

1 **Calibrating the temporal and spatial dynamics of the Ediacaran - Cambrian**  
2 **radiation of animals**

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22

23 **Abstract**

24 The Ediacaran-Cambrian transition, which incorporates the radiation of animals, lacks a robust  
25 global temporal and spatial framework, resulting in major uncertainty in the evolutionary dynamics  
26 of this critical radiation and its relationship to changes in palaeoenvironmental geochemistry. We  
27 first present a new  $\delta^{13}\text{C}_{\text{carb}}$  composite reference curve for the Ediacaran Nama Group of southern  
28 Namibia, and we then outline four new possible global age models (A to D) for the interval 551-  
29 517 million years ago (Ma). These models comprise composite carbonate-carbon isotope ( $\delta^{13}\text{C}_{\text{carb}}$ )  
30 curves, which are anchored to radiometric ages and consistent with strontium isotope  
31 chemostratigraphy, and are used to calibrate metazoan distribution in space and time. These  
32 models differ most prominently in the temporal position of the basal Cambrian negative  
33  $\delta^{13}\text{C}_{\text{carb}}$  excursion (BACE). Regions that host the most complete records show that the BACE nadir  
34 always predates the Ediacaran-Cambrian boundary as defined by the first appearance datum (FAD)  
35 of the ichnospecies *Treptichnus pedum*. Whilst treptichnid traces are present in the late Ediacaran  
36 fossil record, the FAD of the ichnospecies *T. pedum* appears to post-date the LAD of in situ  
37 *Cloudina* and *Namacalathus* in all environments with high-resolution  $\delta^{13}\text{C}_{\text{carb}}$  data. Two age  
38 models (A and B) place the BACE within the Ediacaran, and yield an age of ~538.8 Ma for the  
39 Ediacaran-Cambrian boundary; however models C and D appear to be the most parsimonious and  
40 may support a recalibration of the boundary age by up to 3 Myr younger. All age models reveal a  
41 previously underappreciated degree of variability in the terminal Ediacaran, incorporating notable  
42 positive and negative excursions that precede the BACE. Notwithstanding remaining  
43 uncertainties in chemostratigraphic correlation, all models support a pre-BACE first appearance  
44 of Cambrian-type shelly fossils in Siberia and possibly South China, and show that the Ediacaran-  
45 Cambrian transition was a protracted interval represented by a series of successive radiations.

46 **The Ediacaran-Cambrian radiation occurred over a protracted interval without global**  
47 **mass extinctions and with generally diachronous metazoan appearances.**

48

## 49 **1. Introduction**

50 The late Ediacaran to early Cambrian interval encompasses the Gaskiers glaciation (~580 Ma),  
51 the first appearance of complex macroscopic life (~575 Ma), mobile biota ( $\leq$ 560 Ma), skeletal  
52 metazoans (~550 Ma), and the origin of modern metazoan phyla (Wood et al., 2019).  
53 Understanding the temporal and spatial context of these events is currently limited due to the lack  
54 of high-resolution age models to allow correlation of key sections. The geological record  
55 throughout this interval also contains numerous unconformities and gaps of uncertain duration, a  
56 sparse global distribution of datable stratiform volcanic deposits, and diverse endemic biotas,  
57 resulting in loose chronostratigraphic and biostratigraphic control. As a result, no consistent global  
58 chronostratigraphic correlation exists, particularly for the critical late Ediacaran to lower Cambrian  
59 (Fortunian Stage) interval. Early metazoans evolved in a highly dynamic Earth system, and so  
60 without a high-resolution temporal and spatial framework we are unable to address many profound  
61 uncertainties, including the evolutionary dynamics of the Cambrian Explosion, the response of  
62 metazoans to local and global changes in oceanic redox conditions and nutrient availability, and  
63 whether one or more contemporaneous mass extinctions occurred.

64 The formal placement of the Ediacaran-Cambrian boundary in the Fortune Head section,  
65 Newfoundland, Canada, which is based on the first appearance datum (FAD) of *Treptichnus*  
66 *pedum* ichnospecies (Brasier et al., 1994), has been particularly problematic since it occurs in a  
67 section with few datable volcanics, sparse skeletal biota, and limited potential for

68 chemostratigraphy (Babcock et al., 2014). Indeed, the choice of *T. pedum* as a marker fossil for  
69 the basal Cambrian has also been a source of contention given the strong environmental,  
70 lithological and facies dependency for preservation of this trace, resulting in a notable absence  
71 from carbonate-dominated successions (e.g. Babcock et al., 2014). A similar problem is  
72 encountered when attempting to define the basal Cambrian using the first appearance of  
73 ‘Cambrian-type’ small skeletal fossils, which are themselves absent or rare in siliciclastic-  
74 dominated successions, especially in environments that were not conducive to early  
75 phosphatization. To overcome this complication, a holistic integration of radiometric,  
76 chemostratigraphic and palaeontological data across this interval is crucial. At present, the age of  
77 the Ediacaran-Cambrian boundary is  $541.0 \pm 1.0$  Ma (ICC 2021), however the radiometric age of  
78 a tuff deposit in the Nama Group, Namibia, on the Kalahari Craton, provides a current best estimate  
79 of 538.8 Ma for the maximum age of the first appearance of *T. pedum* (Linnemann et al., 2019;  
80 Xiao and Narbonne, 2020).

81 The carbon isotopic composition of marine carbonates ( $\delta^{13}\text{C}_{\text{carb}}$ ) is most commonly considered  
82 to reflect secular changes in the ratio of  $^{13}\text{C}$  to  $^{12}\text{C}$  in seawater that are associated with changes in  
83 the relative export/burial rates of inorganic versus organic carbon (Kaufman et al., 1991; Keith  
84 and Weber, 1964; Veizer et al., 1980; Veizer and Hoefs, 1976). As a result, secular  $\delta^{13}\text{C}_{\text{carb}}$  profiles  
85 have been used for regional and global correlation (Halverson et al., 2010; Macdonald et al., 2013;  
86 Maloof et al., 2010; Yang et al., n.d.; Zhu et al., 2007). However, a number of local effects have  
87 also been proposed that may partially decouple the local record of primary  $\delta^{13}\text{C}_{\text{carb}}$  from the  
88 composition of dissolved inorganic carbon (DIC) in the open ocean. These include diurnal  
89 coupling between photosynthesis and carbonate saturation in shallow carbonate settings (Geyman  
90 and Maloof, 2019), local DIC pools of distinct isotopic composition (Cui et al., 2020b; Melim et

91 al., 2002), and the possibility for water-column methanogenesis and carbonate recycling under  
92 low-sulfate conditions associated with restriction (Cui et al., 2020b). Additionally, facies-specific  
93 diagenetic regimes can yield distinct  $\delta^{13}\text{C}_{\text{carb}}$  for time-equivalent sections in modern marine basins  
94 (Melim et al., 2002), and this has also been established in the Cryogenian interglacial ocean  
95 (Hoffman and Lamothe, 2019), and the Paleoproterozoic Lomagundi-Jatuli event (Prave et al.,  
96 2021). As a result, changes in  $\delta^{13}\text{C}_{\text{carb}}$  may in fact archive contemporaneous pools of DIC from  
97 adjacent depositional settings with variable C isotope composition. The potential for both local  
98 water column DIC and the effects of carbonate diagenesis to result in significant deviation of  
99  $\delta^{13}\text{C}_{\text{carb}}$  from global seawater  $\delta^{13}\text{C}$  may therefore be problematic when building  $\delta^{13}\text{C}_{\text{carb}}$ -based age  
100 frameworks.

101 Despite these potential complications, it is not clear why during certain intervals of geological  
102 history some depositional settings acquire  $\delta^{13}\text{C}_{\text{carb}}$  values that deviate markedly from mean values  
103 (Hoffman and Lamothe, 2019). For example, integrated  $\delta^{13}\text{C}_{\text{carb}}$ ,  $\delta^{44}\text{Ca}$ ,  $\delta^{26}\text{Mg}$  and sequence  
104 stratigraphic study of the Cryogenian interglacial Trezona  $\delta^{13}\text{C}_{\text{carb}}$  excursion reveals that, whilst  
105 facies-specific trends in  $\delta^{13}\text{C}_{\text{carb}}$  may correspond with fluid vs sediment buffered diagenesis, the  
106 excursion itself is of global significance and may correspond with global changes in siliciclastic  
107 vs carbonate sedimentation, nutrient delivery, and eustatic sea level (Ahm et al., 2021). Therefore,  
108 notwithstanding uncertainties in the driving mechanisms for  $\delta^{13}\text{C}_{\text{carb}}$  records and possible facies-  
109 related, diagenetic offsets, the secular trends represented by gradual unidirectional shifts in  $\delta^{13}\text{C}_{\text{carb}}$   
110 in multiple globally distributed and temporally equivalent open-marine sections may reflect  
111 changes to the carbon cycle that are of global significance, and hence are applicable for  
112 chemostratigraphic correlation.

