1 **A MARINE INCURSION IN THE LOWER PENNSYLVANIAN**
2 **TYNEMOUTH CREEK FORMATION, CANADA: IMPLICATIONS FOR**
3 **PALEOGEOGRAPHY, STRATIGRAPHY AND PALEOECOLOGY**
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17 RRH: MARINE INCURSION INTO THE PENNSYLVANIAN MARITIMES BASIN

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ABSTRACT

29
30 We document the occurrence of a marine bed, and its associated biota, in the
31 Lower Pennsylvanian (Langsettian) Tynemouth Creek Formation of New
32 Brunswick, and discuss its implications for paleogeography, stratigraphy and
33 paleoecology. This is only the second marine interval found in the entire
34 Pennsylvanian fill of the Maritimes Basin of Canada, the other being recently
35 found in the broadly same-age Joggins Formation of Nova Scotia. Evidence for
36 the new marine transgression comprises an echinoderm-rich limestone that
37 infills irregularities on a vertic paleosol surface within the distal facies of a
38 syntectonic fluvial megafan formed under a seasonally dry tropical climate.
39 Gray, platy ostracod-rich shales and wave-rippled sandstone beds that directly
40 overlie the marine limestone contain trace fossils characteristic of the Mermia
41 Ichnofacies, upright woody trees, and adpressed megafloras. This association
42 represents bay-fills fringed by freshwater coastal forests dominated by
43 pteridosperms, cordaites, and other enigmatic plants traditionally attributed to
44 dryland/upland habitats. The fossil site demonstrates that marine transgressions
45 extended farther into the interior of Pangea than has previously been
46 documented, and may allow correlation of the Tynemouth Creek and Joggins
47 Formations with broadly coeval European successions near the level of the
48 *Gastrioceras subcrenatum* and *G. listeri* marine bands. It also helps explain the
49 close similarity of faunas between the Maritimes Basin and other paleotropical
50 basins, if transgressions facilitated migration of marine taxa into the continental
51 interior.
52

INTRODUCTION

The Maritimes Basin of Atlantic Canada (Fig. 1A) is one of the largest Pennsylvanian depocentres in tropical Pangea, covering 210,000 km² (Rehill, 1996). It comprises a complex of small sub-basins separated by basement blocks, each with a distinctive depositional history (van de Poll et al., 1995), developed in a strike-slip context resulting from the oblique convergence of Gondwana with Laurasia (Hibbard and Waldron, 2009). As such, it is recognized as one of the most continental interior basins of tropical Pangea (Gibling et al., 2008). Fluvial deposits dominate the Pennsylvanian fill of the basin, and regional paleocurrent compilations indicate that rivers flowed east to northeast away from the Appalachian Orogen drainage divide towards a 'mid-European sea' (Fig. 2; Gibling et al., 1992; Calder, 1998).

This paper deals with the deposits of the Cumberland sub-basin of northern Nova Scotia and southern New Brunswick (Fig. 1B), which lay in the western part, and judging from regional paleoflow data, the most inland part of the Maritimes Basin complex. This inference is supported by the fact that the Cumberland sub-basin is associated with zones of strong deformation that include strike-slip and thrust faults, along with greenschist facies metamorphism (Nance, 1986, 1987). The Pennsylvanian component of the fill comprises coarse-grained syntectonic alluvium along basin margins (Plint and van de Poll, 1982; Chandler, 1998; Bashforth et al., 2014), and three alternating associations in the basin center: (a) poorly-drained coastal plain deposits with coals, (b) well-drained alluvial deposits with scattered calcrete nodules, and (c) open water deposits with bituminous limestone beds (Davies and Gibling, 2003; Davies et al., 2005). The Cumberland sub-basin also contains important Pennsylvanian fossil sites in the Joggins Formation of Nova Scotia (Falcon-Lang et

77 al., 2006; Grey and Finkel, 2011) and the Lancaster Formation ('Fern Ledges') of
78 New Brunswick (Falcon-Lang and Miller, 2007; Fig. 1B).

79 Due to the absence of documented stenohaline faunas in open water facies, the
80 Cumberland sub-basin – and indeed the Maritimes Basin as a whole – was long
81 regarded as a limnic depocentre (Brand, 1994), positioned too far inland to be
82 influenced by glacio-eustatic transgressions that gave rise to the repeated 'marine
83 bands' of northwest Europe (Flint et al., 1995). That view was challenged by the
84 discovery of agglutinated foraminifera at Joggins, which suggested marine influence
85 and a paralic context for the basin (Archer et al., 1995). Shortly thereafter, diverse
86 aquatic faunas (bivalves, ostracods, microconchids, eurypterids, carideans,
87 xiphosurans, fish), long known from the bituminous limestone beds at Joggins and
88 other localities in the Maritimes Basin, were re-evaluated as brackish-marine
89 indicators (Fig. 2; Calder, 1998; Tibert and Dewey, 2006; Falcon-Lang et al., 2006;
90 Prescott et al., 2014; Zaton et al., 2014; Carpenter et al., 2015).

91 A major breakthrough was the discovery of petrographic fabrics consistent
92 with stenohaline marine faunas (brachiopods, echinoderms) in limestone beds at four
93 horizons in the lower Joggins Formation, which proved that fully marine
94 transgressions did, in fact, make brief incursions into the basin (Fig. 2; Grey et al.,
95 2011) in the early Langsettian (Utting et al., 2010). Here, we document a second
96 marine occurrence and its biota from a site in southern New Brunswick, and discuss
97 its implications for the paleogeography, stratigraphy and palaeoecology of the
98 Maritimes Basin.

99
100

GEOLOGICAL CONTEXT

Evidence for the Pennsylvanian marine transgression documented here was discovered in a coastal section along the Bay of Fundy, on the east side of Emerson Creek, near St Martins, southern New Brunswick, Canada (45°15'37.99''N; 65°46'49.75''W; Fig. 1C). In paleogeographic context, the site is close to the northwestern edge of the Cumberland sub-basin, associated with areas of strong deformation and greenschist facies metamorphism within the orogen (Rast et al., 1984; Nance, 1986, 1987).

Rocks exposed at Emerson Creek belong to the ~ 700 m thick Tynemouth Creek Formation (Cumberland Group), a red-bed-dominated terrestrial succession of Early Pennsylvanian (Langsettian) age based on megafloral and palynofloral content (Fig. 3; Utting et al., 2010; Falcon-Lang et al., 2010; Bashforth et al., 2014). The unit conformably overlies the Boss Point Formation (Plint and van de Poll, 1984; Rygel et al., 2015), and correlates (at least in part) with one or more of the Little River, Joggins and Springhill Mines Formations in the eastern/central part of the Cumberland sub-basin (Fig. 3; Calder et al., 2005; Davies et al., 2005; Utting et al., 2010; Rygel et al., 2014), and the Lancaster Formation further to the west (Falcon-Lang and Miller, 2007).

In the region of deposition of the Tynemouth Creek Formation, crustal rotation caused by strike-slip movement was restrained by a bend in the Cobequid-Chedabucto Fault, resulting in oblique-slip thrusting along part of the southern edge of the Cumberland sub-basin (Fig. 1B; Plint and van de Poll, 1984; Nance, 1986, 1987). The Tynemouth Creek Formation, which lies to the north of the fault zone and shows a large-scale upward-coarsening trend, was interpreted as an alluvial fan sourced from

125 this active thrust-front (Plint and van de Poll, 1982; Rast et al., 1984; Plint, 1985).
126 Evidence for syntectonic sedimentation is widespread, including a remarkable series
127 of buried fault scarps that evidently broke the paleosurface (Plint, 1985).
128 Some of us have recently re-examined the architecture and facies of the
129 Tynemouth Creek Formation (Bashforth et al., 2014), and argued that the
130 predominance of channelized sandstone and pedogenically-altered mudstone in the
131 coarsening-upward succession is best explained in terms of a fluvial megafan model
132 (cf. Hartley et al., 2010; Weissmann et al., 2011). The depositional model envisioned
133 involves proximal gravel-bed fluvial systems that passed basinward into a distributive
134 system of mixed-load fixed-channels and various interfluvial facies (Bashforth et al.,
135 2014), with accumulation occurring under a seasonally dry tropical climate (cf.
136 Nichols, 1987; Wells and Dorr, 1987; Hirst, 1991). A modern analogue might be the
137 Kosi megafan of India (Singh et al., 1993). The Emerson Creek section (the focus of
138 this paper) exposes the lowermost part of the Tynemouth Creek Formation (Fig. 3;
139 Falcon-Lang, 2006), and represents the most distal deposits of the fluvial megafan.

