}	
2255						Calcs Dolosiltstone	O _{T_D}	
2250						Calcs Dolosiltstone	O _{T_D}	
2245						Calcs Dolosiltstone	O _{T_D}	
2240						Calcs Dolosiltstone	O _{T_D}	
2235						Calcs Dolosiltstone	O _{T_D}	
2230						Calcs Dolosiltstone	O _{T_D}	
2225						Calcs Dolosiltstone	O _{T_D}	
2220						Calcs Dolosiltstone	O _{T_D}	
2215						Calcs Dolosiltstone	O _{T_D}	
2210						Calcs Dolosiltstone	O _{T_D}	
2205						Calcs Dolosiltstone	O _{T_D}	
2200						Calcs Dolosiltstone	O _{T_D}	
2195						Calcs Dolosiltstone	O _{T_D}	
2190						Calcs Dolosiltstone	O _{T_D}	
2185						Calcs Dolosiltstone	O _{T_D}	
2180						Calcs Dolosiltstone	O _{T_D}	
2175						Calcs Dolosiltstone	O _{T_D}	
2170						Calcs Dolosiltstone	O _{T_D}	
2165						Calcs Dolosiltstone	O _{T_D}	
2160						Calcs Dolosiltstone	O _{T_D}	
2155						Calcs Dolosiltstone	O _{T_D}	
2150						Calcs Dolosiltstone	O _{T_D}	
2145						Calcs Dolosiltstone	O _{T_D}	
2140						Calcs Dolosiltstone	O _{T_D}	
2135						Calcs Dolosiltstone	O _{T_D}	
2130						Calcs Dolosiltstone	O _{T_D}	
2125						Calcs Dolosiltstone	O _{T_D}	
2120						Calcs Dolosiltstone	O _{T_D}	
2115						Calcs Dolosiltstone	O _{T_D}	
2110						Calcs Dolosiltstone	O _{T_D}	
2105						Calcs Dolosiltstone	O _{T_D}	
2100						Calcs Dolosiltstone	O _{T_D}	
2095						Calcs Dolosiltstone	O _{T_D}	
2090						Calcs Dolosiltstone	O _{T_D}	
2085						Calcs Dolosiltstone	O _{T_D}	
2080						Calcs Dolosiltstone	O _{T_D}	
2075						Calcs Dolosiltstone	O _{T_D}	
2070						Calcs Dolosiltstone	O _{T_D}	
2065						Calcs Dolosiltstone	O _{T_D}	
2060						Calcs Dolosiltstone	O _{T_D}	
2055						Calcs Dolosiltstone	O _{T_D}	
2050						Calcs Dolosiltstone	O _{T_D}	
2045						Calcs Dolosiltstone	O _{T_D}	
2040						Calcs Dolosiltstone	O _{T_D}	
2035						Calcs Dolosiltstone	O _{T_D}	
2030						Calcs Dolosiltstone	O _{T_D}	
2025						Calcs Dolosiltstone	O _{T_D}	
2020						Calcs Dolosiltstone	O _{T_D}	
2015						Calcs Dolosiltstone	O _{T_D}	
2010						Calcs Dolosiltstone	O _{T_D}	
2005						Calcs Dolosiltstone	O _{T_D}	
2000						Calcs Dolosiltstone	O _{T_D}	
1995						Calcs Dolosiltstone	O _{T_D}	
1990						Calcs Dolosiltstone	O _{T_D}	
1985						Calcs Dolosiltstone	O _{T_D}	
1980						Calcs Dolosiltstone	O _{T_D}	
1975						Calcs Dolosiltstone	O _{T_D}	
1970						Calcs Dolosiltstone	O _{T_D}	
1965						Calcs Dolosiltstone	O _{T_D}	
1960						Calcs Dolosiltstone	O _{T_D}	
1955						Calcs Dolosiltstone	O _{T_D}	
1950						Calcs Dolosiltstone	O _{T_D}	
1945						Calcs Dolosiltstone	O _{T_D}	
1940						Calcs Dolosiltstone	O _{T_D}	
1935						Calcs Dolosiltstone	O _{T_D}	
1930						Calcs Dolosiltstone	O _{T_D}	
1925						Calcs Dolosiltstone	O _{T_D}	
1920						Calcs Dolosiltstone	O _{T_D}	
1915						Calcs Dolosiltstone	O _{T_D}	
1910						Calcs Dolosiltstone	O _{T_D}	
1905						Calcs Dolosiltstone	O _{T_D}	
1900						Calcs Dolosiltstone	O _{T_D}	
1895						Calcs Dolosiltstone	O _{T_D}	
1890						Calcs Dolosiltstone	O _{T_D}	
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1880						Calcs Dolosiltstone	O _{T_D}	

