1 **Leaving no stone unturned: the feedback between increased biotic diversity and early**

2 **diagenesis during the Ordovician**

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8 **(Abstract)**

9 Ordovician change in the nature of seafloor carbonates saw rapid decline of previously

10 widespread flat pebble conglomerates and the Palaeozoic peak abundance of hardgrounds.

11 The effective disappearance of flat pebble conglomerates, widely attributed to physical

12 disruption of substrate by bioturbation, is re-interpreted as reflecting increased depth of

13 carbonate precipitation below the Taphonomically Active Zone such that early lithified

14 carbonates were less frequently reworked by scour. With deeper, more stable zones of

15 cementation, exhumed limestones formed hardgrounds, whose mid Ordovician acme

16 supported rapid increase in epizoan diversity. Further deepening of cementation to below

17 normal scour accompanied post-Ordovician decline in submarine hardgrounds.

18 Supplementary material: database for Figure 1 is available at

19 http://www.geolsoc.org.uk/SUP----

20

21 The early Palaeozoic evolutionary and ecological development of benthic metazoans was

22 strongly affected by changes to the nature of the sea floor environment such as increased

23 burrowing activity (e.g. Cambrian Substrate Revolution, Bottjer *et al.* 2000) and widespread

24 development of shallow marine hard substrates (Great Ordovician Biodiversification Event

25 (GOBE); Harper 2006). How did those changes impact upon, and relate to, carbonate

26 systems and shallow sediment diagenesis? Here we consider two characteristic carbonate

27 facies of early Palaeozoic shelf seas: flat pebble conglomerates (FPC) and submarine

28 hardgrounds (carbonate cemented sea floors). Both peak in abundance before rapid decline,

29 the former most widespread in the late Cambrian–early Ordovician, while the latter reach

30 their Palaeozoic acme in the Mid-Late Ordovician (e.g. Taylor 2008, fig. 2).

31   Flat pebble conglomerates (locally breccias) with carbonate intraclasts (rudstones,

32 floatstones) are a striking feature of Late Proterozoic to early Ordovician shallow marine

33 carbonate successions. They were mostly deposited in subtidal, typically offshore settings

34 reflecting storm or tsunami reworking of shallow cemented limestone beds (Mount & Kidder

35 1993; Pratt 2002; Myrow *et al.* 2004; Pratt & Bordonaro 2007). The FPCs are variable in bed

36 geometry and thickness, matrix or clast supported texture, but typically have tabular, thin

37 (<20mm) pebble to cobble sized clasts of fine grainstone to calcimudstone (e.g. Myrow *et al.*

38 2004). This distinctive lithofacies effectively disappears from the stratigraphic record in

39 offshore settings after the Early Ordovician (Sepkoski 1982; Sepkoski *et al.* 1991; Liu &

40 Zhan 2009). The accepted view (e.g. Sepkoski *et al.* 1991) has been that with an Ordovician

41 increase in the extent and depth of burrowing (Droser & Bottjer 1989; Bottjer *et al.* 2000),

42 biotic mixing of the sediment would have prevented early cementation and the formation of

43 thin lithified zones, removing the source for FPCs after scouring by storms or tsunamis.

44   In the Ordovician, submarine hardgrounds become widely developed in shallow seas,

45 colonised by an expanding diversity of encrusting and boring epizoans (e.g. Brett &

46 Brookfield 1984) that form specialized new communities in the GOBE. They have been

47   interpreted as indicating seafloor calcite precipitation and aragonite dissolution in 'calcite

48   seas' (Taylor & Wilson 2003; Palmer & Wilson 2004; Harper 2006; Taylor 2008).

49   The aim of this paper is to provide a single, geochemical explanation for both the

50   decline of subtidal FPC lithofacies and the peak abundance of hardgrounds during the

51   Ordovician.

52

53   **Sea floor diagenesis and changes in sea floor shallow geochemical profiles during the**

54   **early Palaeozoic**

55   The diagenetic processes for mobilization of calcium carbonate during shallow burial have

56   been appreciated for some time (e.g. Sanders 2003; Berkeley *et al.* 2008; Cherns *et al.* 2011).

57   Calcium carbonate, especially the more soluble aragonite, is dissolved in the uppermost

58   sediment layer largely as a result of acidity caused by the oxidation of H_2S, and while most

59   back-fluxes to the water column, some is re-precipitated as calcite in the sediment column in

60   areas of increased alkalinity such as depths where sulfate reduction takes place (e.g. Sanders

61   2003, 2004; Fig. 1). This oxidized zone, effectively the Taphonomically Active Zone (TAZ),

62   will be controlled by diffusion from the overlying water column, if oxygenated, and by

63   mixing caused by bio-irrigation (mainly burrowing; e.g. Aller 1982; Aller & Aller 1998).

64   Organic matter accumulated more among finer grained sediment sources the microbially

65   mediated decay processes that drive skeletal carbonate dissolution and re-precipitation (e.g.

66   Walter & Burton 1990; Walter *et al.* 1993; Hendry 1993). The importance of such processes

67   linked to the mobilization of labile carbonates in the very shallow sediment column forms the

68   basis for understanding the limestone-marl alternations that form a widely developed facies in

69   Phanerozoic epeiric sea settings (Munnecke & Samtleben 1996; Westphal & Munnecke

70   2003; Munnecke & Westphal 2005).

71   Brasier *et al.* (2011) proposed that changes in the position, relative to the sea floor, of

72   the depth of the redox boundary during the Ediacaran–early Cambrian affected the zones of

73   early lithification in the shallow sediment column. Late Proterozoic precipitation of calcium

74   carbonate took place at or very close (<1cm) to the sea floor (also Peters & Gaines 2012), and

75   though the early Cambrian advent of metazoan burrowing and biomineralization depressed

76   the zone of cementation it remained very shallow (early-mid Cambrian subtidal burrow depth

77   <3 cm, typically mm scale: Tarhan *et al.* 2015; Droser & Bottjer 1988). The depth of subtidal

78   bioturbation, and by inference the zone of cementation, remained <6 cm through to the mid

79   Ordovician, before both bioturbation depth (<30 cm) and intensity increased significantly in

80   the Late Ordovician (Droser & Bottjer 1989).

81

Abundance of flat pebble conglomerates and hardgrounds

83   Subtidal FPCs are most common in the late Cambrian–Early Ordovician, before rapid

84   decline, and notably while the TAZ remained very shallow (Fig. 2). Their temporal record,

85   using publications by formation as a proxy for abundance, provides a direct comparison with

86   published data for submarine hardgrounds (Fig. 2; Taylor 2008). A peak FPC distributional

87   map illustrates the extensive occurrence (with a latitudinal control), and suggests any bias

88   from availability of rock formations is likely not significant (Fig. 3). In shallow carbonate

89   epeiric seas of the North China Plate, the subsequent decline of FPCs corresponds to the

90   decrease also in subtidal microbialites and increasing intensity of bioturbation as the shallow

91   sea floor character changed in the late Early Ordovician (early Floian) (Liu 2009; Liu & Zhan

92   2009). Notably, in post-Ordovician times, minor occurrences of subtidal FPCs (Fig. 2)

93   correspond to post-extinction events, when suppression of bioturbation would have led to

94   shallowing of the TAZ (e.g. Wignall & Twitchett 1999; Calner 2005).

95   For submarine hardgrounds (carbonate cemented sea floors) the Palaeozoic peak of

96   abundance is in the Ordovician (Taylor & Wilson 2003; Palmer & Wilson 2004; Harper

97   2006; Taylor 2008; Fig. 2). Early, encrusting hardground faunas are described from surfaces

98   of cemented FPC in the late Cambrian (Brett *et al.* 1983). By the mid Ordovician hard

99   substrate morphologies are variable, some largely comprising reworked, encrusted limestone

100   nodules but others forming beds with complex hummocky and undercut surfaces; hardground

101   biotas are notably more diverse (Brett & Liddell 1978; Brett & Brookfield 1984; Wilson et al.