140

141 EMERSON CREEK SUCCESSION

142 The study interval at Emerson Creek contains sedimentary and biotic
143 associations that are highly unusual (or possibly unique) in the Tynemouth Creek
144 Formation. The section comprises a predominantly gray, horizontally laminated,
145 coarsening-upward succession, 4.5 m thick, which overlies one paleosol and is capped
146 by a second paleosol (Fig. 4A – B). The interval can only be traced laterally for about
147 11 m, as it is truncated by normal faults on both sides. However, the beds show no
148 indication of channelization over this distance. Fossils collected from the section, and

149 illustrated here, are accessioned in the collections of the New Brunswick Museum,
150 Saint John (NBMG 16046–16047, 16831–16834, 18584 – 18602, 18860).

151

152 Sedimentary Facies

153 Five sedimentary units (1 – 5) are recognized in the studied succession (Fig. 4A – B):

154 Unit 1: The lowermost unit is a ≤ 0.56 m thick paleosol (Fig. 4C) with a
155 hackly fracture, concave-up joints, scattered carbonate nodules, and gray/green or red
156 mottling. The upper surface is highly irregular, with hollows, small downward-
157 tapering cracks, and undercut paleo-ledges.

158 Unit 2: Above the paleosol is a ≤ 0.18 m thick, dark gray limestone that
159 contains a marine fauna (Fig. 4C – D), and which infills the underlying irregular
160 paleo-surface. The limestone shows symmetrical ripples on its upper surface.

161 Unit 3. Overlying the limestone is a sharp-based unit of medium gray
162 laminated siltstone, 1.3 m thick, which contains a few thin beds of dark gray
163 carbonaceous shale. The siltstone unit comprises several stacked, coarsening-upward
164 cycles, rare siderite nodules, symmetrical ripple marks, and ripple cross-lamination.
165 Small woody trees, 30 – 50 mm in diameter, (Fig. 4E) are rooted in growth position at
166 two horizons. Other fossils include indeterminate fish scales, ostracods, trace fossils
167 (Ichnocoenosis A) and megafloral remains (Assemblage 1).

168 Unit 4. Coarsening up from the gray, laminated shales is a succession, 2.1 m
169 thick, dominated by thinly bedded, fine- to medium-grained sandstone (Fig. 4A – B).
170 These beds contain symmetrical ripples, shallow scours, and sediment-cast
171 calamitalean trees in growth position surrounded by mounded bedforms, and
172 megafloral remains (Assemblage 2). Two trace fossil assemblages (Ichnocoenoses B

173 and C) are present. Some evidence of red/gray pedogenic weathering is observed,
174 manifest as mottling that penetrates downward from surfaces at 3.2 m and 4.3 m in
175 the section (Fig. 4B).

176 Unit 5. The succession is capped by a red/gray paleosol, ≤ 0.37 m thick, which
177 is not as well-developed as Unit 1, showing color alteration but no pedogenic fabric.

178

179 Limestone Petrology and Fauna

180 The petrology, faunal composition and diagenesis of the limestone bed (Unit
181 2) were examined using transmitted light microscopy. Percentages of bioclastic,
182 terrigenous, authigenic, and diagenetic components were estimated as rare ($< 5\%$),
183 common ($5 - 30\%$), or abundant ($> 30\%$) using a modal abundance chart.
184 Descriptions and abundances of limestone components are given in Table 1.

185 In thin section, Unit 2 comprises a fine-grained intraclastic- and bioclastic-rich
186 wackestone (Fig. 5A). Intraclasts include silt- to granule-sized fragments of lime
187 mudstone, and the bioclastic component comprises abundant echinoderm fragments
188 attributed to echinoids, crinoids and/or blastoids (Fig. 5B – C, E), common ostracods
189 (Fig. 5B) and bryozoans (Fig. 5C), and rare pseudopunctate brachiopods (Fig. 5D),
190 gastropods, bivalves, and fish scales. Authigenic and diagenetic components include
191 rare framboidal pyrite, francolite and sucrosic dolomite (Fig. 5F).

192

193 Ichnocoenoses

194 Three ichnocoenoses occur in the study section. Ichnocoenosis A, at 1.9 m in
195 the section (Unit 3; Fig. 4B), occurs in beds of gray, ostracod-rich siltstone with
196 symmetrical ripples that show a microbial ‘elephant skin’ texture (Schieber et al.,

2007) on their upper surfaces (Fig. 6B). The assemblage includes bilobed trails of *Didymaulichnus lyelli*, ≤ 1 mm wide, associated with similar-sized ‘bean’ shaped *Lockeia siliquaria*, some of which also are bilobed (Fig. 6A), irregular trails of *Helminthoidichnites tenuis*, ≤ 1 mm wide (Fig. 6B), *Arenicolites*, and small, crescent marks of *Selenichnites* isp. (Fig. 6C). Ichnocoenoses B and C, at 2.8 m and 3.9 m in the section (Unit 4; Fig. 4B), respectively, occur in red fine-grained sandstone that locally exhibits small scours or symmetrical ripples. These depauperate assemblages include a crosier-like burrow that represents one partial whorl (Fig. 6D), bilobed trails of *Didymaulichnus lyelli*, ≤ 2 mm wide, which are somewhat larger than examples in Ichnocoenosis A (Fig. 6E), *Cochlichnus anguineus* (Fig. 6F), and shallowly impressed tetrapod footprints cf. *Baropezia*.

208

209 Megafloral Assemblages

210 Two megafloral assemblages occur in the section. Megafloral Assemblage 1, 211 between 1.2 and 1.7 m in the section (Unit 3; Fig. 4B), occurs in gray shale beds 212 associated with small, upright, woody stems. The relatively diverse assemblage is 213 dominated by adpressed foliage of medullosalean pteridosperms, including 214 *Alethopteris* sp. cf. *A. lancifolia* (n = 5; Fig. 7A), *Paripteris pseudogigantea* (n = 11; 215 Fig. 7B), and *Laveineopteris* sp., cf. *L. hollandica* (n = 2; Fig. 7G), typically 216 preserved as isolated pinnules or small pinnae fragments. Taxa of enigmatic affinity, 217 including cf. *Pseudadiantites rhomboideus* (n = 14; Fig. 7C) and “*Sphenopteris*” 218 *valida* (n = 1; Fig. 7D) also are present, as are rare lycopsid remains, represented by 219 *Lepidostrobophyllum* sp. (n = 1; Fig. 7F). Megafloral Assemblage 2 occurs in gray 220 shale at 2.3 m in the section (Unit 4; Fig. 4B), and comprises rare and poorly

221 preserved sphenopsid fragments including *Calamites* sp. (n = 1) and *Annularia* sp., cf.
222 *A. sphenophylloides* (n = 1; Fig. 7E), and cordaitaleans, represented by *Cordaites* sp.
223 leaves (n = 7; Fig. 7H).

224

225 INTERPRETATION OF PALEOENVIRONMENT AND ECOSYSTEMS

226 The ~ 700 m thick Tynemouth Creek Formation is dominated by thick
227 conglomerate and sandstone beds, interpreted as the deposits of braided and fixed-
228 channel belts, and predominantly red mudstone and planar sandstone beds with
229 cumulative Vertisol-like paleosols, interpreted as interfluvial deposits, developed
230 within a seasonally dry, syntectonic, fluvial megafan setting (Bashforth et al., 2014).
231 In contrast, the succession at Emerson Creek, which comprises gray, laminated,
232 upward-coarsening beds and contains aquatic (ichno)faunas, was deposited in a
233 standing body of water (Bashforth et al., 2014). Traverses of the entire 17 km long
234 coastal outcrop belt of the Tynemouth Creek Formation reveal only about half a
235 dozen examples of successions that, similarly, might have been deposited under
236 conditions of standing water (Plint and van de Poll, 1982; Falcon-Lang et al., 2010).
237 However, all of these packages represent small lakes and ponds that developed within
238 interfluvial hollows (Bashforth et al., 2014). In contrast, the Emerson Creek succession
239 is possibly unique in representing the deposits of a shallow marine embayment.