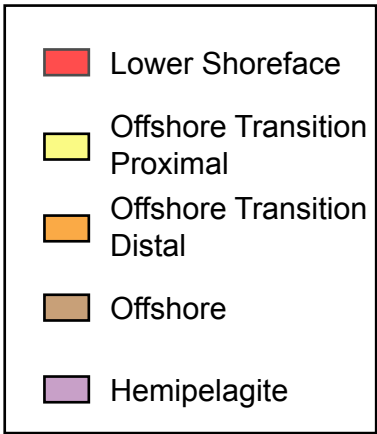
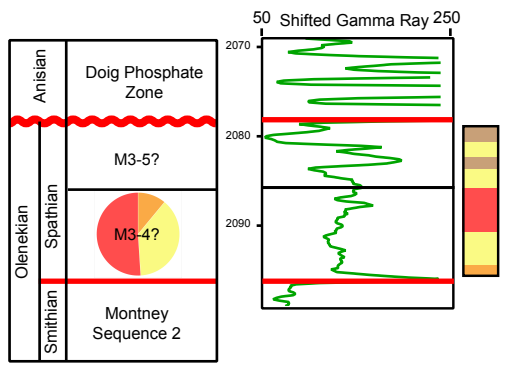
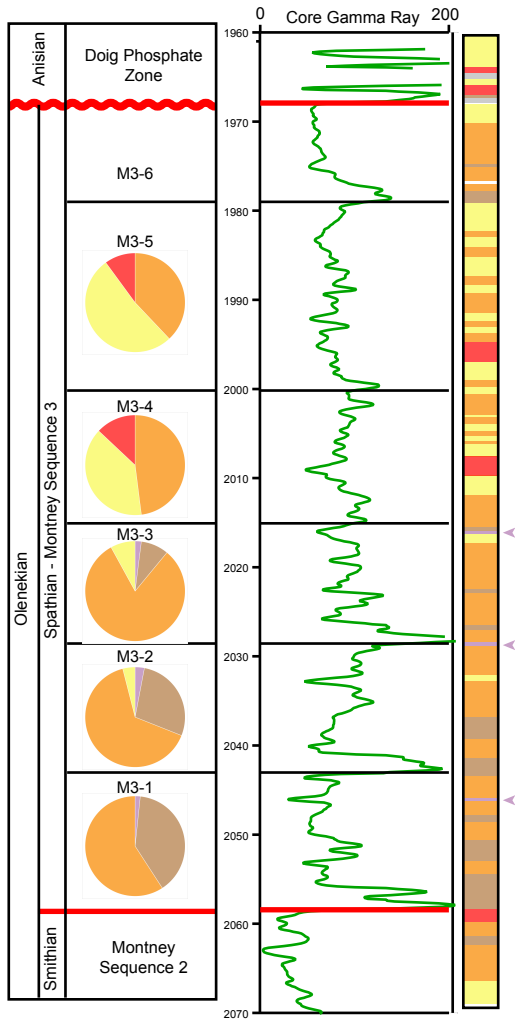
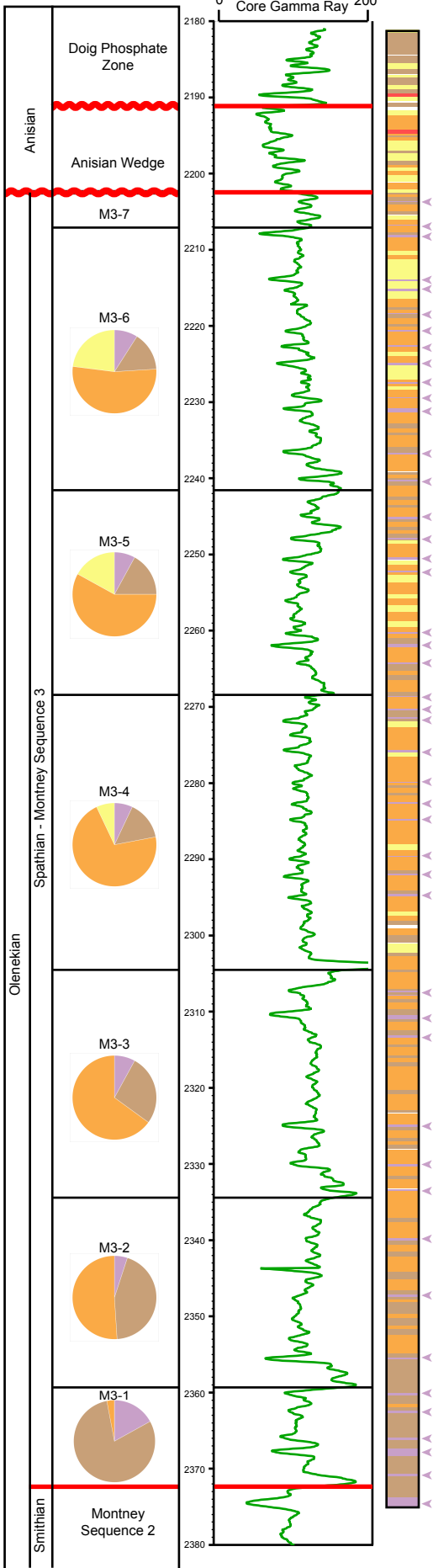