102   1992). Taylor and Wilson (2003, p. 44) suggested that the "Ordovician was a golden age for

103   epizoans on hard substrates" due in part to increased hard substrate availability. The

104   appearance of encrusters makes hardgrounds more recognizable after the early Ordovician

105   (Brett & Liddell 1978) and likely reflects the availability of more stable substrates as

106   compared with the fragmented cemented layers characteristic earlier in the Palaeozoic.

107   Previously the abundance of hardgrounds had been explained by local calcite

108   cementation sourced from carbonate released by sea-floor dissolution of aragonite in

109   undersaturated (with respect to aragonite) Ordovician 'calcite seas' (Wilson et al. 1992;

110   Taylor & Wilson 2003; Palmer & Wilson 2004; Harper 2006). Recent experimental data,

111   however, indicate that aragonite precipitation continued alongside calcite during 'calcite seas'

112   in warm water environments (Balthasar & Cusack 2015). In a study of Ordovician

113   hardgrounds from eastern North America, Kenyon-Roberts (1995) found no direct evidence

114   for sea floor dissolution, but did note petrographic evidence of hardground formation in

115   shallow sub-oxic conditions below the TAZ. Cherns & Wright (2011), when comparing the

116   taphonomy of skeletal lagerstätten between 'aragonite' and 'calcite seas', found no

117   differences, suggesting that 'calcite seas' did not increase aragonitic shell dissolution.

118

119   **Diagenetic model for Early Palaeozoic subtidal settings** (Fig. 4)

120   As the depth and intensity of burrowing increased through the early Palaeozoic, the TAZ

121   thickened and the depth at which secondary carbonate re-precipitated also deepened. This

122   reduced the probability that lithified carbonate would be exhumed by erosional reworking

123   caused by wave scour. The FPCs in shallow subtidal settings formed only while the TAZ

124   was very thin, and hence the zone of cementation was close to the sediment-water interface

125   allowing even relatively small and frequent scour events (storms or tsunamis) to exhume the

126   cemented horizons (Late Precambrian–late Early Ordovician; Figs 2, 4). As the TAZ

127   thickened and the depth of carbonate precipitation increased, these horizons were less likely

128   to be reworked by scouring. The FPC facies was replaced in shallow subtidal settings by less

129   frequently exhumed, and hence more developed and thicker, cemented horizons, which when

130   eventually exposed by scour formed reworked concretions and hardgrounds on which hard

131   substrate biotas expanded (Mid–Late Ordovician; Figs. 2, 4). Development of these carbonate

132   horizons may have been facilitated by increased skeletal input through diversification and

133   faunal expansion during this interval (Porter 2010). In more offshore settings rarely affected

134   by wave-related erosion, the secondary carbonate could accumulate uninterrupted to produce

135   the nodular, diagenetic bedding of limestone-marl alternations. As the TAZ deepened

136   through the later Ordovician the cementation zone was displaced to deeper levels where

137   reduced likelihood of exhumation led to decline in hardground abundance and more

138   widespread development of diagenetic bedding (Late Ordovician; Fig. 3; Westphal 2006, fig.

139   2). An implication is that diagenetic bedding would have been preserved in shallower areas

140   than previously, assuming that shallower sea floors were more susceptible to periodic

141   reworking than deeper ones (Peters & Loss 2012). This hypothesis is testable if it can be

142   demonstrated that diagenetic bedding is found in shallower settings by the Late Ordovician.

143

Discussion

This model proposes that a single trend, namely the deepening of the zone of cementation below the TAZ, can explain the rapid decline of FPCs, and the peak abundance of hardgrounds during the Ordovician, before their subsequent decline. That progressive change was ultimately a consequence of the previously documented increased depth and intensity of bio-irrigation. Rather than destroying the potential for rapid shallow cementation (Sepkoski 1982; Sepkoski et al. 1991), lowering of the TAZ decreased the likelihood of erosional exhumation of thin cemented carbonate layers by wave scour.

Many variables affected early diagenesis during the early Palaeozoic, including increased nutrient-rich organic matter and oxygen levels in sea floor sediments as a result of metazoan evolution (McIlroy & Logan 1999; Bottjer *et al.* 2000, Dornbos *et al.* 2005). The amount of labile aragonite from skeletal carbonate dissolution also likely increased with biomineralization, although the skeletal contribution to carbonate deposition remained limited up to mid Ordovician times (e.g. Pruss *et al.* 2010, fig. 8). Could the thinness of limestone beds ripped up to form FPCs from latest Proterozoic to Early Ordovician be explained by lower flux of carbonate from skeletal dissolution before the GOBE rather than reflecting frequency of exhumation at shallow burial depths? Although the intensity of bio-irrigation increased markedly in the Early Cambrian, bioturbation depth (<6 cm) remained shallow through to the Late Ordovician, when both depth (<30 cm) and average ichnofabric index increased substantially (Droser & Bottjer 1989; Tarhan *et al.* 2015). If changes in the biogeochemical environment of the upper sediment layers were a consequence of that deeper and more intense bio-irrigation, accompanied by increased oxygenation of the seas and oversaturation (Pruss *et al.* 2010) that affected diagenetic carbonate precipitation, what other effects took place in terms of carbonate behaviour? The biogenically reworked mixed layer increased only slowly, from 0.2 cm in the early-mid Cambrian to 1.5 cm in the Ordovian-

169   Silurian (Tarhan *et al.* 2015). Could the presence of a thin TAZ potentially result in higher

170   levels of acidity through sulfide oxidation and a greater degree of undersaturation with

171   respect to aragonite, compared with today's thicker TAZ?

172   Organisms with more labile, aragonitic shells (primarily molluscs) are diverse in the

173   early Cambrian radiation although their fossils are relatively sparse in the trilobite dominated

174   Cambrian–Lower Ordovician skeletal record (Porter 2007; Porter *et al.* 2010). From the mid

175   Ordovician, skeletal material was a major contributor to carbonate sediment; limestone shell

176   beds, most commonly brachiopod-rich, increase in proportion, thickness and abundance in

177   shallow marine settings (Kidwell and Brenchley 1994; Li & Droser 1997, 1999; Pruss *et al.*

178   2010). Molluscs are dominant in some storm beds, most commonly representing local

179   reworking of concentrations of dead gastropod shells accumulated in the upper sediment

180   layers (Li & Droser 1999; Harper 2006, fig. 9). Did a thicker TAZ later in the Ordovician

181   result in less intense sulfide oxidation, less dissolution and a longer survival time of aragonite

182   shells in the TAZ?

183   The Palaeozoic decrease in abundance of hardgrounds after the Ordovician (Fig. 2) is

184   here interpreted as reflecting the lowering of the TAZ and cementation zone to depths in the

185   sediment column affected less frequently by wave (storm or tsunami) reworking. It might

186   also imply that such reworking later rarely affected sediments much below the TAZ at 30cm.

187   Mesozoic peaks of hardground occurrence (Fig. 2) may in part reflect large outcrop areas of

188   marine sediments (Smith and McGowan 2007), such as the Cretaceous Chalk. The extensive

189   hardgrounds of the middle Jurassic are hosted predominantly in very shallow, oolitic facies

190   and are of much more diverse origins than those of the Ordovician (Kenyon-Roberts 1995).

191

192   **Conclusions**

193 The decline of flat pebble conglomerates and the peak abundance of submarine hardgrounds

194 in the Ordovician are interpreted as reflecting the progressive deepening of the zone of

195 carbonate precipitation below the TAZ, resulting in less frequent reworking of the upper part

196 of the sediment column by scour. The deepening was a consequence of increased depth and

197 intensity of bioturbation and bio-irrigation. This shift also created a range of more lithified

198 substrates in subtidal settings, promoting a rapid expansion in epizoan diversity. Thus,

199 changes in bioturbation affected carbonate diagenesis and the composition of the sea floor

200 carbonates, and provided new niches for invertebrates.