113 To date, efforts to produce a global composite Ediacaran  $\delta^{13}\text{C}_{\text{carb}}$  record (e.g. Macdonald et al.,  
114 2013; Yang et al., 2021) have revealed the middle Ediacaran Shuram negative anomaly at around  
115  $<579 - >564$  Ma (Rooney et al., 2020; Yang et al., 2021), followed by a positive shift from ca.  
116 564-550 Ma. The sedimentary record from ca. 564-550 Ma is radiometrically well dated in Baltica  
117 (the East European Platform) (Yang et al., 2021) and Avalonia (Matthews et al., 2020; Noble et  
118 al., 2015); however, siliciclastic strata with poor  $\delta^{13}\text{C}_{\text{carb}}$  resolution dominate these successions. A  
119 subsequent negative excursion with a recovery at  $\sim 550$  Ma (Yang et al., 2021) is followed by a  
120 final late Ediacaran positive plateau (the EPIP, Zhu et al., 2017). This plateau appears to terminate  
121 with the onset of a globally widespread large magnitude (min  $\delta^{13}\text{C}_{\text{carb}}$  of  $-10\text{‰}$ ) negative excursion,  
122 termed ‘1n’ in strata of the Siberian Platform, and in previous global compilations (Kouchinsky et  
123 al., 2007; Maloof et al., 2010). This excursion is considered to be approximately coincident with  
124 the Ediacaran-Cambrian boundary and has also previously been termed the ‘Basal Cambrian  
125 negative  $\delta^{13}\text{C}_{\text{carb}}$  excursion’ (BACE); an acronym that is adopted herein. The age of the BACE is  
126 currently correlated with a radiometrically dated negative excursion in the A4 Member of the Ara  
127 Group, Oman at  $\sim 541$  Ma (Bowring et al., 2007; Hodgin et al., 2020; Maloof et al., 2010; Smith  
128 et al., 2015). Possible mass extinctions have been suggested between the Ediacaran White Sea and  
129 Nama biotic assemblages, and again at the Ediacaran-Cambrian boundary, coincident with the  
130 BACE (e.g. Amthor et al., 2003; Darroch et al., 2018).

131 Determining the global nature and age of the BACE has been particularly problematic, but is  
132 critical for developing a robust biostratigraphic and chronostratigraphic framework across this  
133 interval. The BACE reaches a  $\delta^{13}\text{C}_{\text{carb}}$  nadir of  $-10\text{‰}$  and has been recorded in all fossiliferous  
134 successions with high-resolution  $\delta^{13}\text{C}_{\text{carb}}$  data, except the Nama Group. The FAD of *T. pedum*  
135 occurs above the BACE in all regions that host both features (e.g. Smith et al., 2015, 2016; Hodgin

136 et al., 2020). As a radiometric basis for the age of the Ediacaran-Cambrian boundary derives from  
137 the Nama Group (Linnemann et al., 2019; Xiao and Narbonne, 2020), the position of the BACE  
138 (if present) in the Nama succession must be determined. Recent high precision radiometric and  
139  $\delta^{13}\text{C}_{\text{carb}}$  data from Laurentia appear to constrain the age of the BACE nadir to  $\leq 539.4$  Ma,  
140 coincident with stable positive  $\delta^{13}\text{C}_{\text{carb}}$  data on the Kalahari craton (Hodgin et al., 2020). It has  
141 therefore been suggested that the conflicting  $\delta^{13}\text{C}_{\text{carb}}$  trends between the Laurentian and Kalahari  
142 datasets may result from local pools of dissolved inorganic carbon (DIC) with distinct isotopic  
143 compositions (Hodgin et al., 2020). In order to test whether these data are unrepresentative of  
144 global  $\delta^{13}\text{C}_{\text{carb}}$ , it is first necessary to discount all alternative possibilities associated with  
145 uncertainties in the  $\delta^{13}\text{C}_{\text{carb}}$  age model framework.

146 Here, we present an updated  $\delta^{13}\text{C}_{\text{carb}}$  framework for the Ediacaran Nama Group of southern  
147 Namibia. These data are first correlated regionally by combined litho-, chemo-, and sequence  
148 stratigraphy, then constrained in time using published high precision U-Pb ages determined via  
149 zircon chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS).  
150 We correlate trends in the resulting Nama reference curve with  $\delta^{13}\text{C}_{\text{carb}}$  data from globally  
151 distributed sections that are well constrained by interbedded zircon U-Pb CA-ID-TIMS ages, and  
152 robust high-resolution regional section correlation, for the interval  $\sim 551 - 538.5$  Ma. The  $\delta^{13}\text{C}_{\text{carb}}$   
153 record is then extended to 517 Ma in multiple regions with high resolution litho-, chemo-, and  
154 sequence stratigraphic records. Compiled data from sections that host the most robust radiometric  
155 constraints throughout this interval act as framework curves to reveal trends in the global data that  
156 can be confidently constrained in age. These curves are used to anchor a wider correlation in order  
157 to best fit high-resolution  $\delta^{13}\text{C}_{\text{carb}}$  data from key sections that lack robust radiometric constraints.

158 This allows construction of four possible composite carbon isotope curves and age models,  
159 comprising 130 globally distributed sections (Australia, Brazil, Kazakhstan, Mongolia, Morocco,  
160 Namibia, Mexico, USA, Canada, Oman, Siberia and South China). These curves are consistent  
161 with all reliable radiometric age data and strontium isotope ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) records between ~551 – 517  
162 Ma (Tables S1 and S2). All models reveal a previously underappreciated degree of variability in  
163 the EPIP, incorporating multiple positive and negative excursions preceding the BACE that are  
164 globally widespread. Differences between the four age models result from ongoing uncertainties  
165 which we review in detail. All FADs and, for Ediacaran taxa, Last Appearance Datums (LADs) of  
166 key fossil occurrences are calibrated within this framework (Tables S2 and S3). This provides the  
167 basis for biotic temporal and spatial distributions to be accurately constrained and visualized.

168

## 169 **2. Constructing a $\delta^{13}\text{C}_{\text{carb}}$ reference curve for the Nama Group, Kalahari Craton**

170 The Nama Group in Namibia and South Africa, comprises a richly-fossiliferous mixed  
171 carbonate-siliciclastic succession deposited in a foreland basin on the Kalahari Craton. The  
172 succession developed during flexural subsidence associated with two major orogenies; the Damara  
173 to the north, and the Gariiep to the southwest (Germs, 1983; Germs and Gresse, 1991; Gresse and  
174 Germs, 1993) (Fig. 1). Near-complete exposure and minimal structural deformation across  
175 hundreds of square kilometers have inspired half a century of detailed sedimentological and  
176 palaeontological research, incorporating high resolution litho-, chemo- and sequence stratigraphy  
177 (Darroch et al., 2015, 2016, 2021; Jensen et al., 2000; Saylor, 2003; Saylor et al., 1998; Smith,  
178 1998; Wood et al., 2015). These aspects, in combination with high-precision radiometric age  
179 calibration (Bowring et al., 2007; Grotzinger et al., 1995; Linnemann et al., 2019), make the Nama