Distal ← ————— → Proximal

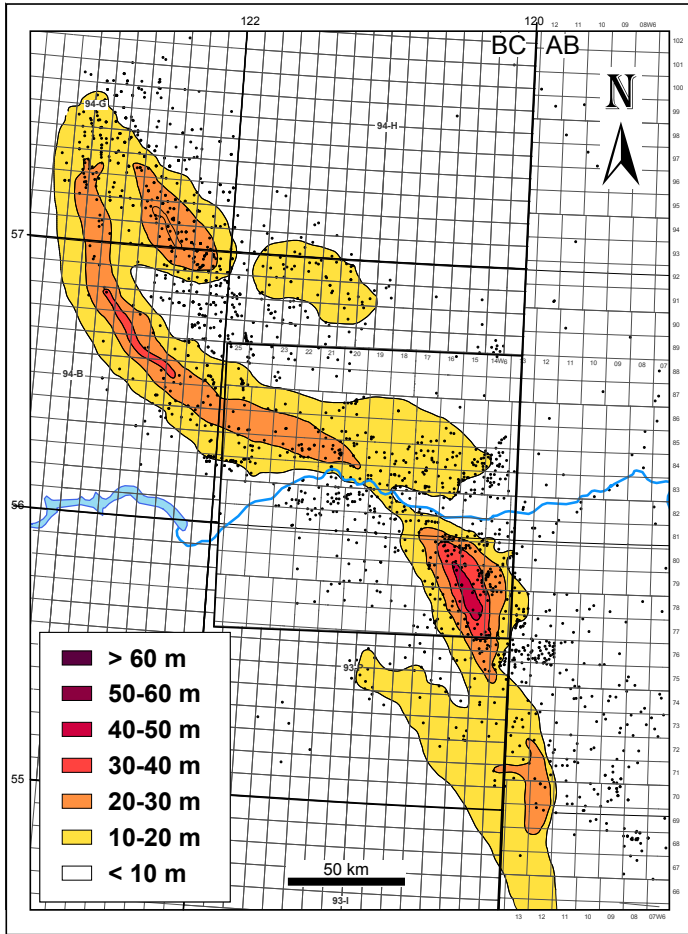
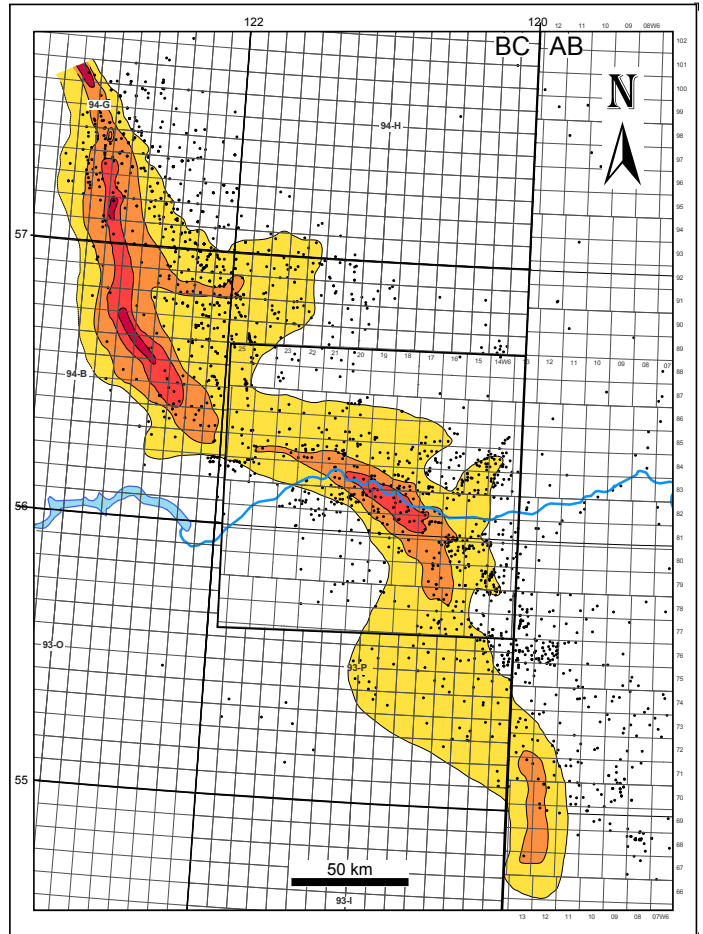