201

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206 **References**

207 Aller, R.C. 1982. Carbonate dissolution in nearshore terrigenous muds: the role of physical

208   and biological reworking. *Journal of Geology*, **90**, 79-95.

209 Aller, R.C. & Aller, J.Y. 1998. The effect of biogenic irrigation intensity and solute exchange

210   on diagenetic reaction rates in marine sediments. *Journal of Marine Research*, **56**,

211   905-936.

212 Balthasar, U. & Cusack, M. 2015. Aragonite-calcite seas—Quantifying the gray area.

213   *Geology*, **43**, 99-102.

214 Berkeley, A., Perry, C.T., Smithers, S.G., Horton, B.P. & Taylor, K.G. 2007. A review of the

215 ecological and taphonomic controls on foraminiferal assemblage development in

216 intertidal environments. *Earth-Science Reviews*, **83**, 205-230.

217 Bottjer, D.J., Hagadorn, J.W. & Dornbos, S.Q. 2000. The Cambrian substrate revolution.

218 *GSA today*, **10**, 1-7.

219 Brasier, M.D., Antcliffe, J.B. & Callow, R.H.T. 2011. Evolutionary trends in remarkable

220 fossil preservation across the Edicaran-Cambrian transition and the impact of

221 metazoan mixing. *In*: Allison, P.A. & Bottjer, D.J. (eds.) *Taphonomy: process and*

222 *bias through time*. Springer, Berlin, 519-567.

223 Brett, C.E. & Brookfield, M.E. 1984. Morphology, faunas and genesis of Ordovician

224 hardgrounds from southern Ontario, Canada. *Palaeogeography, Palaeoclimatology,*

225 *Palaeoecology*, **46**, 233-290.

226 Brett, C.E. & Liddell, W.D. 1978. Preservation and palaeoecology of a Middle Ordovician

227 hardground community. *Paleobiology*, **4**, 329-348.

228 Brett, C.E., Liddell, W.D. & Derstler, K.L. 1983. Late Cambrian hard substrate communities

229 from Montana/Wyoming: the oldest known hardground encrusters. *Lethaia*, **16**, 281-

230 289.

231 Calner, M. 2005. A Late Silurian extinction event and anachronistic period. *Geology*, **33**,

232 305-308.

233 Cherns, L., Wheeley, J.R. & Wright, V.P. 2011. Taphonomic bias in shelly faunas through

234 time: early aragonite dissolution and its implications for the fossil record. *In*: Allison,

235 P.A. & Bottjer, D.J. (eds.) *Taphonomy: process and bias through time*. Springer,

236 Berlin, 79-105.

237 Cherns, L. & Wright, V.P. 2011. Skeletal mineralogy and biodiversity of marine

238   invertebrates: size matters more than seawater chemistry. *Geological Society, London,*

239   *Special Publications,* **358**, 9-17.

240 Dornbos, S.Q., Bottjer, D.J. & Chen, J.-Y. 2005. Paleoecology of benthic metazoans in the

241   Early Cambrian Maotianshan Shale biota and the Middle Cambrian Burgess Shale

242   biota: evidence for the Cambrian substrate revolution. *Palaeogeography,*

243   *Palaeoclimatology, Palaeoecology*, **220**, 47-67.

244 Droser, M.L. & Bottjer, D.J. 1988. Trends in depth and extent of bioturbation in Cambrian

245   carbonate marine environments, western United States. *Geology*, **16**, 233-236.

246 Droser, M.L. & Bottjer, D.J. 1989. Ordovician increase in extent and depth of bioturbation:

247   Implications for understanding early Paleozoic ecospace utilization. *Geology*, **17**, 850-

248   852.

249 Harper, D.A. 2006. The Ordovician biodiversification: setting an agenda for marine life.

250   *Palaeogeography, Palaeoclimatology, Palaeoecology*, **232**, 148-166.

251 Hendry, J.P. 1993. Calcite cementation during bacterial manganese, iron and sulphate

252   reduction in Jurassic shallow marine carbonates. *Sedimentology*, **40**, 87-106.

253 Kenyon-Roberts, S.M. 1995. *The petrography and distribution of some calcite sea*

254   *hardgrounds.* PhD thesis, University of Reading.

255 Kidwell, S.M. & Brenchley, P.J. 1994. Patterns in bioclastic accumulation through the

256   Phanerozoic - changes in input or in destruction?. *Geology*, **22**, 1139-1143.

257 Li, X. & Droser, M.L. 1997. Nature and distribution of Cambrian shell concentrations:

258   Evidence from the Basin and Range Province of the Western United States

259   (California, Nevada, and Utah). *PALAIOS*, **12**, 111-126.

260 Li, X. & Droser, M.L. 1999. Lower and Middle Ordovician shell beds from the Basin and

261   Range province of the western United States (California, Nevada, and Utah).

262   *PALAIOS*, **14**, 215-233.

263 Liu, J. 2009. Marine sedimentary response to the Great Ordovician Biodiversification Event:

264   examples from North China and South China. *Paleontological Research*, **13**, 9-21.

265 Liu, J. & Zhan, R. 2009. Temporal distribution of diagnostic biofabrics in the Lower and

266   Middle Ordovician in North China: clues to the geobiology of the Great Ordovician

267   Biodiversification Event. *Acta Geologica Sinica*, **83**, 513-523.

268 McIlroy, D. & Logan, G.A. 1999. The impact of bioturbation on infaunal ecology and

269   evolution during the Proterozoic-Cambrian transition. *PALAIOS*, **14**, 58-72.

270 Mount, J.F. & Kidder, D. 1993. Combined flow origin of edgewise intraclast conglomerates:

271   Sellick Hill Formation (Lower Cambrian), South Australia. *Sedimentology*, **40**, 315-

272   329.

273 Munnecke, A. & Samtleben, C. 1996. The formation of micritic limestones and the

274   development of limestone–marl alternations in the Silurian of Gotland, Sweden.

275   *Facies*, **34**, 159-176.

276 Munnecke, A. & Westphal, H. 2005. Variations in primary aragonite, calcite, and clay in

277   fine-grained calcareous rhythmites of Cambrian to Jurassic age — an environmental

278   archive? *Facies*, **51**, 611-626.

279 Myrow, P., M. , Tice, L., Archuleta, B., Clark, B., Taylor, J.F. & Ripperdan, R.L. 2004. Flat-
280   pebble conglomerate: its multiple origins and relationship to metre-scale depositional
281   cycles. *Sedimentology*, **51**, 973-996.

282 Palmer, T. & Wilson, M. 2004. Calcite precipitation and dissolution of biogenic aragonite in
283   shallow Ordovician calcite seas. *Lethaia*, **37**, 417-427.

284 Peters, S.E. & Gaines, R.R. 2012 Formation of the 'Great Unconformity' as a trigger for the
285   Cambrian explosion. *Nature*, **484**, 363-366.

286 Peters, S.E. & Loss, D.P. 2012. Storm and fair-weather wave base: A relevant distinction?
287   *Geology*, **40**, 511-514.

288 Porter, S.M. 2007. Seawater chemistry and early carbonate biomineralization. *Science*, **316**,
289   1302-1302.

290 Porter, S.M. 2010. Calcite and aragonite seas and the de novo acquisition of carbonate
291   skeletons. *Geobiology*, **8**, 256-277.

292 Pratt, B.R. 2002. Storms versus tsunamis: Dynamic interplay of sedimentary, diagenetic, and
293   tectonic processes in the Cambrian of Montana. *Geology*, **30** 423-426.

294 Pratt, B.R. & Bordonaro, O.L. 2007. Tsunamis in a stormy sea: Middle Cambrian inner-shelf
295   limestones of western Argentina. *Journal of Sedimentary Research*, **77**, 256-262.