240

241 Marine Bay-Fill Environments

242 The paleosol at the base of the Emerson Creek section (Unit 1) shows features
243 (concave-up joints, carbonate nodules, mottled red/gray color) that are characteristic

244 of calcic Vertisols formed under a dry subhumid to semi-arid climate (Tandon and
245 Gibling, 1994; Driese et al., 2005).

246 The overlying limestone (Unit 2), which infills the paleotopography,
247 represents a marine incursion that flooded this irregular, seasonally dry terrestrial
248 surface. The presence of echinoderms, brachiopods, and framboidal pyrite indicates
249 deposition under marine salinities (Maliva, 1989; Tucker and Wright, 1990;
250 Schreiber, 2002). The co-occurrence of framboidal pyrite and authigenic francolite
251 further implies that accumulating organic matter was broken down via bacterial
252 sulfate reduction to supersaturate and precipitate phosphate in pore water (Arning et
253 al., 2009; Pufahl, 2010). Mechanically broken, articulated ostracod carapaces, filled
254 with blocky calcite and sucrosic dolomite, suggest alteration during meteoric and
255 shallow burial diagenesis rather than being of paleoenvironmental significance (James
256 and Choquette, 1984; Choquette and Hiatt, 2008).

257 The marine body was extensive because detrital quartz grains are relatively
258 rare, suggesting that the shoreline was distant (Gibling and Kalkreuth, 1991).
259 Nonetheless, the water was shallow given the presence of symmetrical ripples,
260 indicative of formation above normal wave base. The dominance of wave processes is
261 consistent with the microtidal nature of peripheral embayments of the North Variscan
262 Sea inferred from modeling (Wells et al., 2005).

263 Siderite-rich, gray, laminated shale (Unit 3) that coarsens-up into thinly
264 bedded sandstone with symmetrical ripples (Unit 4) records the progradation of
265 coastal sediments during a relative highstand following a marine incursion, with the
266 eventual infilling of the marine embayment. These bodies may have consisted of
267 several small deltaic lobes or thin shoreface units that coalesced to form a single

268 coastal package. Red/gray vertic paleosol(s) that cap the succession (Unit 5) mark a
269 resumption of sub-aerial weathering under a seasonal tropical climate and terrestrial
270 conditions more typical of the Tynemouth Creek Formation as a whole.

271

272 Significance of Ichnocoenoses

273 Analysis of the ichnocoenoses helps to improve the resolution of this marine
274 bay-fill interpretation. Ichnocoenosis A, associated with microbially-wrinkled
275 surfaces in gray, siderite-rich shale, records the activity of invertebrate communities
276 in permanently submerged parts of the bay. *Lockeia* and *Didymaulichnus* represent
277 the resting and grazing traces of ostracods, judging by their very small size and
278 bilobed structure. *Helminthoidichnites*, which was produced by a short-bodied animal
279 such as an arthropod given its angular portions, represents another grazing trace
280 (Buatois et al., 1998). *Arenicolites* was the living burrow of an annelid. *Selenichnites*
281 is the resting trace of a xiphosurid (Romano and Whyte, 1987).

282 Ichnocoenoses B and C, found within symmetrically rippled sandstone with
283 paleosol exposure surfaces, represent the communities of a periodically emergent
284 shoreline. *Cochlichnus* was formed by an animal with an elongate vermiform body
285 that moved in a sinuous fashion, such as an annelid (Hitchcock, 1858), nematode
286 (Moussa, 1970) or possibly an insect larva (Metz, 1987). Also present is a larger type
287 of *Didymaulichnus* formed by a grazing arthropod, and crozier-like traces that are
288 very similar to feeding traces produced by extant unionid bivalves in temporarily
289 emergent fluvial bar-top settings (Lawfield and Pickerill, 2006). *Baropezia* are
290 tetrapod tracks (Falcon-Lang et al., 2010), whose faint toe prints suggest wading in
291 shallow water.

292 Collectively, the ichnocoenoses at Emerson Creek are characteristic of the
293 *Mermia* and/or *Scoyenia* Ichnofacies (Buatois et al., 1998), which have been
294 considered freshwater associations. However, the associations reported here are
295 unusually depauperate and noteworthy for their co-occurrence with microbial
296 textures. Similar types of trace fossil assemblages, with limited behavioral repertoires
297 and activities restricted to the epifaunal and shallow infaunal tiers are common in late
298 Paleozoic freshwater environments. They are also more broadly recurrent across
299 space and time in a variety of post-colonization environments, representing the initial
300 exploitation of under-utilized ecospace, a phenomenon termed the ‘Déjà vu Effect’
301 (Buatois and Mángano, 2011). While the stratigraphic proximity to marine deposits
302 raises the possibility of some brackish influence, ichnocoenoses lack many
303 characteristic ichnotaxa of coeval brackish deposits (Buatois et al., 2005; Prescott et
304 al., 2014), although they do contain euryhaline xiphosurans suggesting that marine
305 waters were relatively close by. Thus, we interpret ichnocoenoses as near-freshwater
306 associations, more closely associated with overlying terrestrial paleosols (in Units 4
307 and 5) than with underlying marine limestone (Unit 2).

308

309 Coastal Vegetation

310 Megafloral assemblages associated with the bay-fill facies shed light on the
311 vegetation of Early Pennsylvanian freshwater forests that fringed the coast. Slender
312 upright trees, rooted in ostracod-rich gray shale (Unit 3), are most likely
313 medullosalean pteridosperms given their close association with the foliage of
314 *Alethopteris*, *Laveineopteris*, and *Paripteris*. These three genera (or their close
315 relatives) have been reconstructed as small trees and shrubs (Pfefferkorn et al., 1984;

316 Shute and Cleal, 2002; Zodrow et al., 2007), consistent with the observed woody
 317 stumps, and the same three genera have been interpreted as fringing coastlines in the
 318 Lower Pennsylvanian Lancaster Formation ('Fern Ledges') in New Brunswick
 319 (Falcon-Lang and Miller, 2007). To what degree this medullosalean-dominated
 320 coastal vegetation was saline-tolerant is uncertain (Stull et al., 2012) because, as noted
 321 above, associated ichnological evidence for brackish-influence is limited. Other taxa
 322 found in the wave-rippled shoreline deposits positioned farther inland include
 323 calamitaleans and cordaitaleans, both of which are associated with coastlines of
 324 broadly the same age, and with similar ichnocoenses (Falcon-Lang, 2005, 2015).
 325 Still other taxa found in the bay-fill deposits include *Pseudodiantites*
 326 *rhomboideus* and "*Sphenopteris*" *valida*, plants of uncertain affinity that Bashforth et
 327 al. (2014) included in their 'enigmatic dryland flora'. Wagner (2001) noted that *P.*
 328 *rhomboideus* shares features with some progymnosperms, and "*S.*" *valida* is similar
 329 to the putative noeggerathialean *Palaeopteridium michiganensis* (cf. Arnold, 1949;
 330 Álvarez-Vázquez, 1995). One hypothesis is that these unusual plants may have been
 331 transported into the bay from better-drained, elevated catenas more distant from the
 332 coast. Such upland/dryland plants are disproportionately abundant in marine flooding
 333 surfaces (Stopes and Watson, 1909; Scott et al., 1997), interpreted to reflect the
 334 proximity of upland/dryland environs to the shoreline during highstand (Chaloner,
 335 1958). However, the direct association of the upland/dryland elements with plants
 336 typical of Pennsylvanian wetland habitats suggests that the enigmatic floras most
 337 likely occupied coastal habitats. Many of these upland/dryland taxa have been
 338 interpreted as edaphic specialists that occupied thin, nutrient-poor, and alkaline soils

339 (cf. White, 1931; DiMichele et al., 2010), a hypothesis that is consistent with their
340 close association with calcic paleosols at the study site.

341

342 DISCUSSION

343 The paralic context of the Pennsylvanian Maritimes Basin of Atlantic Canada
344 has been recently proved by the discovery of limestone beds that contain stenohaline
345 marine faunas in the Joggins Formation of Nova Scotia (Grey et al., 2011). This
346 discovery is remarkable given that marine bands had never before been recorded in
347 the Pennsylvanian basin fill despite nearly 200 years of intensive study. The marine
348 bed documented herein – the second known example from the Maritimes Basin – has
349 important implications for developing our understanding of the paleogeography,
350 stratigraphy and paleoecology of the basin during the Pennsylvanian. The discovery
351 of a stenohaline biota at the Emerson Creek site is all the more surprising because the
352 limestone is not a prominent, distinctive unit and because it is present within a
353 relatively coarse-grained fluvial megafan succession.