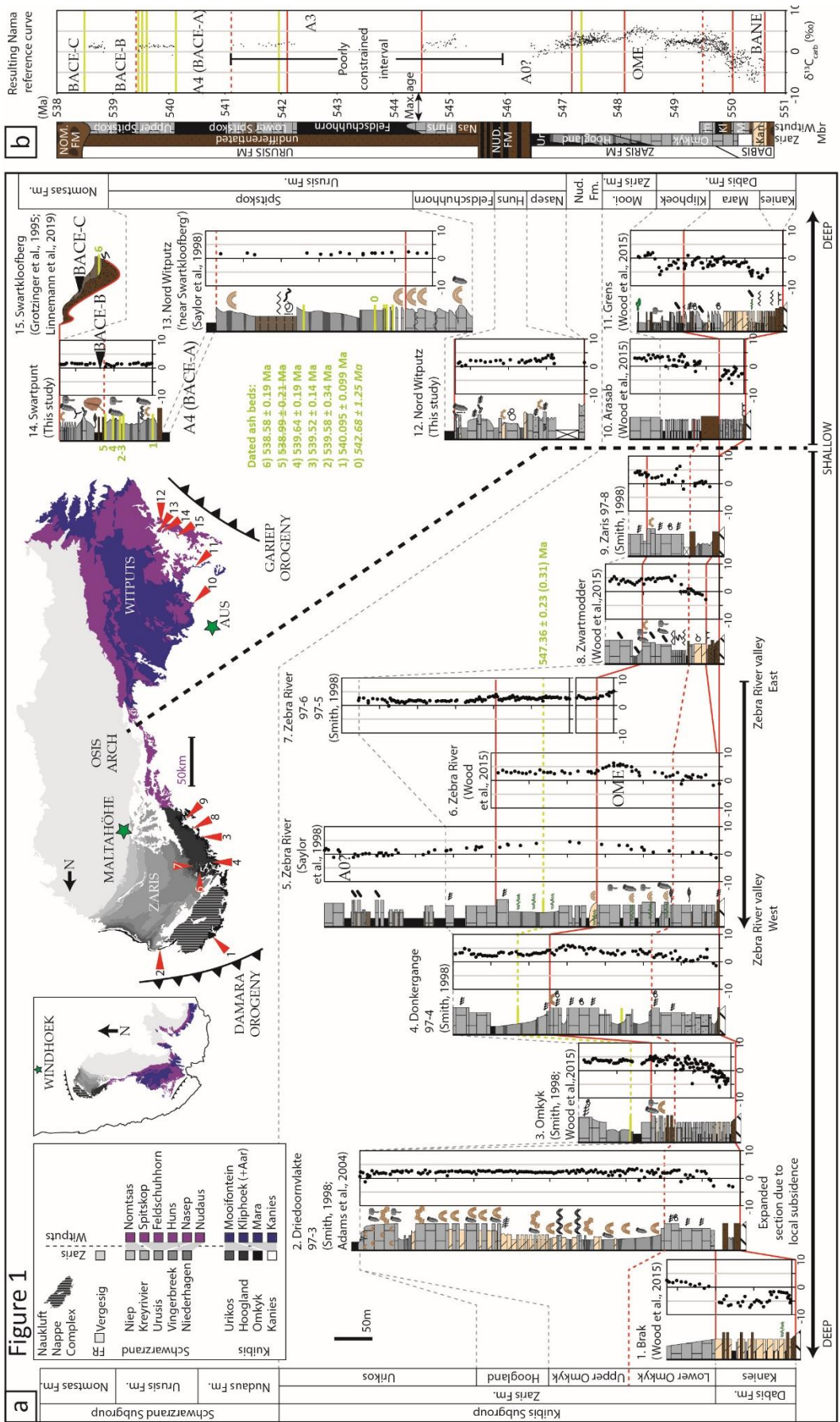


180 Group the best candidate succession globally for construction of a terminal Ediacaran  $\delta^{13}\text{C}_{\text{carb}}$   
181 reference curve. This is especially the case for the lower Nama Group (Kuibus Subgroup), where  
182 carbonate ramp deposits are ubiquitous throughout the northern (Zaris) sub-basin.

183  $\delta^{13}\text{C}_{\text{carb}}$  data from fifteen sections of the Nama Group, Namibia (Saylor et al., 1995; Smith,  
184 1998; Wood et al., 2015), compiled within a sequence stratigraphic framework and calibrated to  
185 dated volcanic tuff interbeds, result in a composite Ediacaran Nama  $\delta^{13}\text{C}_{\text{carb}}$  reference curve (Fig.  
186 1). Gaps in the  $\delta^{13}\text{C}_{\text{carb}}$  record of individual sections are permitted at exposure or erosion surfaces,  
187 or during significant intervals of siliciclastic deposition. Below, we explore implications for global  
188 correlation of the  $\delta^{13}\text{C}_{\text{carb}}$  reference curve derived for the Kuibus (ca. 551 – 546 Ma) and  
189 Schwarzrand (<546 – 538 Ma) subgroups.

## 190 *2.1 The Kuibus Subgroup*

191 In the Kuibus Subgroup succession, positive, laterally consistent  $\delta^{13}\text{C}_{\text{carb}}$  values in the lower  
192 Hoogland Member (Zaris Formation) of the Zaris sub-basin are constrained by a zircon U-Pb CA-  
193 ID-TIMS age of  $547.36 \pm 0.23$  Ma (Bowring et al., 2007) (Fig. 1). Carbonate strata in multiple  
194 sections below this ash bed record a gradual recovery from a negative  $\delta^{13}\text{C}_{\text{carb}}$  excursion. This can  
195 be readily correlated with the  $\delta^{13}\text{C}_{\text{carb}}$  trend expressed in strata of the lower Dengying Formation,  
196 South China. Recovery from this negative  $\delta^{13}\text{C}_{\text{carb}}$  excursion in the lower Dengying Formation is  
197 constrained by a zircon U-Pb CA-ID-TIMS age of  $550.1 \pm 0.6$  Ma (Yang et al., 2021, updated  
198 from  $551.09 \pm 1.02$  Ma, Condon et al., 2005) from an ash bed in the underlying Miaohu Member  
199 at Jijiawan (/Jiuqunao) section (Table S1). The age of the 0‰ crossing point in the lower Kuibus  
200 Subgroup can therefore be anchored to ~550 Ma. The preceding negative excursion ( $\geq 550$  Ma),



202 **Fig. 1. Sequence stratigraphic and carbon isotope chemostratigraphic correlation of the**  
203 **Nama Group, Namibia with resulting reference curve for the Kalahari craton for the interval**  
204 **~550 – 538.5 Ma** (Saylor et al., 1998; Smith, 1998; Wood et al., 2015). (a) Litho-, chemo- and  
205 sequence stratigraphic correlation for sections of the Zaris sub-basin after Smith (1998) and Wood  
206 et al. (2015). New data for sections 12 and 14. (b) Resulting Nama  $\delta^{13}\text{C}_{\text{carb}}$  reference curve showing  
207 position of tuff bed age constraints and sequence boundaries. Note that age model between ca. 547  
208 Ma and 540 Ma remains poorly constrained. BANE: Basal Nama Excursion, OME: Omkyk  
209 Excursion, A0, A3 and A4 named after tentative correlation with radiometrically dated excursions  
210 in the A0, A3 and A4 members of the Ara Group, Oman (see text for details). BACE-A, B and C  
211 correlate to the positions of the 1n/BACE in models A, B and C, respectively (Table S2). See Fig.  
212 2 for key to lithology and sequence stratigraphy. Radiometric data ( $^{238}\text{U}/^{206}\text{Pb}$  CA-ID-TIMS) are  
213 from (Bowring et al., 2007; Linnemann et al., 2019) and italicized data (air abrasion ID-TIMS  
214  $^{207}\text{Pb}/^{206}\text{Pb}$ ) are from Grotzinger et al. (1995) recalculated in Schmitz (2012) (the age of tuff bed  
215 5 is discounted; details in Table S1). See Fig. S1 for a high-resolution version of this figure.

216  
217 whilst present and radiometrically calibrated in South China, is expressed most completely and  
218 with highest resolution in multiple sections by carbonates of the Dabis Formation in both the Zaris  
219 and Witputs sub-basins of the Nama Group. This is a recently recognized distinct negative  $\delta^{13}\text{C}_{\text{carb}}$   
220 excursion (Yang et al., 2021), herein termed the basal Nama excursion (BANE, Fig. 1b).

221 Subsequent to the BANE, peak  $\delta^{13}\text{C}_{\text{carb}}$  values are reached within the upper Omkyk Member of  
222 the Zaris Formation, and lower members of the Dengying Formation. This  $\delta^{13}\text{C}_{\text{carb}}$  peak is herein  
223 termed the Omkyk excursion (OME, Fig. 1b).

224 The onset of a gradual decline prior to  $547.32 \pm 0.31$  Ma (Bowring et al., 2007) is constrained  
225 by a tuff bed within the lower Hoogland Member of the upper Zaris Formation and correlative  
226 intervals of the lower Dengying Formation (Table S2). Declining  $\delta^{13}\text{C}_{\text{carb}}$  values culminate in a  
227 short-lived (<0.5 Ma) negative excursion, with a recovery to  $\sim 0\text{‰}$  recorded at  $546.72 \pm 0.21$  Ma  
228 by a tuff bed in the middle A0 Member of the Ara Group, Oman (see section 5.5, Bowring et al.,  
229 2007; Schmitz, 2012). This minor negative excursion is expressed in carbonate interbeds of the  
230 Urikos Member of the Zaris Formation, Namibia, and the A0 Member of the Ara Group, Oman  
231 (Bowring et al., 2007; Saylor et al., 1998). It may also correspond with a minor negative excursion  
232 recorded in the lower Khatyspyt Fm of the northern Siberian Platform (Cui et al., 2016; Knoll et  
233 al., 1995), although this remains uncertain (see section 5.3).