296 Pruss, S.B., Finnegan, S., Fischer, W.W. & Knoll, A.H. 2010. Carbonates in skeleton-poor
297   seas: new insights from Cambrian and Ordovician strata of Laurentia. *PALAIOS*, **25**,
298   73-84.

299   Sanders, D. 2003. Syndepositional dissolution of calcium carbonate in neritic carbonate

300   environments: geological recognition, processes, potential significance. *Journal of*

301   *African Earth Sciences*, **36**, 99-134.

302   Sanders, D. 2004. Potential significance of syndepositional carbonate dissolution for platform

303   banktop aggradation and sediment texture: a graphic modeling approach. *Austrian*

304   *Journal of Earth Sciences*, **95/96**, 71-79.

305   Sepkoski, J.J., Jr. 1982. Flat-pebble conglomerates, storm deposits, and the Cambrian bottom

306   fauna. *In*: Einsele, G. & Seilacher, A. (eds.) *Cyclic and Event Stratification*. Springer-

307   Verlag, 371-386.

308   Sepkoski, J.J., Jr, Bambach, R.K. & Droser, M.L. 1991. Secular changes in Phanerozoic

309   event bedding and the biological overprint. *In*: Einsele, G., Ricken, W. & Seilacher,

310   A. (eds.) *Cycles and events in stratigraphy*. Springer-Verlag, 298-312.

311   Smith, A.B. & McGowan, A.J. 2007. The shape of the Phanerozoic marine palaeodiversity

312   curve: how much can be predicted from the sedimentary rock record of Western

313   Europe? Palaeontology, **50**, 765-774.

314   Tarhan, L.G., Droser, M.L., Planavsky, N.J. & Johnston, D.T. 2015. Protracted development

315   of bioturbation through the early Palaeozoic Era. *Nature Geoscience*, advance online

316   publication, doi: 10.1038/ngeo2537.

317

318   Taylor, P.D. 2008. Seawater chemistry, biomineralization and the fossil record of calcareous

319   organisms. *In*: Okada, H., Mawatari, S.F., Suzuki, N. & Gautam, P. (eds.) *Origin and*

320   *Evolution of Natural Diversity:* Proceedings of International Symposium "The Origin

321   and Evolution of Natural Diversity", 1-5 October 2007, Sapporo, Japan. Hokkaido

322   University. 21-29.

323

324   Taylor, P.D. & Wilson, M.A. 2003. Palaeoecology and evolution of marine hard substrate

325   communities. *Earth-Science Reviews*, **62**, 1-103.

326   Torsvik, T.H. 2009. *Bugplates software (IGCP503)*. With reconstructions of Torsvik, T. H.

327   and Cocks, L. R. M. (2002-2009). StatoilHydro.

328   http://www.geodynamics.no/bugs/SoftwareManual.pdf.

329   Walter, L.M., Bischof, S.A., Patterson, W.P. & Lyons, T.W. 1993. Dissolution and

330   Recrystallization in Modern Shelf Carbonates - Evidence from Pore-Water and Solid-

331   Phase Chemistry. *Philosophical Transactions of the Royal Society of London, Series*

332   *A,* **344**, 27-36.

333   Walter, L.M. & Burton, E.A. 1990. Dissolution of platform carbonate sediments in marine

334   pore fluids. *American Journal of Science*, **290**, 601-643.

335   Westphal, H. 2006. Limestone–marl alternations as environmental archives and the role of

336   early diagenesis: a critical review. *International Journal of Earth Sciences*, **95**, 947-

337   961.

338   Westphal, H. & Munnecke, A. 2003. Limestone-marl alternations: A warm-water

339   phenomenon? *Geology*, **31**, 263-266.

340   Wignall, P.B. & Twitchett, R.J. 1999. Unusual intraclastic limestones in Lower Triassic

341   carbonates and their bearing on the aftermath of the end-Permian mass extinction.

342   *Sedimentology*, **46**, 303-316.
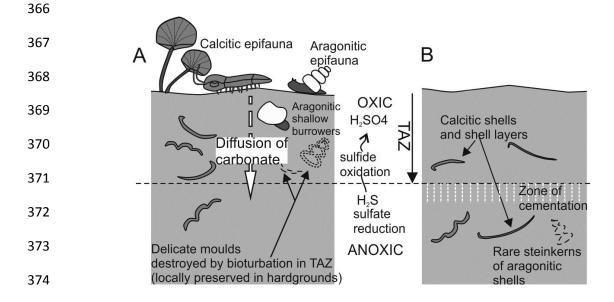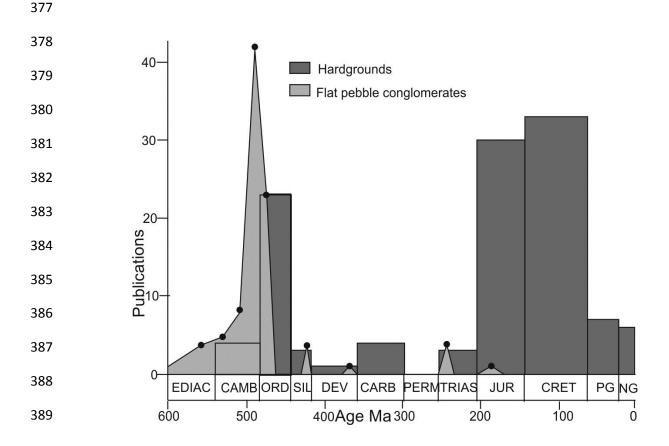
343 **Figure Captions**

344 Figure 1. Shallow burial diagenetic environment and calcium carbonate precipitation. A,

345 labile aragonite shells (molluscs), more susceptible to early dissolution in the oxic upper

346 sediment layers of the Taphonomically Active Zone (TAZ), release carbonate and leave

347 moulds that are readily destroyed through bioturbation. B, calcitic shells more likely to

348 survive early dissolution, and more rarely steinkerns of aragonitic shells; diffused carbonate

349 precipitates in a zone of cementation in the sulfate reduction zone.

350 Figure 2. Abundance (using publications by formation as proxy) of subtidal flat pebble

351 conglomerates (pale, points; supplemental information available online

352 at www.geolsoc.org.uk/SUP0xxxx) and submarine hardgrounds (dark, histogram; based on

353 Taylor 2008 and http://markwilson.voices.wooster.edu/bioerosion-bibliography/). Note:

354 revision of Cambrian stratigraphy into four series is ongoing; divisions into Lower, Middle

355 and Upper series follow standard usage in literature.

356 Figure 3. Palaeogeographic reconstruction for 485 Ma (Bugplates IGCP503; T.H. Torsvik

357 2009) showing late Cambrian–early Ordovician extent of flat pebble conglomerate facies

358 (black stars).

359 Figure 4. Diagenetic model for carbonate precipitation in subtidal Palaeozoic settings,

360 showing early Cambrian through Ordovician changes in the depth of the Taphonomically

361 Active Zone (TAZ) and zone of cementation, susceptibility of lithified limestone layers to

362 scouring, and distribution of flat pebble conglomerates, submarine hardgrounds and the

363 diagenetic nodular bedding of limestone-marl alternations. SWI sediment-water interface.