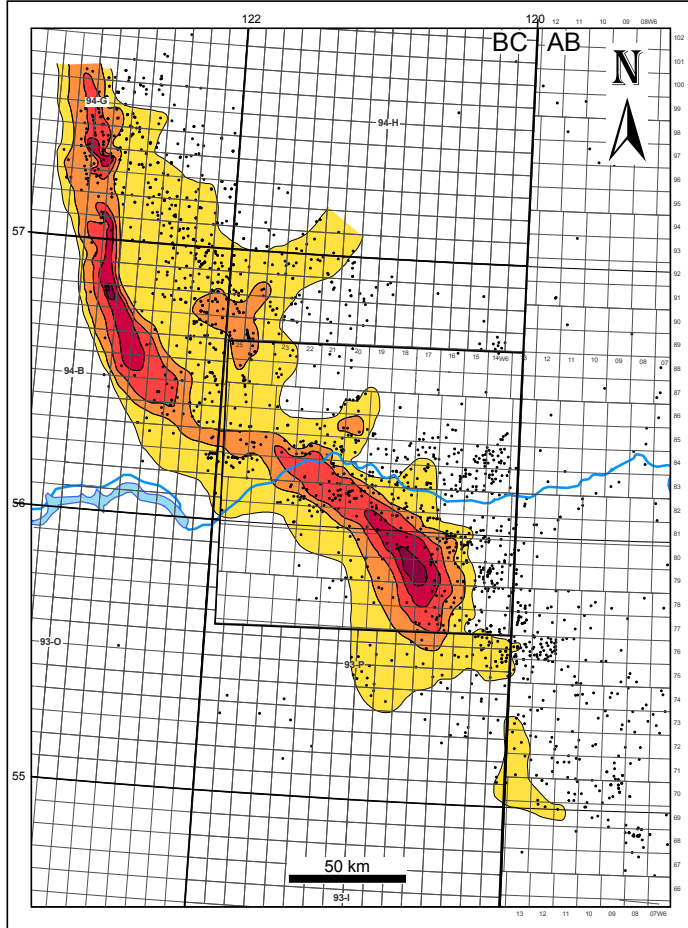
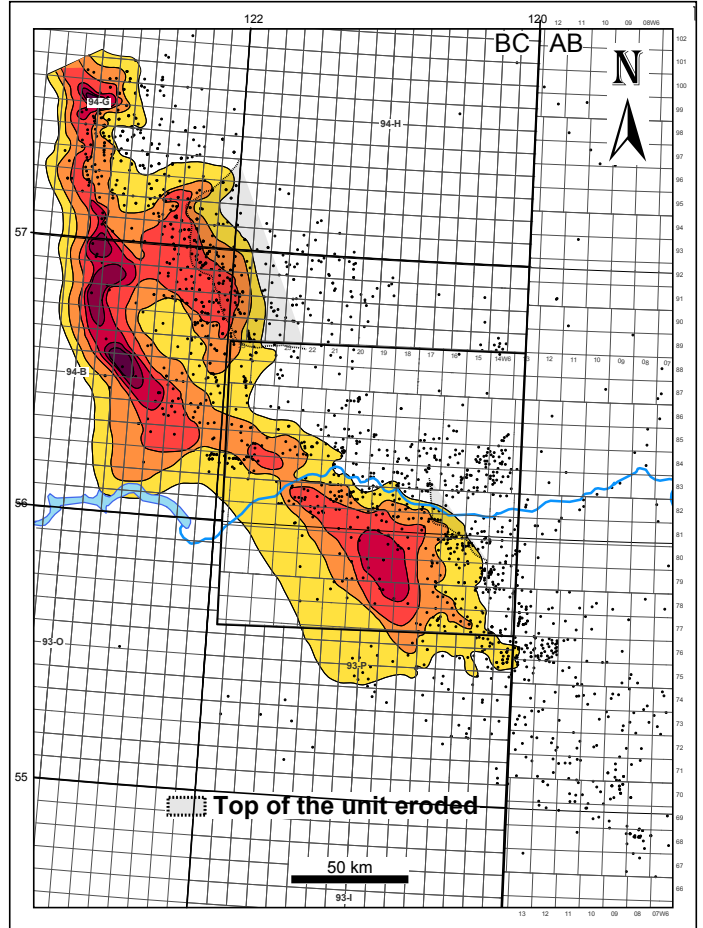
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