354

355 Paleogeographic implications

356 The Maritimes Basin lay in the collisional zone of Pangea, with marine zones
357 progressively narrowed and eliminated through the late Paleozoic. In such a setting,
358 large low-elevation basins would have become increasingly isolated from ocean
359 circulation, with only occasional marine incursions (Averbuch et al., 2005; Wells et
360 al., 2005), and the youngest long-lived marine interval in the Maritimes Basin is
361 represented by the Mississippian (Viséan) Windsor Group (Gibling et al., 2008).

362 As noted above, compilations of Pennsylvanian fluvial paleocurrent data for
363 the Maritimes Basin indicate that drainage (and hence regional slope) was towards the
364 east and northeast during that time (Gibling et al., 1992), implying that the marine
365 transgression documented here would have advanced in a westerly direction,
366 presumably from a ‘mid-European sea’ (Fig. 2; Calder, 1998), towards southern New
367 Brunswick (Fig. 8). Being positioned some 120 km southwest of marine deposits of
368 the broadly similar-aged Joggins Formation (Grey et al., 2011), the Emerson Creek
369 marine band of the Tynemouth Creek Formation therefore records the most inland
370 extension of the sea into the Maritimes Basin during the Pennsylvanian. Lying even
371 farther to the west, the Lancaster Formation contains a brackish water assemblage at
372 the ‘Fern Ledges’ site (Falcon-Lang and Miller, 2007), suggesting that transgressions
373 eventually ran out into freshwater facies (Fig. 8). All three formations are Langsettian
374 in age. Of course, entry points for marine incursions may have been generated or cut
375 off due to tectonic events, and an alternative line of connection closer to the
376 Cumberland sub-basin cannot be ruled out.

377

378 Stratigraphic Implications

379 The general absence of marine bands in the Pennsylvanian fill of the
380 Maritimes Basin (Calder, 1998) has hindered direct correlation of the stratigraphic
381 units with marine-based conodont and goniatite biozones that define IUGS global
382 stage boundaries (Heckel and Clayton, 2006; Heckel et al., 2007). Although index
383 fossils have yet to be recovered from the Emerson Creek marine band, future analyses
384 of this rare occurrence may permit more precise biostratigraphic correlations with
385 other units in the Cumberland sub-basin at Joggins, and more widely across eastern

386 Pangea. Nonetheless, the evidence of sea-level fluctuations alone might also be
387 significant for correlation.

388 The limestone unit documented here from the lower Tynemouth Creek
389 Formation is the only bed that can, to date, be confidently attributed to a marine
390 incursion. Plint and van de Poll (1982) described rare, 20 – 150 mm thick limestone
391 beds (their facies 6) near Giffin Pond and east and west of Tynemouth Creek, both
392 situated in lower parts of the formation, and interpreted the beds as representing
393 freshwater sediment-starved lakes. However, Plint and van de Poll (1982) briefly
394 remarked that the limestone beds contained ostracods, gastropods, ‘spirorbids’
395 (microconchids), and phylloid algae, the latter two components of which are
396 considered brackish to marine indicators (Baars and Torres, 1991; Schultze, 2009;
397 Gierlowski-Kordesch and Cassle, 2015). Despite targeted searches, we were unable to
398 relocate the limestone beds, but these records suggest that additional marine bands
399 may await discovery in the lower part of the formation.

400 Marine limestone beds that contain abundant echinoderms and brachiopods
401 also occur at four horizons in the lower 190 m of the 932.4 m thick type section of the
402 Joggins Formation (Grey et al., 2011). Given that both the Tynemouth Creek and
403 Joggins Formations are of general Langsettian age, the occurrence of multiple closely
404 spaced marine bands in the lower part of both units – which are unique in the
405 Pennsylvanian basin fill – may allow sequence stratigraphic correlation of these
406 intervals (Fig. 9).

407 In the Joggins Formation, marine bands comprise flooding surfaces that mark
408 the base of sedimentary cycles, which represent the complex interplay of glacio-
409 eustasy and rapid basinal subsidence (Davies and Gibling, 2003). In the Tynemouth

410 Creek Formation, the single occurrence of a marine band occurs above a degraded
411 paleosol surface overlain by an aggradational package of fluvial strata. Such paleosol-
412 bound packages of aggradational fluvial deposits are a characteristic motif of the
413 Tynemouth Creek Formation (Bashforth et al., 2014), and may be onshore
414 expressions of the sequence stratigraphic cycles documented in more basinal areas at
415 Joggins (Davies and Gibling, 2003). At Emerson Creek, the maximum flooding
416 surface probably occurs within the marine limestone itself because overlying strata
417 contain near-freshwater ichnotaxa and upright trees. It is possible that progradation of
418 these freshwater coastal plain deposits suppressed the development of underlying
419 marine biofacies, as has been demonstrated in the Appalachian Basin (Bennington,
420 1996, 2002).

421 In the tectonic and paleogeographic setting of the Maritimes Basin, and the
422 Cumberland sub-basin in particular, only the highest amplitude glacio-eustatic sea-
423 level fluctuations might have resulted in marine incursions. In the well-studied
424 Pennsylvanian strata of Britain, which were deposited in a basin undergoing steady
425 thermal subsidence, the most prominent episode of high-amplitude glacio-eustatic
426 marine cycles is in the Yeodonian – early Langsettian interval, whereas only subdued
427 cycles occur in the late Langsettian interval above the *Gastrioceras listeri* Marine
428 Band (Fig. 9; Waters and Condon, 2012). Comparing this pattern with data
429 compilations of marine and brackish bands in the Pennsylvanian fill of the
430 Cumberland sub-basin (Fig. 9), there is no straightforward way to correlate the two
431 successions, presumably due to different paleogeographic settings and basin
432 subsidence rates. However, applying the biostratigraphic framework proposed by
433 Calder et al. (2005), a working hypothesis – requiring testing with conodont-based

434 biozonation – is that the lower Tynemouth Creek and Joggins Formations correlate
435 with marine cycles in the basal and early Langsettian of the British Coal Measures,
436 near the level of the regionally important *Gastrioceras subcrenatum* and *G. listeri*
437 marine bands (Fig. 9).

438

439 Paleoeologic implications

440 Establishing a tentative framework for marine connection between western
441 European basins and the Maritimes Basin has important paleoeologic implications.
442 Marine limestone occurrences in the Joggins and Tynemouth Creek Formations both
443 are echinoderm-dominated with a minor ostracod and brachiopod component, but
444 apparently lack goniatites (Grey et al., 2011; this paper). Crinoids with ostracods and
445 productid brachiopods are dominant components of the shallower facies of the
446 *Gastrioceras subcrenatum* marine band of central England (Calver, 1968), whereas
447 goniatites were restricted to deeper water settings. Echinoderm-dominance in marine
448 bands in the Maritimes Basin is therefore consistent with paleogeographic
449 interpretations as peripheral embayments of European marine bands. Distal dispersal
450 of echinoderms and brachiopods would have been facilitated through their planktonic
451 larval stage and circulation patterns (Wells et al., 2005).

452 More broadly, systematic studies of aquatic faunal groups (fish, bivalves,
453 ostracods, microconchids, eurypterids, carideans, xiphosurans) found in the
454 Pennsylvanian fill of the Maritimes Basin have emphasized their unusually
455 cosmopolitan and euryhaline nature (Calder, 1998; Zaton et al., 2014; Carpenter et al.,
456 2015), showing strong similarities with same-aged faunas of both western and eastern
457 Pangea. The occurrence of widespread but cryptic marine transgressions throughout

458 the Maritimes Basin is an obvious mechanism for the dispersal of aquatic biota, and
459 helps explain the compositional congruity of these faunas both west and further east
460 of the Appalachian drainage divide (Falcon-Lang et al., 2006).