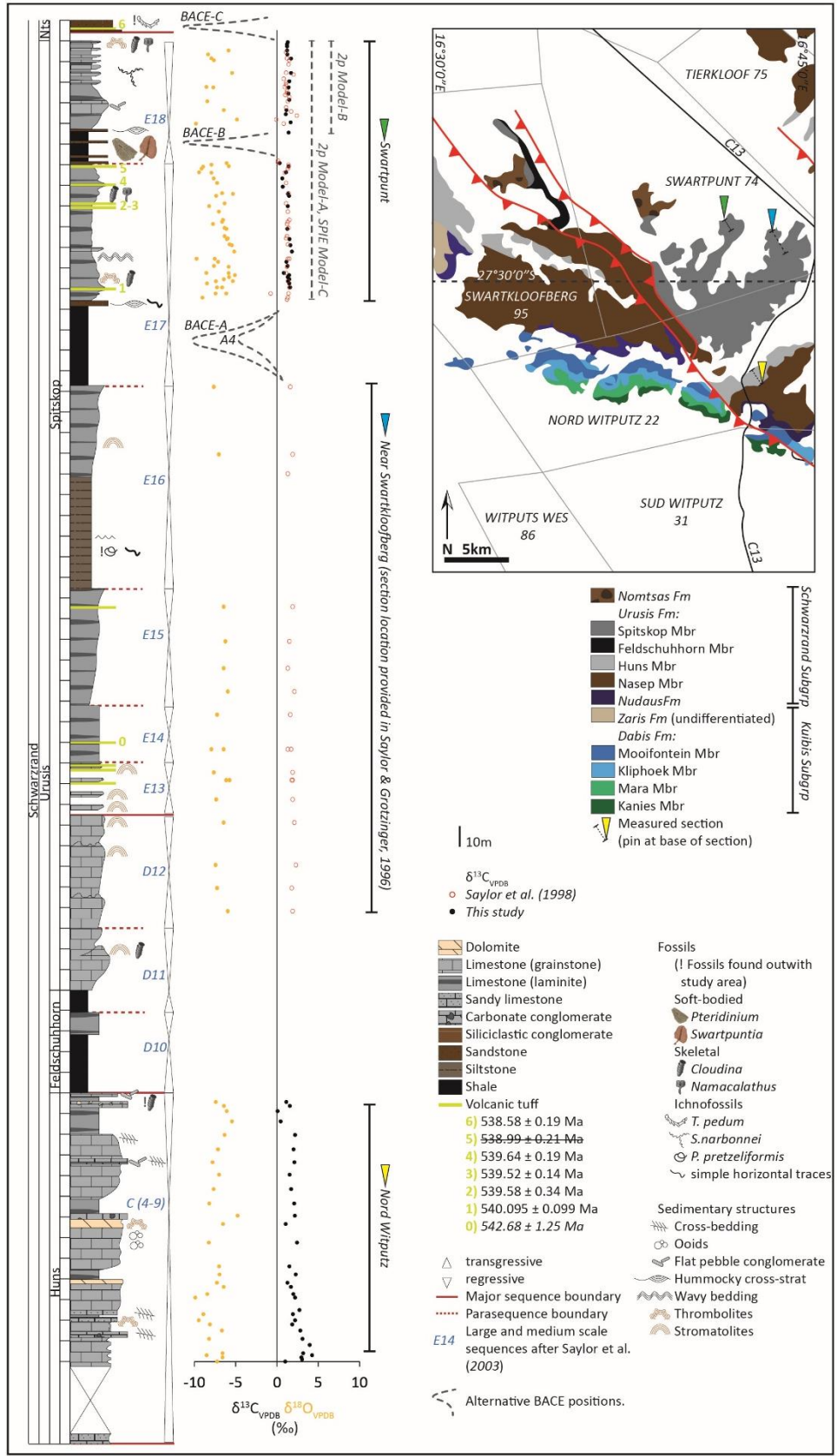
234 Based on the interbasinal  $\delta^{13}\text{C}_{\text{carb}}$  correlation herein (Fig. 1) and published palaeontological  
235 information, carbonates in the lower Kuibis Subgroup (Mara Member of the Dabis Fm) of the  
236 Witputs sub-basin host the earliest FAD of *Cloudina* (Germis, 1983). This FAD may predate the  
237  $0\text{‰}$  recovery from the BANE, however the precise location of the section that hosts the Mara  
238 Member cloudinids and associated  $\delta^{13}\text{C}_{\text{carb}}$  data is undocumented. In the Zaris sub-basin, the  
239 earliest recorded appearance of cloudinids occurs immediately above the  $0\text{‰}$  recovery from the  
240 BANE ( $\sim 550$  Ma) within the lowermost upper Omkyk Member (Fig. 1). Siliciclastics in the lower  
241 Kuibis Subgroup (Kliphhoek Member of the Dabis Formation) of the Witputs sub-basin, deposited  
242 immediately below the  $0\text{‰}$  recovery from the BANE, contain a rich fossil archive of soft-bodied  
243 biota (Maloney et al., 2020). The majority of the soft-bodied fossils in this interval correspond to  
244 the Nama assemblage, however this level may also host the regional last appearance of elements  
245 of the White Sea assemblage, including *Ausia fenestrata* (Hahn and Pflug, 1985; Pickford, 1995).  
246 Fossil impressions interpreted as *Ausia* have previously been noted from the middle Verkhovka

247 Formation of the White Sea area (Grazhdankin, 2004), below a volcanic tuff in the overlying lower  
248 Zimnie Gory Formation recently redated to  $552.96 \pm 0.19$  (Yang et al., 2021) (Table S1).

## 249 *2.2 The Schwarzrand Subgroup*

250 During deposition of the Schwarzrand Subgroup the locus of carbonate sedimentation shifted  
251 to the Witputs sub-basin, and siliciclastic deposits of the Zaris sub-basin record gradual basin infill  
252 (Germs, 1983; Gresse and Germs, 1993). The existing  $\delta^{13}\text{C}_{\text{carb}}$  record of the Schwarzrand  
253 Subgroup consists of a low resolution  $\delta^{13}\text{C}_{\text{carb}}$  dataset from the Huns and lower Spitskop members  
254 of the Urusis Formation, and multiple datasets of varying resolution from the upper Spitskop  
255 Member at Farm Swartpunt (Linnemann et al., 2019; Saylor et al., 1998; Wood et al., 2015). We  
256 present new  $\delta^{13}\text{C}_{\text{carb}}$  data for two sections from the Urusis Fm (Nord Witputz and Swartpunt), and  
257 construct a composite lithostratigraphic and chemostratigraphic column incorporating available  
258 data from the lower Spitskop Member (Saylor et al., 1998) (Fig. 2).

259 Shallow marine facies of the lower Huns Member at Nord Witputz show initially high  $\delta^{13}\text{C}_{\text{carb}}$   
260 values (max = 4.24‰) that gradually decrease to reach 0.08‰ near the top of the section (Fig. 2).  
261 Higher order variability in the  $\delta^{13}\text{C}_{\text{carb}}$  data of the lower Huns Member may be associated with a  
262 series of parasequences, where lower  $\delta^{13}\text{C}_{\text{carb}}$  reflects deepening of the depositional environment.  
263 Samples of both shallow and marginally deeper facies show pronounced and simultaneous  
264 decreases in their mean  $\delta^{13}\text{C}_{\text{carb}}$  composition up-section, which may reflect a gradual trend in  
265 seawater  $\delta^{13}\text{C}_{\text{carb}}$  overprinted by minor perturbations associated with regional facies. Based on  
266 regional stratigraphic correlation, the Urusis Fm of the Witputs sub-basin was deposited equivalent  
267 to siliciclastic deposits of the Schwarzrand Subgroup in the Zaris sub-basin (Germs, 1983), and is  
268 therefore likely to be younger than ~546 Ma (Fig. 1).



270 **Fig. 2. Geological map and sampled sections of the Urusis Formation, Nama Group, southern**  
271 **Namibia.** Composite section after (Saylor, 2003). Geological map shows relative positions of  
272 measured sections. Map redrawn from Saylor and Grotzinger (1996) using the 1:250000 map of  
273 Ai-Ais (2716), Geological Survey of Namibia, Ministry of Mines and Energy. Radiometric data  
274 ( $^{238}\text{U}/^{206}\text{Pb}$  CA-ID-TIMS) are from Linnemann et al. (2019) and italicized data (air abrasion ID-  
275 TIMS  $^{207}\text{Pb}/^{206}\text{Pb}$ ) are from Grotzinger et al. (1995) recalculated in Schmitz (2012) (the age of tuff  
276 bed 5 is discounted; details in Table S1). BACE-A, B and C correlate to the positions of the  
277 1n/BACE in models A, B and C, respectively (Table S2).

278

279 The lower Spitskop Member contains a volcanic tuff deposit with a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of 542.68  
280  $\pm 1.25$  Ma (Grotzinger et al., 1995, recalculated in Schmitz, 2012) (Table S1). Carbon isotope data  
281 of relatively low resolution have previously been presented for the lower Spitskop Member from  
282 the lower part of a composite section described as ‘near Swartkloofberg’ (Saylor et al., 1998) (Fig.  
283 2). The lower part of this section (corresponding to medium scale sequences D11 – E16 of Saylor,  
284 2003) lies to the north of our Huns Member section, and the upper part (medium scale sequences  
285 E17 and E18 of Saylor, 2003) corresponds to the Swartpunt section (Fig. 2, and see Fig. 1 of Saylor  
286 and Grotzinger, 1996). According to Saylor (2003), a total thickness of ~370 m of interbedded  
287 shale and carbonate, for which only 18 data points are currently published, separates the Huns  
288 Member at Nord Witputz from the upper Spitskop Member at Swartpunt (Fig. 2) (Saylor et al.,  
289 1998). However, an alternative correlation for the relative position of the lower Spitskop Member  
290 data is discussed in the Supplementary Information. Future high resolution resampling for  $\delta^{13}\text{C}_{\text{carb}}$ ,  
291 in addition to re-dating of ash beds throughout the lower Spitskop Member southeast of Swartpunt

292 using the updated CA-ID-TIMS methodology, should yield valuable information to better  
293 constrain this interval in the global age model.