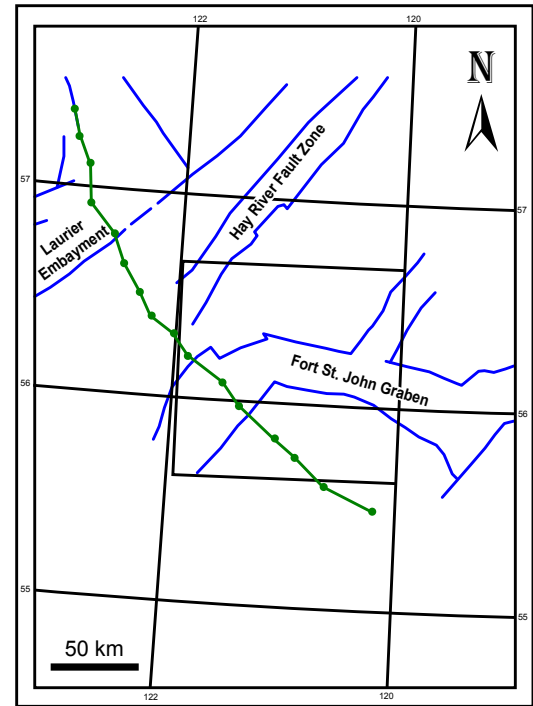
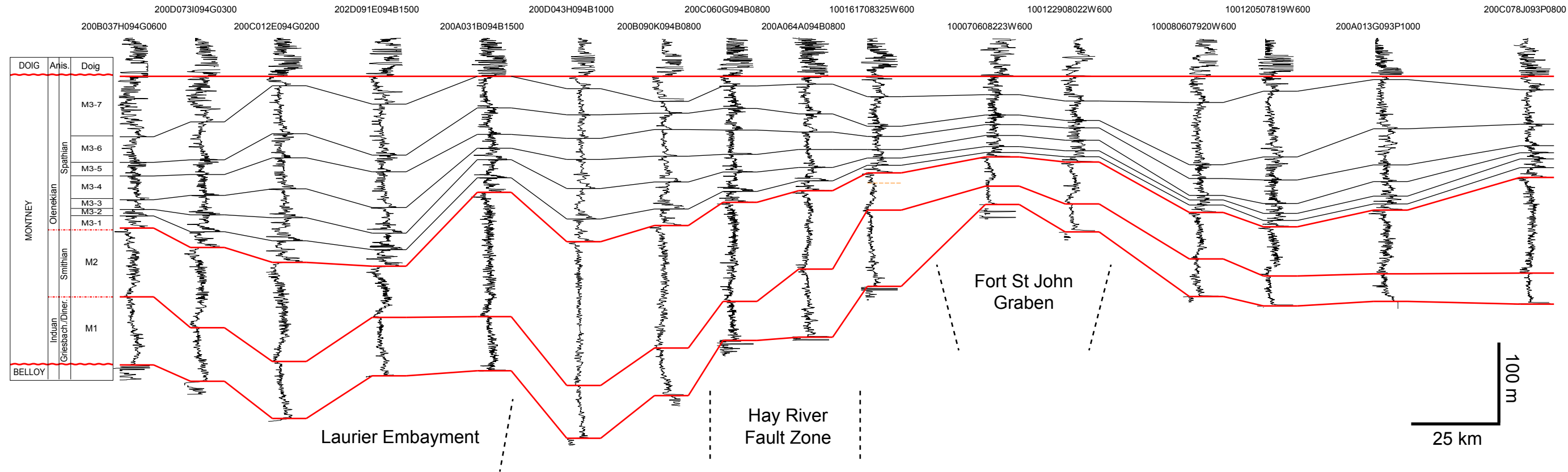