461

462 CONCLUSIONS

- 463 1. We report only the second confirmed example of a stenohaline marine suite in
464 the Pennsylvanian fill of the Maritimes Basin of Atlantic Canada, despite
465 nearly 200 years of investigation in the succession.
- 466 2. The marine band, which comprises an echinoderm-rich wackestone occurs in
467 the distal deposits of a seasonally-dry, syntectonic fluvial megafan represented
468 by the Lower Pennsylvanian (Langsettian) Tynemouth Creek Formation of
469 southern New Brunswick.
- 470 3. Pteridosperm- and cordaite-rich plant communities, interspersed with plants of
471 enigmatic affinity, fringed the margins of this marine embayment, rooted in
472 shallow, coastal muds that probably were of near-freshwater salinities based
473 on the depauperate ichnofaunas.
- 474 4. A stratigraphic hypothesis that requires testing with conodont-based
475 biozonation is that the marine band correlates with similar units in the
476 Langsettian Joggins Formation of Nova Scotia, and with levels near the
477 *Gastrioceras subcrenatum* and *G. listeri* marine bands in western Europe.
- 478 5. Recognition of marine transgressions in the Maritimes Basin helps to explain
479 the congruence of aquatic faunas with those seen in other paralic basins of
480 tropical Pangea.

481

482

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REFERENCES

500

ÁLVAREZ-VÁZQUEZ, C., 1995, Macroflora del Westfaliense inferior de la Cuenca de

501

Peñarroya-Belmez-Espiel (Córdoba): Ph.D. Thesis, Universidad Oviedo, Spain.

502

ARCHER, A.W., CALDER, J.H., GIBLING, M.R., NAYLOR, R.D., REID, D.R., and

503

WIGHTMAN, W.G., 1995, Invertebrate trace fossils and agglutinated foraminifera as

504

indicators of marine influences within the classic Carboniferous section at Joggins,

505

Nova Scotia, Canada: Canadian Journal of Earth Sciences, v. 32, p. 2027–2039.

506 ARNING, E.T., BIRGEL, D., BRUNNER, B., and PECKMANN, J., 2009, Bacterial formation
 507 of phosphatic laminites off Peru: *Geobiology*, v. 7, p. 295–307.

508 ARNOLD, C.A., 1949, Fossil flora of the Michigan Coal Basin: Contributions from the
 509 Museum of Paleontology, University of Michigan, v. 7, p. 131–269.

510 AVERBUCH, O., TRIBOVILLARD, N., DEVLEESCHOUWER, X., RIQUIER, L., MISTIAEN, B.,
 511 and VAN VLIET-LANOE, B., 2005, Mountain building-enhanced continental
 512 weathering and organic carbon burial as major causes for climatic cooling at the
 513 Frasnian-Famennian boundary (c. 376 Ma)?: *Terra Nova*, v. 17, p. 25–34.

514 BAARS, D.L., and TORRES, A.M., 1991, Late Paleozoic phylloid algae – a pragmatic
 515 review: *Palaaios*, v. 6, p. 513–516.

516 BASHFORTH, A.R., CLEAL, C.J., GIBLING, M.R., FALCON-LANG, H.J., and MILLER,
 517 R.F., 2014, Paleoecology of Early Pennsylvanian vegetation on a seasonally dry
 518 tropical landscape (Tynemouth Creek Formation, New Brunswick, Canada):
 519 *Review of Palaeobotany and Palynology*, v. 200, p. 229–263.

520 BENNINGTON, J Bret, 1996, Stratigraphic and biofacies patterns in the Middle
 521 Pennsylvanian Magoffin Marine Unit in the Appalachian Basin, U.S.A.:
 522 *International Journal of Coal Geology*, v. 31, p. 169–194.

523 BENNINGTON, J Bret, 2002, Eustacy in cyclothems is masked by loss of marine
 524 biofacies with increasing proximity to a detrital source: An example from the
 525 Central Appalachian Basin, U.S.A. In: L.V. Hills, C.M. Henderson, and E.W.
 526 Bamber, (Eds.), *Carboniferous and Permian of the World*, Canadian Society of
 527 Petroleum Geologists, Memoir, v. 19, p.12–21.

528 BRAND, U., 1994, Continental hydrology and climatology of the Carboniferous
 529 Joggins Formation (lower Cumberland Group) at Joggins, Nova Scotia: evidence

530 from the geochemistry of bivalves: *Palaeogeography, Palaeoclimatology,*
531 *Palaeoecology*, v. 106, p. 307–321.

532 BUATOIS, L.A., and MÁNGANO, M.G., 2011, The déjà vu effect: recurrent patterns in
533 exploitation of ecospace, establishment of the mixed layer, and distribution of
534 matgrounds: *Geology*, v. 39, p. 1163–1166.

535 BUTAOIS, L.A., MÁNGANO, M.G., GENISE, J.F., and TAYLOR, T.N., 1998, The
536 ichnological record of the continental invertebrate invasion: evolutionary trends,
537 environmental expansion, ecospace utilization, and behavioral complexity: *Palaaios*,
538 v. 13, p. 217–240.

539 BUATOIS, L.A., GINGRAS, M.K., MACEACHERN, J., MÁNGANO, M.G., ZOONEVELD,
540 J.P., PEMBERTON, S.G., NETTO, R.G., and MARTIN, A., 2005, Colonization of
541 brackish-water systems through time: evidence from the trace-fossil record:
542 *Palaaios*, v. 20, p. 321–347.

543 CALDER, J.H., 1998, The Carboniferous evolution of Nova Scotia. In: BLUNDELL,
544 D.W., and SCOTT, A.C. (Eds.), *Lyell: The Past is the Key to the Present:*
545 *Geological Society of London, Special Publication*, v. 143, p. 261–302.

546 CALDER, J.H., RYGEL, M.C., HEBERT, B.L., and FALCON-LANG, H.J., 2005,
547 *Sedimentology and stratigraphy of Pennsylvanian red beds near Joggins, Nova*
548 *Scotia: The proposed Little River Formation with redefinition of the Joggins*
549 *Formation: Atlantic Geology*, v. 41, p. 143–167.

550 CALVER, M.A., 1968, Distribution of Westphalian marine faunas in northern England
551 and adjoining areas: *Proceedings of the Yorkshire Geological Society*, v. 37, p. 1–
552 72.

553 CARPENTER, D., FALCON-LANG, H.J., BENTON, M.J., and GREY, M., 2015, Early
 554 Pennsylvanian (Langsettian) fish assemblages from the Joggins Formation,
 555 Canada, and their paleoecological and palaeogeographic implications:
 556 *Palaeontology*, v. 50, xxx–xxx.

557 CHALONER, W.G., 1958, The Carboniferous upland flora: *Geological Magazine*, v. 95,
 558 p. 261–262.

559 CHANDLER, F.W., 1998, Geology of and climatic indicators in the Westphalian A New
 560 Glasgow Formation, Nova Scotia, Canada: implications for the genesis of coal and
 561 of sandstone-hosted lead deposits: *Atlantic Geology*, v. 34, p. 39–56.

562 CHOQUETTE, P.W., and HIATT, E.E., 2008, Shallow-burial dolomite: a major
 563 component of many ancient sucrosic dolomites: *Sedimentology*, v. 55, p. 423–460.

564 DAVIES, S.J., and GIBLING, M.R., 2003, Architecture of coastal and alluvial deposits
 565 in an extensional basin: the Carboniferous Joggins Formation of eastern Canada:
 566 *Sedimentology*, v. 50, p. 415–439.

567 DAVIES, S.J., GIBLING, M.R., RYSEL, M.C., CALDER, J.H., and SKILLITER, D.M., 2005,
 568 The Pennsylvanian Joggins Formation of Nova Scotia: sedimentological log and
 569 stratigraphic framework of the historic fossil cliffs: *Atlantic Geology*, v. 41, p. 115–
 570 142.

571 DiMICHELE, W.A., CECIL, C.B., MONTAÑEZ, I.P., and FALCON-LANG, H.J., 2010,
 572 Cyclic changes in Pennsylvanian paleoclimate and effects on floristic dynamics in
 573 tropical Pangaea: *International Journal of Coal Geology*, v. 83, p. 329–344.

574 DRIESE, S.G., NORDT, L.C., LYNN, W., STILES, C.A., MORA, C.I., and WILDING, L.P.,
 575 2005, Distinguishing climate in the soil record using chemical trends in a Vertisol
 576 climosequence from the Texas Coastal Prairie, and application to interpreting

577 Paleozoic paleosols in the Appalachian basin: *Journal of Sedimentary Research*, v.
578 75, p. 340-353.

579 FALCON-LANG, H.J., 2005, Small cordaitalean trees in a marine-influenced coastal
580 habitat in the Pennsylvanian Joggins Formation, Nova Scotia, Canada: *Journal of*
581 *the Geological Society*, London, v. 162, p. 485–500.