364

365   Figure 1.

366

376   Figure 2.

17

390   Figure 3.

391

485 Ma

Laurentia

S China

Green-
land

Siberia

N China

Baltica

401   Figure 4.

Late Precambrian–
Early Ordovician

Mid–Late Ordovician

Late Ordovician ...

exhumation
by scouring

SWI

FLAT PEBBLES

HIATUS
CONCRETIONS

HARDGROUNDS

max.depth
of scouring

Thickening and deepening of
carbonate layer
- longer residence time
- exhumation less likely

IN SITU NODULAR
DIAGENETIC BEDDING

TAZ and carbonate
precipitation zone

402

404   Flat pebble conglomerates from subtidal settings (Fig. 2)

AGE	LOCATION	FORMATION	SHELF SETTING	PROPOSED PROCESS	AUTHOR(S)
Mesoproterozoic	China, Hebei Province	Gaoyuzhuang Formation	Subtidal within storm wave base	storms	Luo *et al.* 2014
Proterozoic, Pre-Marinoan glaciation	NW Canada, Mackenzie Mountains	Keele Fm	mid to outer ramp	storms	Day *et al.* 2004
Vendian	Gourma, West Africa		slope	bottom currents'	Bertrand-Sarfati & Moussine-Pouchkine 1983
Ediacaran	South Africa	Swartpunt Fm	Low energy deeper ramp	storm	Narbonne *et al.* 1997
Ediacaran	Canadian Arctic	Gametrail Fm	subtidal ramp	storms	MacNaughton *et al.* 2008
Ediacaran	Kazakhstan	Kyrshabakty Formation	shallow carbonate platform	high energy events	Heubeck *et al.* 2013
Ediacaran - Lower Cambrian	Oman	Ara Group	carbonate platform		Grotzinger & Al-Rawahi 2014
Lower Cambrian	South Australia	Sellick Hill Formation	subtidal	storms	Mount & Kidder 1993
Lower Cambrian	W Mongolia	Bayan Gol Fm, Zavkhan Basin	shallow subtidal	storms	Kruse *et al.* 1996
Lower Cambrian	South China	Shuijingtuo Fm	subtidal		Ishikawa *et al.* 2008
Middle Cambrian	Canadian Arctic		ramp		Dewing & Nowlan 2012
Middle Cambrian	British Columbia, Canada	Jubilee Fm			Pope 1990

Middle Cambrian	Argentina	La Laja Fm	subtidal shelf	tsunamis	Pratt & Bordonaro 2007
Middle Cambrian	Australia	Ranken Lst	low energy shallow subtidal	storms	Kruse 1996
Middle Cambrian	Wyoming, USA	Upper Gros Ventre Shale			Csonka 2009
upper Middle Cambrian	W Utah, USA	upper Wheeler, Marjum fms	middle carbonate belt - subtidal shelf		Robison 1964
Middle-Upper Cambrian	NW China		Supratidal to subtidal fpc	storms	Liang *et al.* 1993
Middle Cambrian - Lower Ordovician	Siberia	Ust'-Brus,Labaz, Orakta, Kulyumbe, Ujgur and Iltyk fms			Kouchinsky *et al.* 2008
Upper Cambrian	NW Siberia	Chopko Fm, Chopka River	carbonate platform, turbidites	submarine landslides	Varlamov *et al.* 2006
Upper Cambrian	N China	Gushan, Chanshang formations	subtidal shelf	storms	Ding *et al.* 2008; Meng *et al.* 1997
Upper Cambrian	China, Shandong Province	Chaomidian Formation (Furongian)	shallow subtidal		Lee *et al.* 2010; Chen 2014; Chen *et al.* 2009, Chen *et al.* 2010; Van Loon *et al.* 2013
Upper Cambrian	S Korea	Hwajeol Formation	subtidal, relatively deep		Kim & Lee 2000
U Cambrian	Western USA		Outer detrital belt (subtidal lagoon)	Storms	Sepkoski 1982
Upper Cambrian	Rocky Mts USA	Snowy Range Fm (Sunwaptan-L Skullrockian)	Inner detrital belt, subtidal	Storms (leading to slope failure)	Brett *et al.* 1983; Myrow *et al.* 2004; Myrow *et al.* 2012
Upper Cambrian	Montana USA	Deadwood Fm	subtidal shelf	tsunamis	Pratt 2002

Upper Cambrian	Wyoming, USA	Snowy Range Fm - Upper Deadwood Formation	subtidal intrashelf basin	storms	Saltzman 1999; Myrow *et al.* 2004
Upper Cambrian	Wyoming, USA			fpc produced by dewatering	Wiison 1985; Kozub 1997
Upper Cambrian	Virginia, USA	Nolichucky Formation	shallow subtidal basin facies	storms	Markello & Read 1981, 1982
Upper Cambrian	Nevada and Utah, USA	SPICE interval	Intrashelf basin	storms	Saltzman *et al.* 1998
Upper Cambrian	Montana USA	Grove Creek, Snowy Range, Maurice formations			Dorf & Lochman 1940
Upper Cambrian	Maryland, USA	Conococheague Limestone	sand shoal environments		Demicco 1985; Demicco *et al.* 1991
Upper Cambrian	Virginia, USA	Conococheague Limestone, Copper Ridge Dolomite	Group I outer shelf	storms	Whisonant 1987
Upper Cambrian	Tennessee, USA	Maynardsville Fm, Conosauga Group	subtidal		Glumac and Walker 1997
Upper Cambrian	Wisconsin and Minnesota, USA	Tunnel City Group	shallow subtidal	storms	Eoff 2014
Upper Cambrian	California, USA	Nopah Fm (Sunwaptan); also Desert Valley Formation, Whipple Cave Formation, Notch Peak Formation, Ajax Dolomite	shallow subtidal	storms	Shapiro & Awramik 2006
Upper Cambrian	S Alberta, Canada	Bison Creek and Mistaya formations	shallow subtidal shelf	storms	Westrop 1989

Upper Cambrian - Lower Ordovician	Alberta , Canada	Survey Peak Fm; Ibexian-Tremadoc			Ji & Barnes 1996
Upper Cambrian - Lower Ordovician	Mexico	Ti˜nu Fm	subtidal dysoxic shelf	debris flows	Landing *et al.* 2007
Upper Cambrian - Lower Ordovician	N China	Fengshan Formation - Yeli Formation	subtidal shelf		Yang *et al.* 2002
Upper Cambrian - Lower Ordovician	China, Jilin Province	candidate GSSP Xiaoyangqiao	subtidal	storms	Chen *et al.* 1988
Upper Cambrian - Lower Ordovician	Utah, USA; Nevada USA	Notch Peak and House Limestone fms; Whipple Cove and House Limestone fms	shoals on shallow carbonate shelf		Popov *et al.* 2002; Cook & Taylor 1975, 1977
Upper Cambrian - Lower Ordovician	Colorado, USA	Dotsero Fm, Manitou Fm			Berg 1960
Lower and Upper Cambrian, Lower Ordovician	Appalachians , USA	Dunham Fm; Pine Plains Fm; Ogdenburg and Tribes Hill fms		storms	Friedman 1994
Upper Cambrian - Lower Ordovician	Siberia	Nya sequence	shallow carbonate platform		Dronov *et al.* 2009
Upper Cambrian - Lower Ordovician	Mid-East Korea	Choson Supergroup	subtidal	storm, diagenetic lsts	Kwon *et al.* 2002
Lower Ordovician	Newfound-land	Watt's Bight and Boat harbour fms	deep subtidal to peritidal	storms	Pruss *et al.* 2010

Lower Ordovician	Utah, USA	Pogonip Group - Notch Peak Formation, House Limestone, Fillmore Formation, and Wah Wah Limestone	shallow subtidal to peritidal		Pruss *et al.* 2010
Lower Ordovician	S Korea	Dumugol Fm	shallow to deep ramp	storms	Lee & Kim 1992
Lower Ordovician	Korea	Mungok Fm	subtidal shelf	storms	Kim and Lee 1995; Choi, Kim & Lee 1993
Lower Ordovician	NY, USA	Tribes Hill Fm	intertidal to supratidal	desiccation and high energy events (seismic /storm /tsunami?)	Braun & Friedman 1969
Lower Ordovician (Tremadoc)	Pingquan, Hebei Province, N China		shallow subtidal to shaly basinal		Liu & Zhan 2009
Lower Ordovician	Pingquan, Hebei Province, N China and Xingshan, Hubei Province, S China		Lower Tremadoc shallow subtidal, Upper Tremadoc shallow to deep subtidal		Liu 2009
Lower Ordovician	NW Hubei	Nantsinkian-lower Dawan fms; Tremadoc - early Floian	shallow marine carbonate platform; shallow to deeper subtidal		Liu *et al.* 2011
Lower Ordovician	Nevada, USA	Ninemile Shale	within storm wave base	storms	Sprinkle & Guensburg 1995