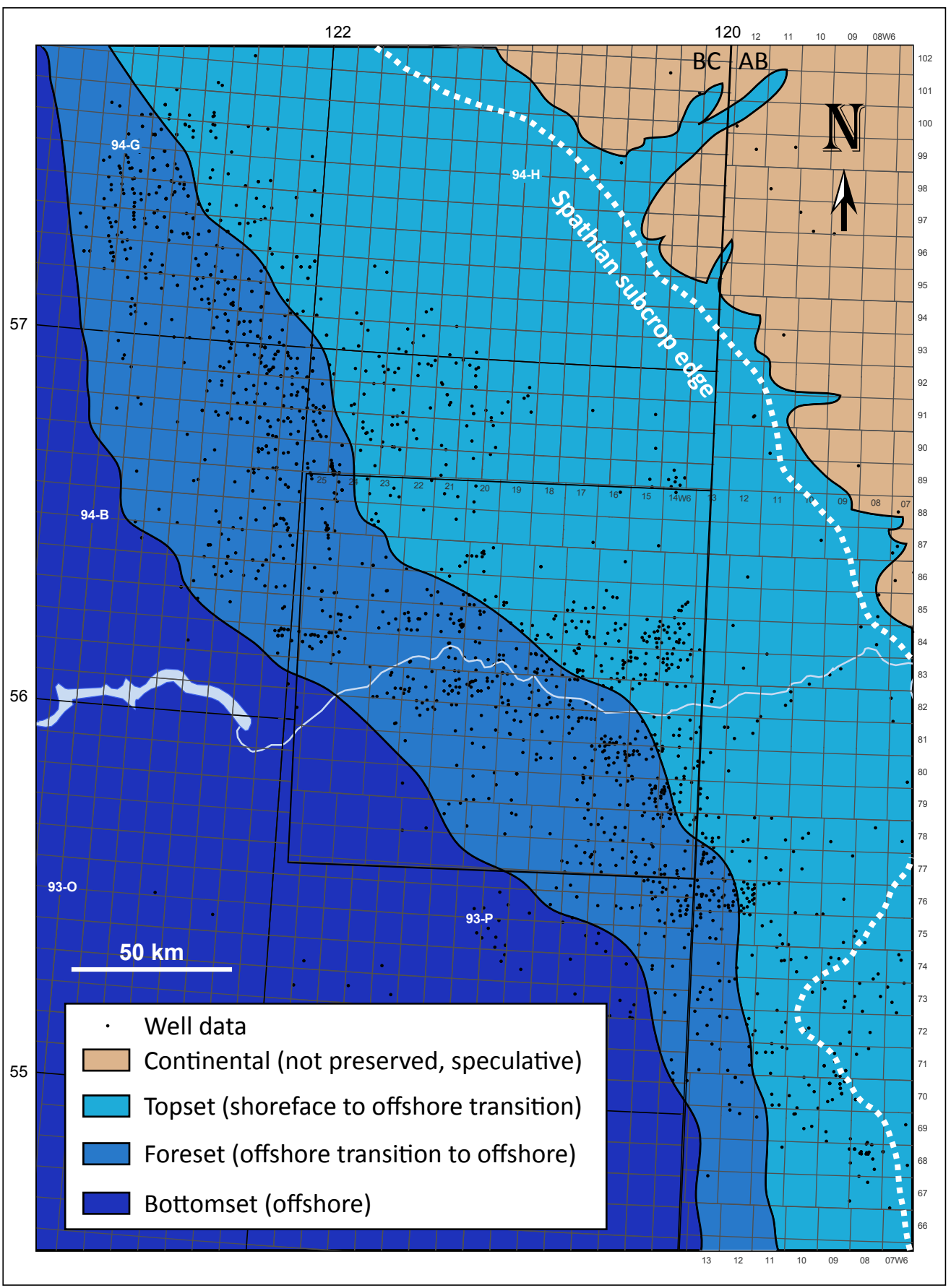
20 m

M3-1**M3-2****M3-3****M3-4**