294

### 295 **3. Developing Age Models and the stratigraphic position of the BACE in Namibia**

#### 296 *3.1 The terminal Ediacaran (546–541 Ma)*

297 The  $\delta^{13}\text{C}_{\text{carb}}$  record between 546 Ma and 543 Ma remains poorly constrained globally due to a  
298 dearth of  $\delta^{13}\text{C}_{\text{carb}}$  data interbedded with tuff beds dated by reliable radiometric methods (Fig. 3a).  
299 However, when the new  $\delta^{13}\text{C}_{\text{carb}}$  data of the Huns Member are compared to other  $\delta^{13}\text{C}_{\text{carb}}$  profiles  
300 from ca. 546–543 Ma from other cratons (e.g. Yangtze Block, Laurentia, Amazonia and Siberia,  
301 Fig. 3), the magnitude and overall trend in the data are consistent with a temporal position  
302 coincident with the initial downturn from positive values of up to 5‰ recorded in the middle  
303 Member of the Dengying Formation (Gaojiashan Member and equivalent units). We stress that  
304 this is a maximum age estimate based on the assumption that the age constraint from the overlying  
305 lower Spitskop Member ( $542.68 \pm 1.25$  Ma, Grotzinger et al., 1995, updated in Schmitz, 2012)  
306 approximates the true age of the lower Spitskop Member (see Supplementary Text for further  
307 discussion). A subsequent recovery to a positive  $\delta^{13}\text{C}_{\text{carb}}$  peak is well constrained by 5 radiometric  
308 ages;  $543.40 \pm 3.5$  Ma from the Baimatuo Member of the Yangtze Platform (Huang et al., 2020),  
309  $542.90 \pm 0.12$  Ma and  $542.33 \pm 0.11$  Ma from the lower and upper A3 Member of the Ara Group  
310 (Bowring et al., 2007), and  $542.37 \pm 0.28$  Ma and  $541.85 \pm 0.75$  Ma from the upper Tamengo  
311 Formation, Brazil (Parry et al., 2017). Here,  $\delta^{13}\text{C}_{\text{carb}}$  values increase once more to 3–5.6‰ (herein  
312 termed the ‘A3’ anomaly, Fig. 3) and then decline to a plateau of 0–2‰ prior to 541 Ma (Tables

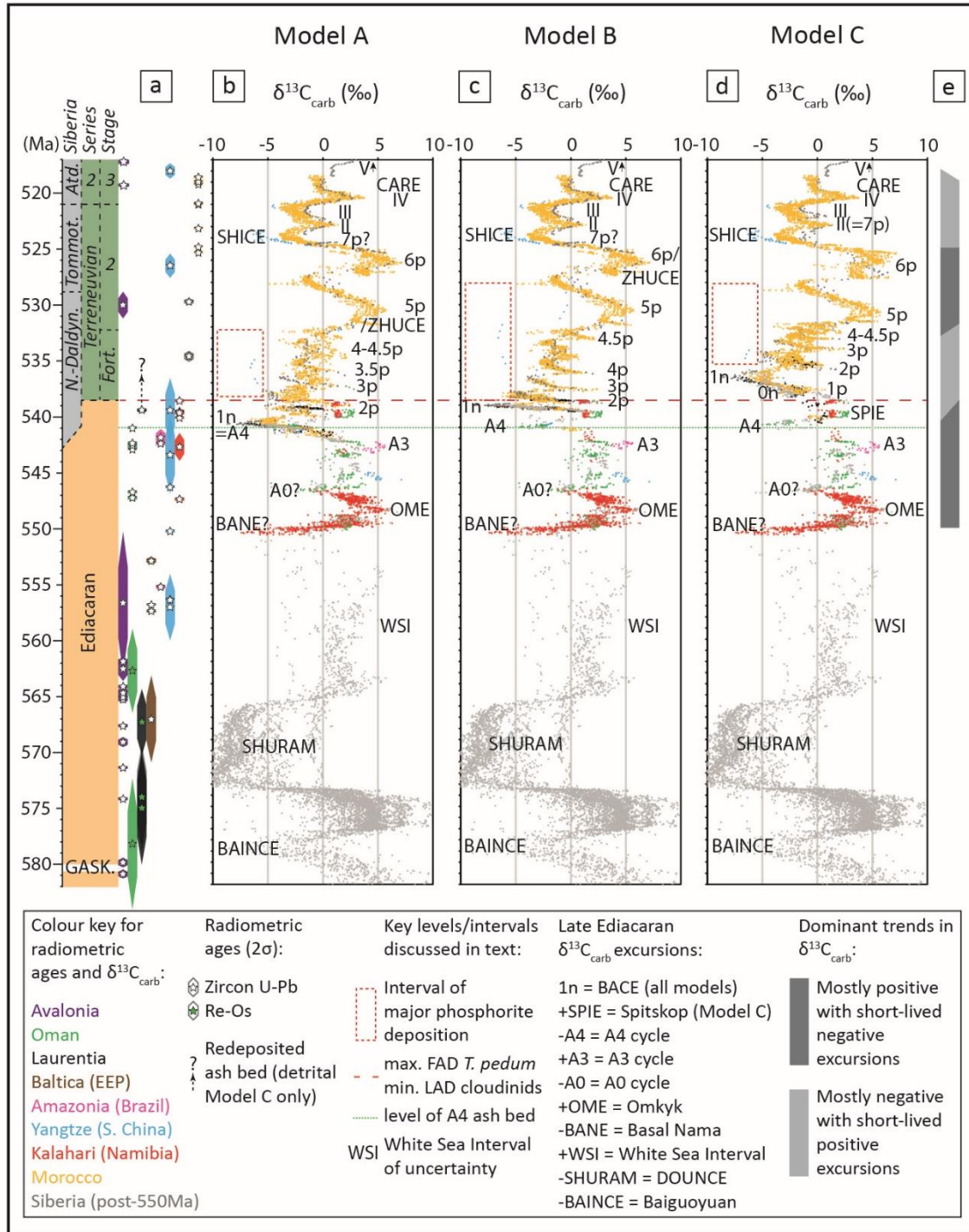


313 S1 and S2). The available data from the lower Spitskop Member, though sparse, correlate with  
314 predominantly positive  $\delta^{13}\text{C}_{\text{carb}}$  values that precede the negative excursion recorded in the A4  
315 Member of the Ara Group (Fig. 3).

316 There are three possible positions for the BACE in the Nama Group, all of which are consistent  
317 with available radiometrically-dated tuff deposits and occur in siliciclastic units without  $\delta^{13}\text{C}_{\text{carb}}$   
318 data (Fig. 2). These give rise to three alternative age models A, B and C (Fig. 3). In each, we  
319 assume that the age of the A4 Member accurately constrains the  $\delta^{13}\text{C}_{\text{carb}}$  excursion recorded in the  
320 A4 Member, as shown by Bowring et al. (2007) (see section 5.5 for further discussion of the Ara  
321 Group age model). For ease of distinction, the excursion in the A4 Member is herein termed the  
322 ‘A4 anomaly’. The position of the BACE in relation to the Spitskop Member is inferred either  
323 within the shale interval of medium scale sequence E17, stratigraphically beneath the ca. 540 Ma  
324 tuff bed at the base of the Swartpunt section (Model A), within the shale interval of medium scale  
325 sequence E18 above the well dated horizon constrained by multiple tuff deposits at ca. 539.6 Ma  
326 (Linnemann et al., 2019) (Model B), or in strata younger than the Swartpunt section (<538 Ma,  
327 Model C) (Figs. 2, 3).

328 Models A and B are consistent with a recent radiometric constraint from the La Ciénega  
329 Formation, Mexico (Hodgin et al., 2020). However, models B and C imply that the A4 anomaly  
330 does not correspond to the BACE, but rather to an earlier negative excursion with a recovery at or  
331 before ca. 540 Ma (Figs. 3c and d). In models A and B, the apparent absence of the BACE nadir  
332 in the Nama Group is interpreted simply as a function of coincident deposition of outer shelf shale  
333 for which  $\delta^{13}\text{C}_{\text{carb}}$  data are lacking (Fig. 2). Indeed, if the A4 anomaly is of global significance and

334



335

336 **Fig. 3. Carbon isotope chemostratigraphic correlation models A–C.** Ediacaran  $\delta^{13}\text{C}_{\text{carb}}$  data are  
 337 only presented for sections that are anchored by associated radiometric ages (e.g. Swartpunt), or  
 338 where high resolution  $\delta^{13}\text{C}_{\text{carb}}$  data are confidently correlated regionally to sections that contain  
 339 radiometrically dated beds (e.g. La Ciénega Fm and Kuibis Subgroup sections). All data are