582 FALCON-LANG, H.J., 2006, Vegetation ecology of Early Pennsylvanian alluvial fan
583 and piedmont environments in southern New Brunswick, Canada:
584 *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 233, p. 34–50.

585 FALCON-LANG, H.J., 2015, A calamitalean forest preserved in growth position in the
586 Pennsylvanian (late Langsettian) coal measures of South Wales: implications for
587 coastal palaeoecology and stem-cast taphonomy: *Review of Palaeobotany and*
588 *Palynology*, v. 214, p. 51–67.

589 FALCON-LANG, H.J., and MILLER, R.F., 2007, Palaeoenvironments and palaeoecology
590 of the Pennsylvanian Lancaster Formation (“Fern Ledges”) of Saint John, New
591 Brunswick, Canada: *Journal of the Geological Society*, London, v. 164, p. 945–
592 958.

593 FALCON-LANG, H.J., BENTON, M.J., BRADDY, S.J., and DAVIES, S.J., 2006, The
594 Pennsylvanian tropical biome reconstructed from the Joggins Formation of
595 Canada: *Journal of the Geological Society*, London, v. 163, p. 561–576.

596 FALCON-LANG, H.J., GIBLING, M.R., BENTON, M.J., MILLER, R.F., and BASHFORTH,
597 A.R., 2010, Diverse tetrapod trackways in the Lower Pennsylvanian Tynemouth
598 Creek Formation, southern New Brunswick, Canada: *Palaeogeography,*
599 *Palaeoclimatology, Palaeoecology*, v. 296, p. 1–13.

600 FLINT, S., AITKEN, J., and HAMPSON, G., 1995, Application of sequence stratigraphy to
601 coal-bearing coastal plain successions: implications for the UK Coal Measures:
602 Geological Society of London, Special Publication, 82, 1–16.

603 GIBLING, M.R., and KALKREUTH, W.D., 1991, Petrology of selected carbonaceous
604 limestones and shales in Late Carboniferous coal basins of Atlantic Canada:
605 International Journal of Coal Geology, v. 17, p. 239–271.

606 GIBLING, M.R., CALDER, J.H., RYAN, R., VAN DE POLL, H.W., and YEO, G.M., 1992,
607 Late Carboniferous and Early Permian drainage patterns in Atlantic Canada:
608 Canadian Journal of Earth Sciences, v. 29, p. 338–352.

609 GIBLING, M.R., CULSHAW, N., RYGEL, M.C., and PASCUCCI, V., 2008, The Maritimes
610 Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone
611 of Pangea. In: Miall, A.D. (Ed.), The Sedimentary Basins of the United States and
612 Canada, Elsevier, p. 211–244.

613 GIERLOWSKI-KORDESCH, E.H., and CASSLE, C.F., 2015, The '*Spirorbis*' problem
614 revisited: sedimentology and biology of microconchids in marine-nonmarine
615 transitions: Earth-Science Reviews, v. 148, p. 229–247.

616 GREY, M., and FINKEL, Z.V., 2011, The Joggins Fossil Cliffs UNESCO World Heritage
617 site: a review of recent research: Atlantic Geology, v. 47, p. 185–200.

618 GREY, M., PUFAHL, P.K., and AZIZ, A.A., 2011, Using multiple environmental proxies
619 to determine degree of marine influence and paleogeographical position of the
620 Joggins Fossil Cliffs UNESCO World Heritage Site: Palaios, v. 26, p. 256–263.

621 HARTLEY, A.J., WEISSMANN, G.S., NICHOLS, G.J., and WARWICK, G.L., 2010, Large
622 distributive fluvial systems: characteristics, distribution, and controls on
623 development: Journal of Sedimentary Research, v. 80, p. 167–183.

624 HECKEL, P.H., and CLAYTON, G., 2006, Use of the new official names for the
 625 subsystems, series and stages of the Carboniferous System in international
 626 journals: Proceedings of the Geologists' Association, v. 117, p. 1–4.
 627 HECKEL, P.H., ALEKSEEV, A.S., BARRICK, J.E., BOARDMAN, D.R., GOREVA, N.B.,
 628 NEMYROVSKA, T.I., UENO, K., VILLA, E., and WORK, D.M., 2007, Cyclothem
 629 [“digital”] correlation and biostratigraphy across the global Moscovian–
 630 Kasimovian–Gzhelian stage boundary interval (Middle–Upper Pennsylvanian) in
 631 North America and eastern Europe. *Geology*, v. 35, p. 607–610.
 632 HIBBARD, J., and WALDRON, J.W.F., 2009, Truncation and translation of Appalachian
 633 promontories: Mid-Paleozoic strike-slip tectonics and basin initiation: *Geology*, v.
 634 37, p. 487–490.
 635 HIRST, J.P.P., 1991, Variations in alluvial architecture across the Oligo-Miocene
 636 Huesca fluvial system, Ebro Basin, Spain. In: MIAL, A.D., and TYLER, N. (Eds.),
 637 The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and
 638 Its Implications for Hydrocarbon Discovery and Recovery: Concepts in
 639 Sedimentology and Paleontology, Society of Economic Palaeontologists and
 640 Mineralogists, p. 111–121.
 641 HITCHCOCK, E., 1858, Ichnology of New England. A Report on the Sandstone of the
 642 Connecticut Valley, Especially its Fossil Footmarks. W. White, Boston, 220 pp.
 643 JAMES, N.P., and CHOQUETTE, P.W., 1984, Diagenesis 9: Limestones: The meteoric
 644 diagenetic environment: *Geoscience Canada*, v. 11, p. 161–194.
 645 LAWFIELD, A.M.W., and PICKERILL, R.K., 2006, A novel contemporary fluvial
 646 ichnocoenose: unionid bivalves and the *Scoyenia-Mermia* ichnofacies transition:
 647 *Palaos*, v. 21, p. 391–396.

648 MALIVA, R.G., 1989, Displacive calcite syntaxial overgrowths in open marine
649 limestones: *Journal of Sedimentary Research*, v. 59, p. 397–403.

650 METZ, R., 1987, Insect traces from nonmarine ephemeral puddles: *Boreas*, v. 16, p.
651 189–195.

652 MOUSSA, M.T., 1970, Nematode fossil trails from the Green River Formation
653 (Eocene) in the Uinta Basin, Utah: *Journal of Paleontology*, v. 44, p. 304–307.

654 NANCE, R.D., 1986, Late Carboniferous tectonostratigraphy in the Avalon Terrane of
655 southern New Brunswick: *Maritimes Sediments and Atlantic Geology*, v. 22, p.
656 308–326.

657 NANCE, R.D., 1987, Dextral transpression and Late Carboniferous sedimentation in
658 the Fundy coastal zone of southern New Brunswick. In: Beaumont, C., Tankard,
659 A.J. (Eds.), *Sedimentary basins and basin-forming mechanism*. Calgary, Alberta,
660 Canadian Society of Petroleum Geologists, Memoir, v. 12, p. 363–377.

661 NICHOLS, G.J., 1987, Structural controls on fluvial distributary systems – the Luna
662 System, northern Spain. In: F.G. Ethridge, R.M. Flores and M.D. Harvey (Eds.),
663 *Recent Developments in Fluvial Sedimentology*: Society of Economic
664 Paleontologists and Mineralogists, Special Publication, v 39, p. 269–277.

665 PFEFFERKORN, H.W., GILLESPIE, W.H., RESNICK, D.A., and SCHEIHING, M.H., 1984,
666 Reconstruction and architecture of medullosan pteridosperms (Pennsylvanian): *The*
667 *Mosasaur*, v. 2, p. 1–8.

668 PLINT, A.G., 1985, Possible earthquake-induced soft-sediment faulting and
669 remobilization in Pennsylvanian alluvial strata, southern New Brunswick, Canada:
670 *Canadian Journal of Earth Sciences*, v. 22, p. 907–912.