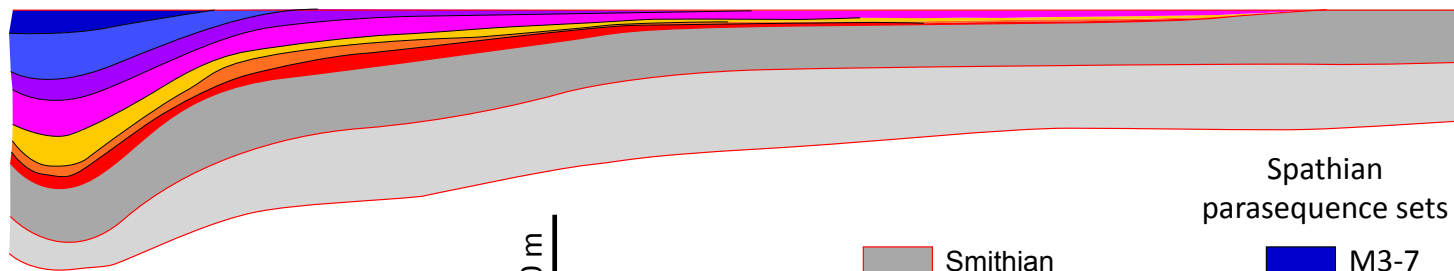
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SE