Lower Ordovician	Utah and Nevada, USA	Kanosh Shale	Intrashelf basin	storms	Wilson *et al.* 1992
Lower Ordovician	Utah	Fillmore Formation	storm dominated shelf	storms	Sprinkle & Guensburg 1995; Dattilo 1993; Benner *et al.* 2004
Upper Silurian	Gotland, Sweden	upper Hemse-Eke fms	subtidal to very shallow, microbial shoals	anachronistic facies - suppressed burrowing	Cherns 1982, 1983; Calner 2005
Upper Silurian	Somerset Is., Arctic Canada	Reach Bay Fm	Subtidal within storm wave base	storms	Jones & Dixon 1976
Upper Devonian (Frasnian)	Holy Cross Mts, Poland		Shallow subtidal	storms or tsunamis	Kazmierczak & Goldring 1978
Lower Triassic	S Turkey	Dienerian Fm	storms affecting shallow shelf	anachronistic facies - suppressed burrowing	Pruss *et al.* 2006
Lower Triassic	South China; North Italy		storm-dominated shelf to deep basin; mid ramp carbonates	anachronistic facies - suppressed burrowing	Wignall & Twitchett 1999
Lower Triassic	SW USA	Moenkopi - Union Wash formations	subtidal to deep	anachronistic facies - suppressed burrowing	Pruss *et al.* 2005; Woods 2009
Lower Jurassic	Portugal	Achada Dolomites and Limestones	Subtidal	dip-slip movements causing tsunamis	Kullberg *et al.* 2001

405

406 **Reference list:**

407 Benner, J.S., Ekdale, A.A. & De Gibert, J.M. 2004. Macroborings (Gastrochaenolites) in

408 Lower Ordovician hardgrounds of Utah: Sedimentologic, paleoecologic, and

409 evolutionary implications. *PALAIOS*, **19**, 543-550, doi: 10.1669/0883-

410 1351(2004)019<0543:mgiloh>2.0.co;2.

411 Berg, R.R. 1960. Cambrian and Ordovician history of Colorado *In*: Weimar, R.J. & Haun,

412   J.D. (eds) *Guide to the geology of Colorado*. Geological Society of America, Rocky

413   Mountain Association of Geologists, and Colorado Scientific Society, Denver, 10-17

414 Bertrand-Sarfati, J. & Moussine-Pouchkine, A. 1983. Platform-to-basin facies evolution: the

415   carbonates of Late Proterozoic (Vendian) Gourma (West Africa). *Journal of*

416   *Sedimentary Research*, **53,** 275-293.

417 Braun, M. & Friedman, G.M. 1969. Carbonate lithofacies and environment of the Tribes

418   Hill Formation (Lower Ordovician) of the Mohawk Valley, New York. *Journal of*

419   *Sedimentary Petrology*, **39**, 113-135.

420 Brett, C.E., Liddell, W.D. & Derstler, K.L. 1983. Late Cambrian hard substrate

421   communities from Montana/Wyoming: the oldest known hardground encrusters

422   *Lethaia*, **16**, 281-289.

423 Calner, M. 2005. A Late Silurian extinction event and anachronistic period. *Geology*, **33**,

424   305-308.

425 Chen, J. 2014. Surface and subsurface reworking by storms on a Cambrian carbonate

426   platform: evidence from limestone breccias and conglomerates. *Geologos*, **20**, 13-

427   23.

428 Chen, J., Chough, S.K., Chun, S.S. & Han, Z. 2009. Limestone pseudoconglomerates in the

429   Late Cambrian Gushan and Chaomidian Formations (Shandong Province, China):

430   soft-sediment deformation induced by storm-wave loading. *Sedimentology*, **56**,

431   1174-1195.

432 Chen, J., Han, Z., Zhang, X., Fan, A. & Yang, R. 2010. Early diagenetic deformation

433   structures of the Furongian ribbon rocks (Shandong Province, China) – a new

434   perspective of the genesis of limestone conglomerates. *Science China Earth*

435   *Sciences* **53,** 241-252**.**

436 Chen, J., Qian, Y., Zhang, J., Lin, Y., Yin, L., Wang, Z.-h., Wang, Z.-z., Yang, J. & Wang,

437   Y. 1988. The recommended Cambrian-Ordovician global boundary stratotype of the

438   Xiaoyangqiao section (Dayangcha, Jilin Province), China. *Geological Magazine*,

439   **125**, 415-444.

440 Cherns, L. 1982. Palaeokarst, tidal erosion surfaces and stromatolites in the Silurian Eke

441   Formation of Gotland, Sweden. *Sedimentology*, **29**, 819-833.

442 Cherns, L. 1983. The Hemse-Eke boundary facies relationships in the Ludlow series of

443   Gotland, Sweden. *Sveriges Geologiska Undersökning, Series C*, **800**, 1-45.

444 Choi, Y.S., Kim, J.C. & Lee, Y.I. 1993. Subtidal, flat-pebble conglomerates from the Early

445   Ordovician Mungok Formation, Korea : origin and depositional process. *Journal of

446   the Geological Society, Korea*, **29**, 15-29.

447 Cook, H.E. & Taylor, M.E. 1975. Early Paleozoic continental margin sedimentation,

448   trilobite biofacies, and the thermocline, western United States. *Geology*, **3**, 559-562.

449 Cook, H.E. & Taylor, M.E. 1977. Comparison of continental slope and shelf environments

450   in the Upper Cambrian and lowest Ordovician of Nevada *In*: Cook, H.E. & Enos, P.

451   (eds) *Deep-Water Carbonate Environments. Society of Economic Paleontologists

452   and Mineralogists Special Publication* , **25**, 51-81.

453 Csonka, J.D. 2009. *Sedimentary dynamics and stratinomy of a Middle Cambrian ichnofossil

454   lagerstätte, Gros Ventre Formation, Wyoming, USA*. MS thesis, Michigan State

455   University, ProQuest, UMI 1468318, 91 p.

456 Dattilo, B.F. 1993. The Lower Ordovician Fillmore Formation of western Utah: storm-

457   dominated sedimentation on a passive margin. *Brigham Young University Geology

458   Studies*, **39,** 71-100.

459   Day, E.S., James, N.P., Narbonne, G.M. & Dalrymple, R. 2004. A sedimentary prelude to

460   Marinoan glaciation, Cryogenian (Middle Neoproterozoic) Keele Formation,

461   Mackenzie Mountains, northwestern Canada. *Precambrian Research*, **133**, 223-247.

462   Demicco, R., V., Spencer, R.J., Waters, B.B. & Cloyd, K.C. 1991. Two-dimensional models

463   of a Cambrian carbonate shelf deposit. Kansas Geological Survey Bulletin, **233** 463-

464   472.

465   Demicco, R.V. 1985. Platform and off-platform carbonates of the Upper Cambrian of

466   western Maryland. *Sedimentology*, **32**, 1-22.

467   Dewing, K. & Nowlan, G. 2012. The Lower Cambrian to Lower Ordovician carbonate

468   platform and shelf margin, Canadian Arctic Islands. *In*: Derby, J.R., Fritz, R.D.,

469   Longacre, S.A., Morgan, W.A. & Sternbach, C.A. (eds) *The great American*

470   *carbonate bank: The geology and economic resources of the Cambrian-Ordovician*

471   *Sauk megasequence of Laurentia. AAPG Memoir*, **98**, 627-647.