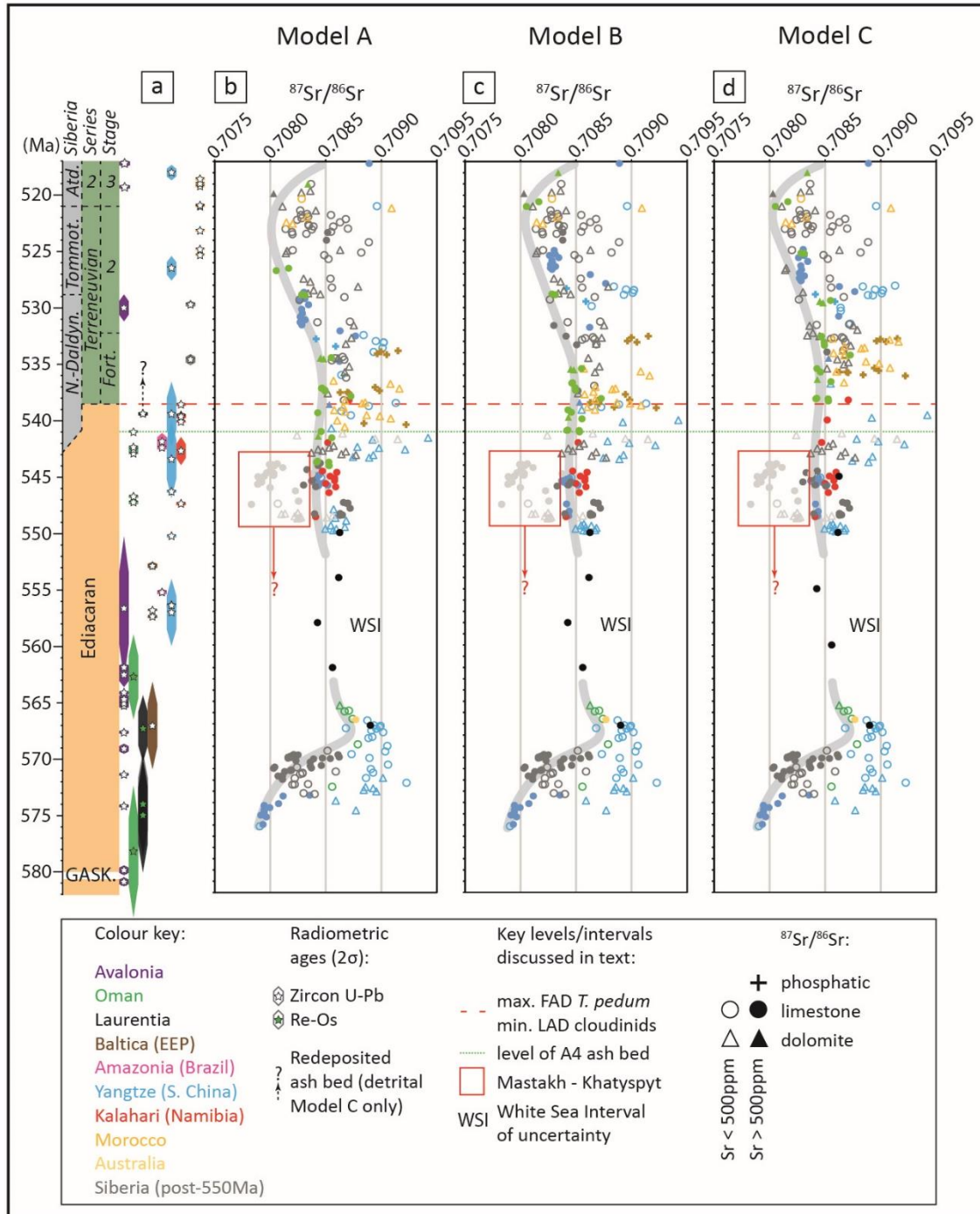
340 coloured by craton (or region). Age model for 582–550 Ma interval in grey after Yang et al. (2021).  
341 **(a)** Available radiometric ages with associated internal/analytical uncertainty. See Supplementary  
342 Materials (Tables S1 and S2) for references to radiometric and  $\delta^{13}\text{C}_{\text{carb}}$  data, in addition to  
343 biostratigraphic and section information. BANE marks the basal Nama negative  $\delta^{13}\text{C}_{\text{carb}}$  excursion,  
344 OME marks the positive  $\delta^{13}\text{C}_{\text{carb}}$  peak recorded in the Omkyk Member of the Zaris Formation of  
345 the Nama Group, Namibia. A0, A3 and A4 mark the relative positions of  $\delta^{13}\text{C}_{\text{carb}}$  excursions with  
346 radiometric ages in the Ara Group, Oman.  $\delta^{13}\text{C}_{\text{carb}}$  peaks 1p–6p, and II–V are labelled after direct  
347 correlation with the Sukharikha River section and Lena River sections of Siberia (e.g. Kouchinsky  
348 et al., 2007). 1n is equivalent to the BACE in all models.

349

350 correctly constrained in time (see section 5.5), it is sequestered within a shale interval  
351 stratigraphically beneath the Swartpunt section in all models.

### 352 *3.2 $^{87}\text{Sr}/^{86}\text{Sr}$ chemostratigraphy of the Ediacaran-Cambrian transition*

353 Matching  $\delta^{13}\text{C}_{\text{carb}}$  excursions in fossiliferous Ediacaran sections that display one or more  
354  $\delta^{13}\text{C}_{\text{carb}}$  excursions but lack radiometric ages is complicated by the finding here of multiple global  
355 late Ediacaran  $\delta^{13}\text{C}_{\text{carb}}$  excursions. This is equally problematic for the multiple excursions present  
356 in the Fortunian Stage of the lower Cambrian. In an attempt to address this issue, we compile a  
357 further database of published  $^{87}\text{Sr}/^{86}\text{Sr}$  data as an independent chronostratigraphic test (Table S2,  
358 Fig. 4). These  $^{87}\text{Sr}/^{86}\text{Sr}$  data have been screened on a case-by-case basis using available  
359 geochemical data to account for modification of the Sr isotope composition associated with  
360 diagenetic alteration or common Rb (see Supplementary Text, Table S2). Reliable  $^{87}\text{Sr}/^{86}\text{Sr}$  data



**Fig. 4. Sr isotope chemostratigraphy with associated radiometric ages (a) resulting from carbon isotope chemostratigraphy after Model A (b), Model B (c) and Model C (d) for the**

364 **interval ~576–517 Ma.** Red boxes highlight unusually depleted values of the Mastakh and  
365 Khatyspyt formations. Data coloured according to craton (or region).

366

367 are anchored directly to the prescribed age of the corresponding  $\delta^{13}\text{C}_{\text{carb}}$  value in the same sample.  
368 In this way, we are able to constrain trends that we consider the most robust estimate of seawater  
369  $^{87}\text{Sr}/^{86}\text{Sr}$  composition, and use  $^{87}\text{Sr}/^{86}\text{Sr}$  as an independent chronostratigraphic indicator for age  
370 models A, B and C for sections that lack radiometric ages (Fig. 4).

371 Revision of the age of the Shuram excursion after Rooney et al. (2020) and Yang et al. (2021)  
372 results in a highly uncertain interval ('WSI' in Figs. 3, 4) where  $^{87}\text{Sr}/^{86}\text{Sr}$  data are largely  
373 unconstrained with the possible exception of values corresponding to the Blueflower Formation of  
374 NW Canada (Narbonne et al., 1994). The resulting late Ediacaran  $^{87}\text{Sr}/^{86}\text{Sr}$  record (~551 – 538  
375 Ma) is characterized by values that are relatively invariant about 0.70842–0.70846, and these  
376 values are consistent between Namibia, South China, Mongolia and southeastern Siberia (Table  
377 S2). The Khatyspyt Formation yields inconsistent outlier values down to 0.70784 (boxed data in  
378 Fig. 4b-d), accompanied by a high degree of scatter in  $\delta^{13}\text{C}_{\text{carb}}$ . The position of the Khatyspyt  
379 Formation remains problematic due to uncertainties in the nature of the boundary with the  
380 overlying Turkut Formation (see section 5.3). However, we consider the correlation proposed  
381 herein to be a reasonable estimate based on consistent  $\delta^{13}\text{C}_{\text{carb}}$  trends between the Khatyspyt  
382 Formation and globally distributed sections throughout this interval.  $^{87}\text{Sr}/^{86}\text{Sr}$  values remain  
383 constant throughout much of the Fortunian, but begin to decline approximately coincident with  
384 rising  $\delta^{13}\text{C}_{\text{carb}}$  values in Cambrian Stage 2, reaching a nadir of ~0.70805 near the boundary between  
385 stages 2 and 3, prior to gradual recovery during upper Stage 3.