671 PLINT, A.G., and VAN DE POLL, H.W., 1982, Alluvial fan and piedmont sedimentation
 672 in the Tynemouth Creek Formation (Lower Pennsylvanian) of southern New
 673 Brunswick: *Maritimes Sediments and Atlantic Geology*, v. 18, p. 104–128.
 674 PLINT, A.G., and VAN DE POLL, H.W., 1984, Structural and sedimentary history of the
 675 Quaco Head area, southern New Brunswick: *Canadian Journal of Earth Sciences*,
 676 v. 21, p. 753–761.
 677 PUFAHL, P.K., 2010, Bioelemental sediments. In: James, N.P. and Dalrymple, R.W.
 678 (Eds.), *Facies Models 4th Edition*, Geological Association of Canada, p. 477–503.
 679 PRESCOTT, Z., STIMSON, M.R., DAFOE, L.T., GIBLING, M.R., MACRAE, R.A., CALDER,
 680 J.H., and HEBERT, B., 2014, Microbial mats and ichnofauna of a fluvial-tidal
 681 channel in the Lower Pennsylvanian Joggins Formation, Canada: *Palaios*, v. 29,
 682 624–645.
 683 RAST, N., GRANT, R.H., PARKER, J.S.D., and TENG, H.C., 1984, The Carboniferous
 684 succession in southern New Brunswick and its state of deformation. In: Geldsetzer,
 685 H.H.J. (Ed.), *Atlantic Coast Basins: 9th International Congress on Carboniferous*
 686 *Stratigraphy*, *Compte Rendu*, v. 3, p. 13–22.
 687 REHILL, T.A., 1996, Late Carboniferous nonmarine sequence stratigraphy and
 688 petroleum geology of the Central Maritimes Basin, Eastern Canada, Unpublished
 689 Ph.D. thesis, Dalhousie University, Halifax, 406 pp.
 690 ROMANO, M., and WHYTE, M.A., 1987, A limulid trace fossil from the Scarborough
 691 Formation (Jurassic) of Yorkshire; its occurrence, taxonomy and interpretation:
 692 *Proceedings of the Yorkshire Geological Society*, v. 46, p. 85–95.
 693 RYSEL, M.C., SHELDON, E.P., STIMSON, M.R., CALDER, J.H., ASHLEY, K.T., and
 694 SALG, J.L., 2014, The Pennsylvanian Springhill Mines Formation:

695 sedimentological framework of a portion of the Joggins Fossil Cliffs UNESCO
696 World Heritage Site: *Atlantic Geology*, v. 50, p. 249–289.

697 RYGEL, M.C., LALLY, C., GIBLING, M.R., IELPI, A., CALDER, J.H., and BASHFORTH, A.R.,
698 2015, Sedimentology and stratigraphy of the type section of the Pennsylvanian Boss
699 Point Formation, Joggins Fossil Cliffs, Nova Scotia, Canada. *Atlantic Geology*, v. 51,
700 1–43.

701 SCHRIEBER, J., 2002, Sedimentary pyrite: a window into the microbial past: *Geology*, v.
702 30, p. 531–534.

703 SCHIEBER, J., BOSE, P.K., ERIKSSON, P.G., BANERJEE, S., SARKAR, S., ALTERMANN, W.,
704 and CATUNEANU, O., 2007, Atlas of Microbial Mat Features Preserved within the
705 Siliciclastic Rock Record: Amsterdam, Elsevier Science, 324 p.

706 SCHULTZE, H-P., 2009, Interpretation of marine and freshwater paleoenvironments in
707 Permo-Carboniferous deposits: *Palaeogeography, Palaeoclimatology,*
708 *Palaeoecology*, v. 281, p. 126–136.

709 SCOTT, A.C., GALTIER, J., MAPES, R.H., and MAPES, G., 1997, Palaeoecological and
710 evolutionary significance of anatomically preserved terrestrial plants in Upper
711 Carboniferous marine goniatite bullions. *Journal of the Geological Society*,
712 London, v. 154, p. 61–68.

713 SHUTE, C.H., and CLEAL, C.J., 2002, Ecology and growth habit of *Laveineopteris*: a
714 gymnosperm from the Late Carboniferous tropical rain forests: *Palaeontology*, v.
715 45, p. 943–972.

716 SINGH, H., PARKASH, B., and GOHAIN, K., 1993, Facies analysis of the Kosi megafan
717 deposits: *Sedimentary Geology*, v. 85, p. 87–113.

718 STULL, G., DiMICHELE, W.A., FALCON-LANG, H.J., NELSON, W.J., and ELRICK, S.,

719 2012, Palaeoecology of *Macroneuropteris scheuchzeri*, and its implications for
 720 resolving the paradox of 'xeromorphic' plants in Pennsylvanian wetlands.
 721 Palaeogeography, Palaeoclimatology, Palaeoecology, v. 331–332, p. 162–176.
 722 TANDON, S.K., and GIBLING, M.R., 1994, Calcrete and coal in late Carboniferous
 723 cyclothems of Nova Scotia, Canada: Climate and sea-level changes linked:
 724 Geology, v. 22, p. 755–758.
 725 TIBERT, N.E., and DEWEY, C.P., 2006, *Velatomorpha*, a new healdioidean ostracode
 726 genus from the early Pennsylvanian Joggins Formation, Nova Scotia, Canada:
 727 Micropaleontology, v. 52, p. 51–66.
 728 TUCKER, M.E., and WRIGHT, V.P., 1990, Carbonate Sedimentology: Blackwell
 729 Scientific Publications, London, 482 pp.
 730 UTTING, J., GILES, P., and DOLBY, G., 2011, Palynostratigraphy of Mississippian and
 731 Pennsylvanian rocks, Joggins area, Nova Scotia and New Brunswick, Canada:
 732 Palynology, v. 34, p. 43–89.
 733 VAN DE POLL, H.W., GIBLING, M.R., and HYDE, R.S., 1995, Introduction: Upper
 734 Paleozoic rocks (Chapter 5). In: Williams, H. (Ed), Geology of the Appalachian-
 735 Caledonian Orogen in Canada and Greenland: Geological Society of America, The
 736 Geology of North America, F-1, 449–455.
 737 WAGNER, R.H., 2001, The extrabasinal elements in lower Pennsylvanian floras of the
 738 Maritimes Provinces, Canada: description of *Adiantites*, *Pseudadiantites* and
 739 *Rhacopteridium*: Revista Española de Paleontología, v. 16, p. 187–207.
 740 WATERS, C., and CONDON, D.J., 2012, Nature and timing of Late Mississippian to
 741 Mid-Pennsylvanian glacio-eustatic sea-level changes of the Pennine Basin, UK.
 742 Journal of the Geological Society of London, v. 169, p. 37–51.

743 WEISSMANN, G.S., HARTLEY, A.J., NICHOLS, G.J., SCUDERI, L.A., OLSON, M.E.,
 744 BUEHLER, H.A., and MASSENGILL, L.C., 2011, Alluvial facies distributions in
 745 continental sedimentary basins – distributive fluvial systems. In: S. Davidson, S.
 746 Leleu, C.P. North (Eds.), From River to Rock Record: The Preservation of Fluvial
 747 Sediments and their subsequent Interpretation. SEPM, Tulsa, Oklahoma, USA,
 748 327–355.

749 WELLS, M.R., ALLISON, P.A., HAMPSON, G.J., PIGGOTT, M.D., and PAIN, C.C., 2005,
 750 Modelling ancient tides: the Upper Carboniferous epi-continental seaway of
 751 Northwest Europe: Sedimentology, v. 52, p. 715–735.

752 WELLS, N.A., and DORR, J.A., 1987, A reconnaissance of sedimentation on the Kosi
 753 Alluvial Fan of India. In: Ethridge, F.G. Flores, R.M., Harvey, M.D. (Eds.), Recent
 754 Developments in Fluvial Sedimentology: Society of Economic Paleontologists and
 755 Mineralogists, Special Publication, v. 39, p. 51–61.

756 WHITE, D., 1931, Climatic implications of Pennsylvanian flora: Illinois State
 757 Geological Survey Bulletin, v. 60, p. 271–281.

758 ZATON, M., GREY, M. and VINN, O., 2014, Microconchid tubeworms (Class
 759 Tentaculita) from the Joggins Formation (Pennsylvanian), Nova Scotia, Canada:
 760 Canadian Journal of Earth Sciences, v. 51, p. 669–676.

761 ZODROW, E.L., TENCHOV, Y.G., and CLEAL, C.J., 2007, The arborescent *Linopteris*
 762 *obliqua* plant (Medullosales, Pennsylvanian). Bulletin of Geosciences, v. 82, p.
 763 51–84.