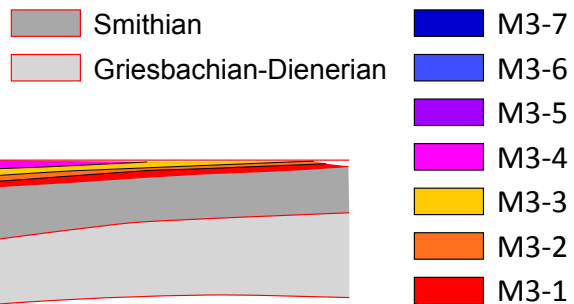




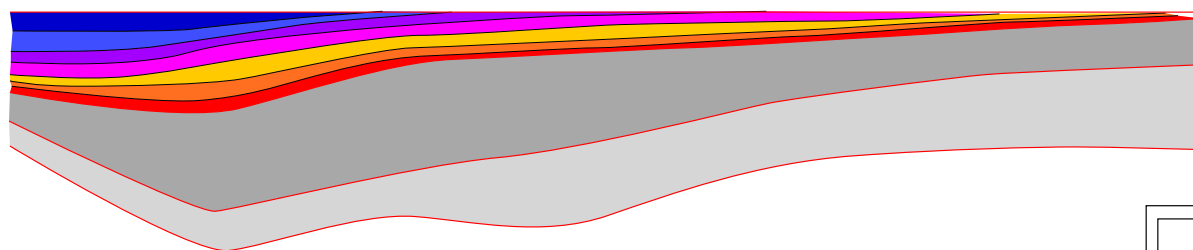
Beg



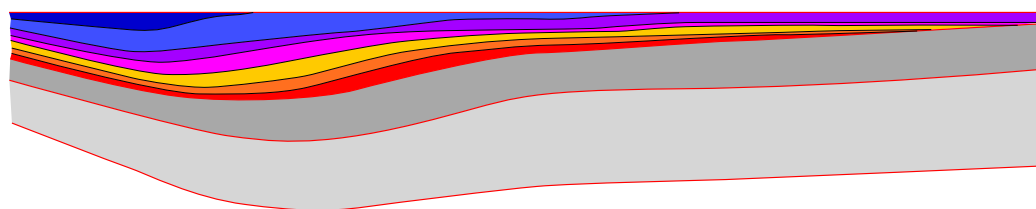
Spathian
parasequence sets



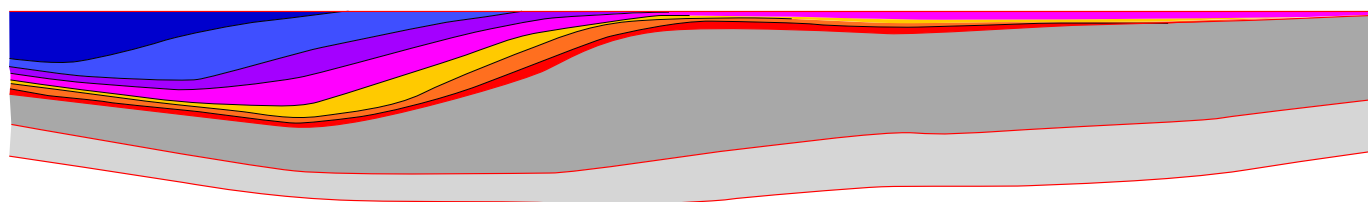
Town



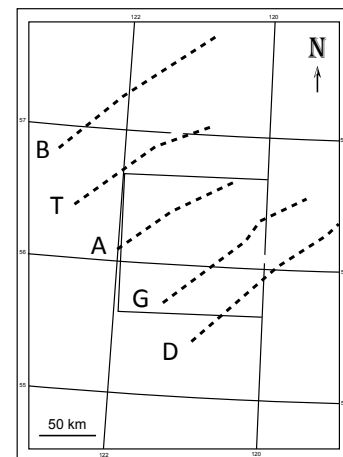
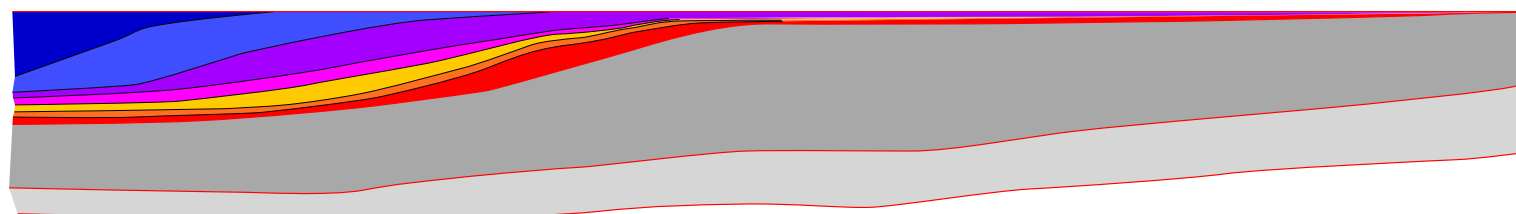
Altares



Groundbirch



Dawson



BC | AB

BC | AB