### 386 3.3 Incorporating additional section data

387 In order to test the validity of our Nama reference curve for global  $\delta^{13}\text{C}_{\text{carb}}$  correlation, and to  
388 explore the three alternative age models, we expand our dataset to incorporate published data from  
389 correlative strata into the early Cambrian from other cratons and regions (e.g. Yangtze Block,  
390 Oman, Laurentia, Amazonia, Morocco, Siberia, Mongolia, Fig. 3). We first prioritise sections with  
391  $\delta^{13}\text{C}_{\text{carb}}$  data and interbedded volcanic deposits dated via zircon U-Pb CA-ID-TIMS. Values of  
392  $\delta^{13}\text{C}_{\text{carb}}$ , anchored by the age of interbedded tuff deposits (within internal/analytical uncertainty)  
393 provide the scaffold for wider correlation, and intervals that lack constraint from radiometric ages  
394 are considered to be the most uncertain (Tables S1 and S2). Within this framework, we utilize  
395 regional sequence stratigraphic models that incorporate gaps in the carbon isotope record of  
396 individual sections, due to unconformities or intervals of siliciclastic deposition, while excluding  
397 unreasonable sedimentation rates for given tectonic settings (Table S2). Individual sections are  
398 subdivided into units of consistent lithofacies, and relative sedimentation rates are permitted to  
399 vary accordingly (Table S2). Deeper marine carbonate facies (e.g. organic-rich thinly bedded  
400 limestone laminae) and intervals of phosphorite deposition typically exhibit lower rates of  
401 deposition than shallow marine carbonate facies (e.g. dolostone and oolitic limestone deposited  
402 above fair weather wave base) within each region (Table S2).

403 Several high resolution  $\delta^{13}\text{C}_{\text{carb}}$  correlation frameworks have been assembled for the lower  
404 Cambrian (e.g. Brasier et al., 1994; Knoll et al., 1995; Kouchinsky et al., 2017, 2007, 2005; Maloof  
405 et al., 2010; Smith et al., 2015, Table S2). Our new framework is consistent with that derived by  
406 Maloof et al., (2010), but updates their model through incorporation of more recent high resolution  
407  $\delta^{13}\text{C}_{\text{carb}}$  datasets (e.g. Kouchinsky et al., 2017; Smith et al., 2015) and radiometric constraints (e.g.

408 Hodgin et al., 2020; Landing et al., 2020; Linnemann et al., 2019). We also consider updated  
409 biostratigraphic information integrated with  $\delta^{13}\text{C}_{\text{carb}}$  from sections in South China (Steiner et al.,  
410 2020), Australia (Betts et al., 2018) and Laurentia (Dilliard et al., 2007).

411 All global  $\delta^{13}\text{C}_{\text{carb}}$  correlation models reveal widespread, but short-lived, negative excursions  
412 in an interval dominated by positive  $\delta^{13}\text{C}_{\text{carb}}$  values in the terminal Ediacaran ~551–538 Ma (Fig.  
413 3e). These models differ most prominently in their correlation of the BACE nadir, either within  
414 the latest Ediacaran (models A and B) or within the lowermost Cambrian (Model C), as defined  
415 by its position relative to the radiometric age that currently constrains the FAD of *T. pedum* in  
416 Namibia (Fig. 3). However, *T. pedum* has not been reported in strata older than the BACE nadir in  
417 any region that hosts the BACE, and so the BACE nadir may in fact be older than the Ediacaran-  
418 Cambrian boundary in all models (discussed further below). Models B and C offer valid  
419 alternatives to the generally accepted Model A that are consistent with radiometric (models B and  
420 C) and stratigraphic (Model C) information in all regions. The relative likelihood of each of these  
421 three models, and their biostratigraphic implications, are further discussed below.

422

#### 423 **4. Implications for the age of the BACE and the Ediacaran-Cambrian boundary**

424 The A4 anomaly records minimum  $\delta^{13}\text{C}_{\text{carb}}$  values of -5‰ and one outlier value of -6.7‰  
425 (Amthor et al., 2003; Bowring et al., 2007) (Figs. 3 and 5). The onset of this negative excursion is  
426 anchored by an age of  $541.00 \pm 0.13$  Ma (Bowring et al., 2007). The overlying A5 Member of the  
427 Ara Group records stable positive values of 2-3‰, prior to the onset of another negative excursion  
428 (Amthor et al., 2003). The radiometric age of the A4 Member has been used to constrain an onset  
429 age for the BACE of ~541 Ma (Model A, e.g. Bowring et al., 2007; Hodgin et al., 2020; Linnemann

430 et al., 2019; Maloof et al., 2010). As previously noted, the BACE reaches a nadir of -10‰ and is  
431 recorded in all fossiliferous successions with high-resolution  $\delta^{13}\text{C}_{\text{carb}}$  data, except the Nama Group,  
432 Namibia (Figs. 3 and 5, Table S2). A maximum age of  $539.40 \pm 0.23$  Ma derives from a sandy  
433 dolostone bed in the La Ciénega Formation, Mexico, which lies within negative  $\delta^{13}\text{C}_{\text{carb}}$  values  
434 inferred to correspond to the BACE interval (Tables S1 and S2, Hodgins et al., 2020). However,  
435 strata of the upper Spitskop Member of the Urusis Formation (Nama Group, southern Namibia) at  
436 the Swartpunt section record relatively stable positive  $\delta^{13}\text{C}_{\text{carb}}$  values about 1‰ that are consistent  
437 with values from the A5 Member and constrained by 4 high resolution tuff bed ages between ca.  
438 540 Ma and 539.5 Ma (Figs. 2, 3, 5, Table S1) (Linnemann et al., 2019).

439 In Model A (Fig. 3b), the A4 anomaly and BACE are equivalent and constrained below the  
440 Swartpunt section in the shale interval of medium scale sequence E17 (Fig. 2). In this model, the  
441 BACE onset is at ca. 541 Ma, constrained in the A4 Member, and the recovery occurs at or before  
442 540 Ma, constrained at the base of Swartpunt section. This is also consistent with the interpreted  
443 depositional age being close to the radiometric age determined for the sandy dolostone bed in the  
444 La Ciénega Fm, Mexico (Hodgins et al., 2020). However, this implies that 1) the clastic unit that  
445 hosts the sandy dolostone bed was deposited at a slower depositional rate above the BACE nadir,  
446 2) the BACE recovery and plateau recorded at Swartpunt are constrained within the clastic horizon  
447 of the La Ciénega Fm and are therefore not recorded, and 3) a second more minor negative  
448 excursion is recorded above the level of the dolostone bed (possibly equivalent to the onset of 2n  
449 or a preceding minor negative excursion).

450 In Model A, positive  $\delta^{13}\text{C}_{\text{carb}}$  values in the uppermost Spitskop Member at Swartpunt may  
451 correlate with the 2p interval in Siberia (Kouchinsky et al., 2007), Mongolia (Smith et al., 2015)



452 and possibly Morocco (Maloof et al., 2010), all of which postdate the BACE nadir (Fig. 3b).  
453 However, in all areas that host high-resolution Fortunian  $\delta^{13}\text{C}_{\text{carb}}$  records, peaks 2p-4.5p appear to  
454 be short-lived positive excursions in an interval dominated by negative mean  $\delta^{13}\text{C}_{\text{carb}}$  values (Fig.  
455 3e). The duration of the 2p interval implied by the Swartpunt radiometric data therefore appears  
456 to contradict the best-fit  $\delta^{13}\text{C}_{\text{carb}}$  correlations of Fortunian sections (Maloof et al., 2010),  
457 notwithstanding the possibility for stratigraphic condensation in other regions at the 2p level (Figs.  
458 3b and e). We consider the caveats associated with the La Ciénega Fm correlation and  
459 inconsistencies relating to inferred peak duration between Swartpunt and 2p to make Model A less  
460 likely than models B or C for the BACE position, although it remains possible.

461 By contrast, models B and C imply that the A4 anomaly and BACE are two distinct excursions,  
462 with nadirs that are separated from one another by up to 5 million years (Figs. 3-5). In Model B  
463 (Fig. 3c) a return to positive  $\delta^{13}\text{C}_{\text{carb}}$  values following the A4 anomaly is constrained by the age of  
464  $540.095 \pm 0.099$  Ma at the base of the Swartpunt section, Namibia (Fig. 2) (Linnemann et al.,  
465 2019). The BACE onset occurred after  $\sim 539.6$  Ma, as constrained by three radiometric ages from  
466 the Swartpunt section immediately below carbonates that record a decrease in  $\delta^{13}\text{C}_{\text{carb}}$  to 0‰ (Figs.  
467 2 and 3c, Table S1, Linnemann et al., 2019), which is consistent with the aforementioned  
468 radiometric constraint of 539.4 Ma from the La Ciénega Formation, Mexico (Hodgin et al., 2020).  
469 In this model, recovery from the BACE in Namibia occurred prior to  $\sim 538.6$  Ma, consistent with  
470 a likely minimum age for the uppermost Spitskop Member at Swartpunt, as constrained by an ash  
471 bed age within the overlying Nomtsas Formation at a neighboring section (Linnemann et al., 2019)  
472 (Figs. 1 and 2). Although this model is consistent with all radiometric constraints, it implies that  
473 the BACE was a very short-lived event on the order of 1 Myr. This model demands that some  
474 sections (e.g. Sukharikha River) exhibited significantly higher sedimentation rates during the

475 BACE (1n) interval than the overlying 2p-5p interval, which appears inconsistent with the  
476 relatively monotonous lithofacies documented throughout.