472   Ding, Y., Bai, Z., Liu, J. & Han, Z. 2008. Multiple origins of flat-pebble conglomerate and

473   sedimentary environments of the Gushan Formation at Tangwangzhai in Shandong

474   Province. *Journal of Palaeogeography*, **10**, 125-138.

475   Dorf, E. & Lochman, C. 1940. Upper Cambrian formations in southern Montana.

476   *Geological Society of America Bulletin*, **51**, 541-556.

477   Dronov, A., Kanygin, A., Timokhin, A., Tolmacheva, T.Y. & Gonta, T. 2009. Correlation

478   of eustatic and biotic events in the Ordovician paleobasins of the Siberian and

479   Russian platforms. *Paleontological Journal*, **43**, 1477-1497.

480   Eoff, J.D. 2014. Sedimentary facies of the upper Cambrian (Furongian; Jiangshanian and

481   Sunwaptan) Tunnel City Group, Upper Mississippi Valley: New insight on the old

482   stormy debate. Sedimentary Geology, **302**, 102-121, doi:

483   http://dx.doi.org/10.1016/j.sedgeo.2013.09.008.

484   Friedman, G.M. 1994. Upper Cambrian-Lower Ordovician (Sauk) platform carbonates of

485   the northern Appalachian (Gondwana) passive margin. *Carbonates and Evaporites*,

486   **9**, 143-150.

487   Glumac, B. & Walker, K.R. 1997. Selective dolomitization of Cambrian microbial

488   carbonate deposits: A key to mechanisms and environments of origin. *PALAIOS*, 98-

489   110.

490   Grotzinger, J. & Al-Rawahi, Z. 2014. Depositional facies and platform architecture of

491   microbialite-dominated carbonate reservoirs, Ediacaran-Cambrian Ara Group,

492   Sultanate of Oman. *AAPG Bulletin*, **98**, 1453-1494.

493   Heubeck, C., Ergaliev, G. & Evseev, S. 2013. Large-scale seismogenic deformation of a

494   carbonate platform straddling the Precambrian-Cambrian Boundary, Karatau Range,

495   Kazakhstan. *Journal of Sedimentary Research*, **83**, 1005-1025, doi:

496   10.2110/jsr.2013.76.

497   Ishikawa, T., Ueno, Y., Komiya, T., Sawaki, Y., Han, J., Shu, D., Li, Y., Maruyama, S. &

498   Yoshida, N. 2008. Carbon isotope chemostratigraphy of a Precambrian/Cambrian

499   boundary section in the Three Gorge area, South China: prominent global-scale

500   isotope excursions just before the Cambrian Explosion. *Gondwana Research*, **14**,

501   193-208.

502   Ji, Z. & Barnes, C.R. 1996. Uppermost Cambrian and Lower Ordovician conodont

503   biostratigraphy of the Survey Peak Formation (Ibexian/Tremadoc), Wilcox Pass,

504   Alberta, Canada. *Journal of Paleontology*, **70**, 871-890.

505   Jones, B. & Dixon, O.A. 1976. Storm deposits in the Reach Bay Formation (upper Silurian),

506   Sumerset Island, Arctic Canada (An application of Markov chain analysis). *Journal

507   of Sedimentary Petrology*, **46**, 393-401.

508   Kazmierczak, J. & Goldring, R. 1978. Subtidal flat-pebble conglomerate from the Upper

509   Devonian of Poland: a multiprovenant high-energy product. *Geological Magazine*,

510   **115**, 359-366.

511   Kim, J.C. & Lee, Y.I. 1995. Flat-pebble conglomerate: a characteristic lithology of Upper

512   Cambrian and Lower Ordovician shallow-water carbonate sequences. *In:* Cooper, J.

513   D., Droser, M. L. & Finney, S. C. (eds) *Ordovician Odyssey: Short Papers for the*

514   *Seventh International Symposium on the Ordovician System, 1995. Pacific Section*

515   *SEPM*, **77**, 371-4.

516   Kouchinsky, A., Bengtson, S., Gallet, Y., Korovnikov, I., Pavlov, V., Runnegar, B., Shields,

517   G., Veizer, J., Young, E. & Ziegler, K. 2008. The SPICE carbon isotope excursion in

518   Siberia: a combined study of the upper Middle Cambrian–lowermost Ordovician

519   Kulyumbe River section, northwestern Siberian Platform. *Geological Magazine*,

520   **145**, 609-622.

521   Kozub, P. 1997. The origin of flat-pebble conglomerates in the Upper Cambrian of the

522   Clarks Fork region, Park County, Wyoming. *In:* Mendelson, C.V., Maniewicz, C.M.

523   *(eds), Tenth Keck Research Symposium in Geology Proceedings. Department of*

524   *Geology, Beloit College, South Beloit, Illinois*, 134-7.

525   Kruse, P.D. 1996. Update on the northern Australian Cambrian sponges Rankenella,

526   Jawonya and Wagima. *Alcheringa*, **20**, 161-178, doi: 10.1080/03115519608619188.

527   Kruse, P.D., Gandin, A., Debrenne, F. & Wood, R. 1996. Early Cambrian bioconstructions

528   in the Zavkhan Basin of western Mongolia. *Geological Magazine*, **133**, 429-444.

529   Kullberg, J.C., OloÂriz, F., Marques, B., Caetano, P.S. & Roch, R.B. 2001. Flat-pebble

530   conglomerates: a local marker for Early Jurassic seismicity related to syn-rift

531   tectonics in the Sesimbra area (Lusitanian Basin, Portugal). *Sedimentary Geology*,

532   **139** 49-70.

533   Kwon, Y., Chough, S., Choi, D. & Lee, D. 2002. Origin of limestone conglomerates in the

534   Choson Supergroup (Cambro–Ordovician), mid-east Korea. *Sedimentary Geology*,

535   **146**, 265-283.

536   Landing, E., Westrop, S.R. & Keppie, J.D. 2007. Terminal Cambrian and lowest Ordovician

537   succession of Mexican West Gondwana: biotas and sequence stratigraphy of the

538   Tiñu Formation. *Geological Magazine*, **144**, 909-936.

539   Lee, J.-H., Chen, J. & Chough, S. 2010. Paleoenvironmental implications of an extensive

540   maceriate microbialite bed in the Furongian Chaomidian Formation, Shandong

541   Province, China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **297**, 621-

542   632.

543   Lee, Y.I. & Kim, J.C. 1992. Storm-influenced siliciclastic and carbonate ramp deposits, the

544   Lower Ordovician Dumugol Formation, South Korea. *Sedimentology*, **39**, 951-969.

545   Liang, C.M., Friedman, G.M. & Zheng, Z.C. 1993. Carbonate storm deposits (tempestites)

546   of Middle to Upper Cambrian age in the Helan Mountains, northwest China.

547   *Carbonates and Evaporites*, **8**, 181-190.

548   Liu, J. & Zhan, R. 2009. Temporal distribution of diagnostic biofabrics in the Lower and

549   Middle Ordovician in North China: clues to the geobiology of the Great Ordovician

550   Biodiversification Event. *Acta Geologica Sinica*, **83**, 513-523.

551   Liu, J., Zhan, R., Dai, X., Liao, H., Ezaki, Y. & Adachi, N. 2011. Demise of Early

552   Ordovician oolites in South China: Evidence for paleoceanographic changes before

553   the GOBE. *In*: Gutiérrez-Marco, J. C., Rábano, I. & Garcia-Bellido, D. (eds)

554   *Ordovician of the World*. Cuadernos del Museo Geominero, **14**, 309-317.

555

556   Luo, G., Junium, C.K., Kump, L.R., Huang, J., Li, C., Feng, Q., Shi, X., Bai, X. & Xie, S.

557   2014. Shallow stratification prevailed for∼ 1700 to∼ 1300 Ma ocean: Evidence from

558   organic carbon isotopes in the North China Craton. *Earth and Planetary Science*

559   *Letters*, **400**, 219-232.