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FIGURE CAPTIONS

768 **FIGURE 1**—Location details and geological context of study site. A., Southwestern
769 outcrop belt of the Maritimes Basin of Atlantic Canada. B., Cumberland sub-basin
770 of central Nova Scotia and southern New Brunswick on the edge of the
771 Appalachian Orogen. C., Outcrop belt of the Pennsylvanian (Langsettian)
772 Tynemouth Creek Formation of southern New Brunswick. Note position of the
773 study locality at Emerson Creek on the southwestern margin of the coastal
774 exposure. (After van de Poll et al., 1995; Plint and van de Poll, 1982; Falcon-Lang,
775 2006; Bashforth et al., 2014).

776 **FIGURE 2**—Paleogeographical setting of the ‘brackish seas’ developed at Joggins,
777 Nova Scotia (After Falcon-Lang, 2005). A., Global paleogeography showing
778 putative connection of Maritimes Basin to the Tethys Ocean during marine
779 maximum flooding. B., Reconstruction of central tropical Pangaea at maximum sea
780 level, showing an extensive brackish embayment into the Maritimes Basin.
781 Transgression direction inferred from the inverse of fluvial paleocurrents (After
782 Gibling et al. 1992).

783 **FIGURE 3**—Stratigraphic relationships of Lower Pennsylvanian (Langsettian)
784 lithostratigraphic units of the Cumberland sub-basin, Nova Scotia and New
785 Brunswick (After Davies et al., 2005; Falcon-Lang, 2006; Bashforth et al., 2014),
786 and their approximate relationship to European regional chronostratigraphic
787 boundaries.

788 **FIGURE 4**—Geology of the study locality at Emerson Creek. A., Photograph of the
789 measured section lying between two paleosols, with location of ichnocoenoses
790 marked as IA, IB and IC. Logged section in Fig. 4B shown by line. Scale: hammer

791 (0.4 m long). B., Stratigraphic log of 4.5 m thick succession that contains marine
 792 limestone (Unit 2) near base. C., Limestone (Unit 2) infilling irregularities on
 793 paleosol surface (Unit 1) at 0.5 m on log. D., Gastropods in limestone (Unit 2) at
 794 0.6 m on log. Scale: 5 mm. E., Base of a small (gymnosperm?) stem with roots at
 795 1.2 m on log (Unit 3).

796 **FIGURE 5**—Micrographs of shelly fauna and other features in limestone at 0.6 m on
 797 log in Fig. 4B. All images in plane-polarized light, NBMG 18860. A., Fine-
 798 grained, ostracod-rich, intraclastic wackestone; scale: 1 mm. B., Articulated
 799 ostracod (o) infilled with blocky calcite. In addition to carbonate intraclasts and
 800 lime mud, the matrix contains rare echinoid spines (s) and sucrosic dolomite
 801 rhombs (d); scale: 100 μm . C., Bryozoan fragment (b) and echinoderm clasts (e);
 802 scale: 200 μm . D., Pseudopunctate brachiopod shell; scale: 100 μm . E.,
 803 Echinoderm fragments (e), scale: 100 μm . F., Framboidal pyrite (f). Shell
 804 fragments are ostracods; scale: 200 μm .

805 **FIGURE 6**—Ichnocoenoses at the Emerson Creek site. All images show the base of
 806 bedding surface except (C), which shows broken surface. A., Small bilobed trails
 807 of *Didymaulichnus lyelli* (1) and similar-sized ‘bean’ shaped *Lockeia*, some of
 808 which are bilobed (2), NBMG 16047, Ichnocoenosis A, scale: 5 mm. B., Irregular
 809 trails of *Helminthoidichnites tenuis*, which move up and down relative to bedding.
 810 Some surfaces show microbial wrinkling (arrow), Ichnocoenosis A, NBMG 16046,
 811 scale: 5 mm. C., *Selenichnites* isp., Ichnocoenosis A, not collected, scale 10 mm.
 812 D., Crosier-like burrow, Ichnocoenosis B, not collected, scale: 5 mm. E., Small
 813 bilobed trails of *Didymaulichnus lyelli*, but somewhat larger than in (A),

814 Ichnocoenosis C, not collected, scale: 5 mm. F., *Cochlichnus* isp., Ichnocoenosis
815 C, not collected, scale: 5 mm.

816 **FIGURE 7**—Megafloral remains at the Emerson Creek site (in part, EC-1 of
817 Bashforth et al., 2014). A., *Alethopteris* sp. cf. *A. lancifolia*, specimen on right, not
818 collected, scale: 5 mm. B., *Paripteris pseudogigantea*, NBMG16831, scale: 4 mm.
819 C., cf. *Pseudadiantites rhomboideus*, NBMG16833B, scale: 7 mm. D.,
820 “*Sphenopteris*” *valida*, not collected, scale: 6 mm. E., *Annularia* sp. cf. *A.*
821 *sphenophylloides*, not collected, scale: 10 mm. F., *Lepidostrobohyllum* sp.,
822 NBMG16834, scale: 10 mm. G., *Laveineopteris* sp. cf. *L. hollandica*, not collected,
823 scale: 10 mm. H., *Cordaites* sp. (?), not collected, scale: 25 mm.

824 **FIGURE 8**—Schematic block diagram illustrating a marine incursion into the
825 Cumberland sub-basin of central Nova Scotia and southern New Brunswick (after
826 Falcon-Lang, 2006). Arrows show direction of transgression. Red dotted line
827 delineates the current coastline of the Bay of Fundy.

828 **FIGURE 9**—Patterns of marine and brackish transgressions in the Cumberland sub-
829 basin (compiled from various paleontological data in Dawson, 1868; Calder et al.,
830 2005; Falcon-Lang and Miller, 2007; Grey et al., 2011; Rygel et al., 2014, 2015;
831 Carpenter et al., 2015; this paper) compared with patterns in the cratonic Pennine
832 Basin of the UK (Waters and Condon, 2012). The relative extent (area covered in
833 the Pennine Basin) and salinity of marine incursion is shown. Key: transgressions –
834 blue, fully marine; purple, brackish; dotted purple, possible brackish. In the
835 Pennine Basin dataset, salinity of brackish bands is inferred to increase from (E)
836 *Estheria* band to (F) foraminifer band to (L) *Lingula* band to (B) brachiopod band
837 (Waters and Condon, 2012).

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TABLE CAPTION

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TABLE 1—Limestone petrography at Emerson Creek locality, southern New

841

Brunswick. Abundance index: rare (< 5%), common (5 – 30%), abundant (> 30%).

842

Composition	Frequency	Description
<i>(1) Detrital component</i>		
lime mud	abundant	matrix
intraclasts	common	silt to granule-size lime mudstone clasts
detrital quartz	common	sub-rounded to angular, silt to fine-grained sand
detrital chert	rare	rounded, silt size grains
muscovite	rare	
<i>(2) Bioclastic component</i>		
echinoderms	abundant	echinoids, crinoids and/or blastoids; silt to fine-grained sand size fragments with unit extinction; some with epitaxial cement
ostracods	common	mostly disarticulated and fragmented, but rarely articulated; articulated carapaces occluded with blocky calcite
bivalves	rare	recrystallized shell fragments
brachiopods	rare	unrecrystallized, pseudopunctate shell fragments
bryozoans	rare	fine-grained sand size fragments
echinoid spines	rare	characteristic radial arrangement of pores within individual spines
fish scales	rare	individual scales are honey-brown color and slightly abraded
gastropods	rare	recrystallized shell fragments
<i>Authigenic component</i>		
francolite	rare	apatite peloids; characteristic honey-brown color
framboidal pyrite	rare	
<i>Diagenetic component</i>		
sucrosic dolomite	rare	silt-sized, sucrosic dolomite rhombs

Abundance Index: rare (1 – 5%); common (6 – 30%); abundant (> 30%)

A

B

EASTERN/CENTRAL BASIN

Lithology

	Limestone
	Dark gray mudstone
	Medium gray mudstone
	Green-gray mudstone
	Red mudstone
	Sandstone

Sedimentary structures

	Siderite nodules
	Calcrete nodules
	Green-gray/red mottles
	Ripple cross-lamination
	Horizontal lamination
	Symmetrical ripple marks
	Concave-up joint sets

Megafloral remains

	Cordaite
	Calamitalean foliage
	Calamitalean axis (upright)
	Woody tree (upright)
	Pteridosperms (and allies)
	Indeterminate rootlets

Faunal remains

	Ostracods
	Fish
	Brachiopods
	Gastropods
	Echinoderms