560   MacNaughton, R. B., Roots, C.F. & Martel, E. 2008. Neoproterozoic-(?) Cambrian

561   lithostratigraphy, northeast Sekwi Mountain map area, Mackenzie Mountains,

562   Northwest Territories: new data from measured sections. *Geological Survey of*

563   *Canada, Current Research 2008-16*, 17p.

564   Markello, J.R. & Read, J.F. 1981. Carbonate ramp-to-deeper shale shelf transitions of an

565   Upper Cambrian intrashelf basin, Nolichucky Formation, Southwest Virginia

566   Appalachians. *Sedimentology*, **28**, 573-597.

567   Markello, J.R. & Read, J.F. 1982. Upper Cambrian Intrashelf Basin, Nolichucky Formation,

568   Southwest Virginia Appalachians. *AAPG Bulletin*, **66** 860-878.

569   Meng, X., Ge, M. & Tucker, M.E. 1997. Sequence Sequence stratigraphy, sea-level changes

570   and depositional systems in the Cambro-Ordovician of the North China carbonate

571   platform. *Sedimentary Geology*, **114**, 189-222.

572   Mount, J.F. & Kidder, D. 1993. Combined flow origin of edgewise intraclast

573   conglomerates: Sellick Hill Formation (Lower Cambrian), South Australia.

574   *Sedimentology*, **40**, 315-329.

575   Myrow, P., M. , Tice, L., Archuleta, B., Clark, B., Taylor, J.F. & Ripperdan, R.L. 2004.

576   Flat-pebble conglomerate: its multiple origins and relationship to metre-scale

577   depositional cycles. *Sedimentology*, **51**, 973-996.

578   Myrow, P.M., Taylor, J.F., Runkel, A.C. & Ripperdan, R.L. 2012. Mixed siliciclastic-

579   carbonate upward-deepening cycles of the Upper Cambrian inner detrital belt of

580   Laurentia. *Journal of Sedimentary Research*, **82**, 216-231, doi: 10.2110/jsr.2012.20.

581   Narbonne, G.M., Saylor, B.Z. & Grotzinger, J.P. 1997. The youngest Ediacaran fossils from

582   southern Africa. *Journal of Paleontology*, **71**, 953-967.

583   Pope, A. 1990. The geology and mineral deposits of the Toby-Horsethief Creek map area,

584   northern Purcell Mountains, southeast British Columbia (82K). *British Columbia*

585   *Geological Survey, Mineral Resources Division, Geological Survey Branch*, *Open*

586   *File **1990-26***, 57p.

587   Popov, L.E., Holmer, L.E. & Miller, J.F. 2002. Lingulate brachiopods from the Cambrian-

588   Ordovician boundary beds of Utah. *Journal of Paleontology*, **76,** 211-228.

589   Pratt, B.R. 2002. Storms versus tsunamis: Dynamic interplay of sedimentary, diagenetic,

590   and tectonic processes in the Cambrian of Montana. *Geology*, **30 ,** 423-426.

591   Pratt, B.R. & Bordonaro, O.L. 2007. Tsunamis in a stormy sea: Middle Cambrian inner-

592   shelf limestones of western Argentina. *Journal of Sedimentary Research*, **77**, 256-

593   262.

594   Pruss, S.B., Bottjer, D.J., Corsetti, F.A. & Baud, A. 2006. A global marine sedimentary

595   response to the end-Permian mass extinction: examples from southern Turkey and

596   the western United States. *Earth-Science Reviews*, **78**, 193-206.

597   Pruss, S.B., Corsetti, F.A. & Bottjer, D.J. 2005. The unusual sedimentary rock record of the

598   Early Triassic: a case study from the southwestern United States. *Palaeogeography,*

599   *Palaeoclimatology, Palaeoecology*, **222**, 33-52.

600   Pruss, S.B., Finnegan, S., Fischer, W.W. & Knoll, A.H. 2010. Carbonates in skeleton-poor

601   seas: new insights from Cambrian and Ordovician strata of Laurentia. *PALAIOS*, **25**,

602   73-84, doi: http://dx.doi.org/10.2110/palo.2009.p09-101r.

603   Robison, R.A. 1964. Upper Middle Cambrian stratigraphy of western Utah. *Geological*

604   *Society of America Bulletin*, **75**, 995-1010.

605   Saltzman, M.R. 1999. Upper Cambrian carbonate platform evolution,Elvinia and

606   Taenicephalus zones (Pterocephaliid—Ptychaspid biomere boundary), Northwestern

607   Wyoming. *Journal of Sedimentary Research*, **69** 926-938.

608 Saltzman, M.R., Runnegar, B. & Lohmann, K.C. 1998. Carbon isotope stratigraphy of

609   Upper Cambrian (Steptoean Stage) sequences of the eastern Great Basin: Record of

610   a global oceanographic event. *Geological Society of America Bulletin*, **110**, 285-297.

611 Sepkoski, J.J.J. 1982. Flat-pebble conglomerates, storm deposits, and the Cambrian bottom

612   fauna. *In*: Einsele, G. & Seilacher, A. (eds) *Cyclic and Event Stratification*.

613   Springer-Verlag, 371-386.

614 Shapiro, R.S. & Awramik, S.M. 2006. *Favosamaceria cooperi* new group and form: a

615   widely dispersed, time-restricted thrombolite. *Journal of Paleontology*, **80,** 411-422.

616 Sprinkle, J. & Guensburg, T.E. 1995. Origin of echinoderms in the Paleozoic evolutionary

617   fauna: The role of substrates. *PALAIOS*, **10,** 437-453.

618 Van Loon, A., Han, Z. & Han, Y. 2012. Slide origin of breccia lenses in the Cambrian of the

619   North China Platform: new insight into mass transport in an epeiric sea. *Geologos*,

620   **18**, 223-235.

621 Varlamov, A., Pak, K. & Rosova, A. 2006. The Upper Cambrian of the Chopko River

622   section, Norilsk region, northwestern Siberian platform: Stratigraphy and trilobites.

623   Paleontological Journal, **40**, S1-S56.

624 Westrop, S.R. 1989. Facies anatomy of an Upper Cambrian grand cycle: Bison Creek and

625   Mistaya formations, southern Alberta. *Canadian Journal of Earth Sciences*, **26,**

626   2292-2304.

627 Whisonant, R. 1987. Paleocurrent and petrographic analysis of imbricate intraclasts in

628   shallow-marine carbonates, Upper Cambrian, southwestern Virginia. *Journal of*

629   *Sedimentary Petrology*, **57**, 983-994.

630 Wignall, P.B. & Twitchett, R.J. 1999. Unusual intraclastic limestones in Lower Triassic

631   carbonates and their bearing on the aftermath of the end-Permian mass extinction.

632   *Sedimentology*, **46**, 303-316.

633   Wilson, M.A., Palmer, T.J., Guensburg, T.E., Finton, C.D. & Kaufman, L.E. 1992. The

634   development of an Early Ordovician hard ground community in response to rapid

635   sea-floor calcite precipitation. *Lethaia*, **25**, 19-34.

636   Wilson, M.D. 1985. Origin of Upper Cambrian flat pebble conglomerates in the northern

637   Powder River Basin. *In*: Longman, M.W., Shanley, K.W., Lindsay, R.F. & Eby,

638   D.E. (eds) *Rocky Mountain carbonate reservoirs*. *SEPM* Core Workshop, **7**, 1-50.

639   Woods, A.D. 2009. Anatomy of an anachronistic carbonate platform: Lower Triassic

640   carbonates of the southwestern United States. *Australian Journal of Earth Sciences*,

641   **56**, 825-839, doi: 10.1080/08120090903002649.

642   Yang, Z., Otofuji, Y.-i., Sun, Z. & Huang, B. 2002. Magnetostratigraphic constraints on the

643   Gondwanan origin of North China: Cambrian/Ordovician boundary results.

644   *Geophysical Journal International*, **151**, 1-10.

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