477 Figure 5 presents age Model C for selected successions that host the highest resolution  $\delta^{13}\text{C}_{\text{carb}}$   
478 data for the critical late Ediacaran to Cambrian Stage 3 (Atdabanian) interval, in regions without  
479 significant Fortunian phosphorite deposition. Sections in Morocco, the Zavkhan terrane of  
480 Mongolia, and the Siberian Platform have limited Ediacaran-Fortunian radiometric ages, and  
481 therefore rely upon best-fit  $\delta^{13}\text{C}_{\text{carb}}$  correlation throughout this interval. In Model C (Figs. 3d and  
482 5), the onset of the BACE is inferred to post-date the Swartpunt section (<538.5 Ma). Stable  
483 positive  $\delta^{13}\text{C}_{\text{carb}}$  values in the interval ~540 – 539.5 Ma, as constrained at Swartpunt, separate the  
484 A4 anomaly from the BACE with the resulting peak herein termed the Spitskop excursion (SPIE,  
485 Figs. 3d and 5). Model C implies that 1) the A4 anomaly is distinct from the BACE, and 2) the age  
486 derived from the La Ciénega Formation (Hodgin et al., 2020) is best interpreted as detrital (Fig.  
487 5). In this model, the sandy dolostone bed in the La Ciénega Formation was deposited up to 3 Myr  
488 after eruption of the incorporated tuffaceous material based on best fit with the  $\delta^{13}\text{C}_{\text{carb}}$  curve and  
489 constant average rates of sedimentation.

490 Figure 5 also shows that age-calibrated stratigraphy in many successions record a striking  
491 regional lithostratigraphic transition across the Ediacaran-Cambrian boundary interval. In many  
492 regions, the transition is marked by a widespread erosive unconformity or exposure surface (e.g.  
493 Namibia, NE Siberia), and/or a subsequent change in dominant lithofacies which may reflect  
494 changes in global sea level. Whilst invoking a eustatic driver for combined litho- and  
495 chemostratigraphic variability across this transitional interval is complicated by regional tectonics,  
496 this may have significant biostratigraphic implications that warrant future consideration.

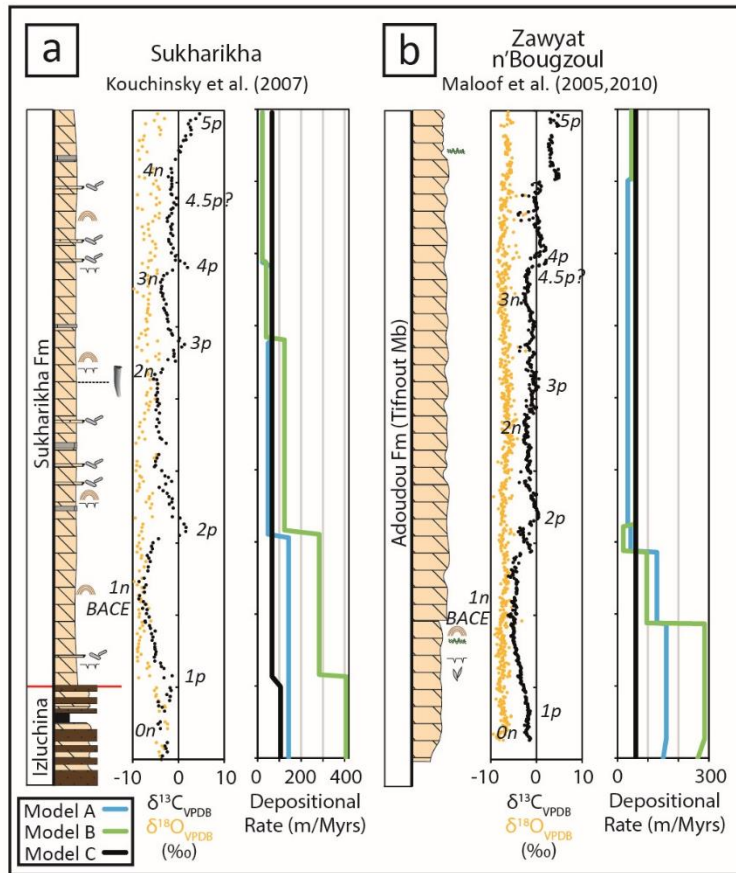


498 **Fig. 5. High-resolution age model correlation by region for Model C only.** Grey shading  
499 represents intervals of greatest uncertainty (see text for details). As in Fig. 3, the excursion marked  
500 as 1n represents the BACE. See Fig. S2 for a high resolution version of this figure.

501  
502 Model C is our preferred correlation when considering best fit between sections that host  
503 continuous Fortunian  $\delta^{13}\text{C}_{\text{carb}}$  data, whereby dominantly negative  $\delta^{13}\text{C}_{\text{carb}}$  values are interrupted by  
504 short-lived positive excursions (Kouchinsky et al., 2007; Maloof et al., 2010) (e.g. Morocco,  
505 Siberia, Figs. 3d, e and 6). This model also permits a short-lived pre-BACE excursion (herein  
506 termed 0n) which is recorded in sections with high-resolution  $\delta^{13}\text{C}_{\text{carb}}$  data from Morocco (e.g.  
507 Oued Sdas and Oued n'Oulili sections, Maloof et al., 2005), Siberia (Sukharikha and Nokhtuysk  
508 sections, Kouchinsky et al., 2007; Pelechaty, 1998), Mongolia (Zavkhan terrane, Smith et al.,  
509 2015), and possibly Laurentia (Hodgin et al., 2020; Smith et al., 2016) (Figs. 5 and 6).

510 Model C also maintains near constant sedimentation rates in multiple Fortunian – Stage 2  
511 sections (Table S2). Taking two of the most continuous carbonate successions known with limited  
512 facies variation, Sukharikha River, Siberian Platform, and Zawyat n'Bougzoul, Morocco, we show  
513 that while Models A and B both show markedly declining sedimentation rates in both successions,  
514 Model C maintains a constant sedimentation rate (Fig. 6). At the resolution of lithostratigraphic  
515 detail afforded for each of these sections in the published literature, Model C appears to be the  
516 simplest and most parsimonious solution.

517 The maximum age for the regional FAD of *T. pedum* on the Kalahari Craton is associated with  
518 the radiometric age of the lower Nomtsas Formation, Namibia (Linnemann et al., 2019). We note,



519

520 **Fig. 6. Changes in sedimentation rate implied by models A to C for selected sections that**  
 521 **capture the BACE and show limited facies variation through continuous carbonate**  
 522 **successions. (a) Sukharikha River section (Igarka-Norilsk Uplift, Siberian Platform) and (b)**  
 523 **Zawyat n'Bougzoul section (Anti-Atlas, Morocco), with lithostratigraphy and  $\delta^{13}\text{C}_{\text{carb}}$  after**  
 524 **Kouchinsky et al. (2007) and Maloof et al. (2005), respectively. See Fig. 2 for key to lithology and**  
 525 **sequence stratigraphy.**

526

527 however, that *T. pedum* has not been reported from the section (Farm Swartkloofberg, Linnemann  
 528 et al., 2019) from which this radiometric age is derived. Instead, the FAD of *T. pedum* is reported  
 529 from entirely siliciclastic valley fill deposits of the Nomtsas Formation on Farms Sonntagsbrunn

530 and Vergelee, >100 km to the east of Farm Swartkloofberg (Table S3). By contrast, the FAD of *T.*  
531 *pedum* in Laurentia is well constrained above the nadir of the BACE recorded in carbonate  
532 interbeds of the Esmeralda Member of the Deep Spring Formation, Nevada (Fig. 5c, Smith et al.,  
533 2016). If Model C is correct, then the integrated  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphy and biostratigraphy of  
534 the Mount Dunfee section may imply a far younger age for the FAD of *T. pedum* (~535.5 Ma),  
535 and by extension the Ediacaran-Cambrian boundary, than currently defined (Fig. 5). This may  
536 therefore also support a case for repositioning the Ediacaran-Cambrian GSSP to the Mount Dunfee  
537 section based on the best-fit calibration of the FAD of *T. pedum*.

538

## 539 **5. Ongoing uncertainties and biostratigraphic constraints**

540 The process of constructing these age models has exposed the largest remaining uncertainties  
541 in late Ediacaran – early Cambrian stratigraphic correlation, which occur mainly due to insufficient  
542 radiometric control. Despite these uncertainties, we build on the biostratigraphic framework of  
543 Maloof et al. (2010) and constrain the FADs of key Cambrian-type small skeletal fossil groups  
544 within each age model (Table S2).

### 545 *5.1 The possibility for a multimodal $\delta^{13}\text{C}_{\text{carb}}$ record*

546 High resolution  $\delta^{13}\text{C}_{\text{carb}}$  and sequence stratigraphic assessment of Cryogenian and early  
547 Ediacaran carbonates of the Congo Craton has revealed significant facies-dependency in the  
548 expression of presumed-global  $\delta^{13}\text{C}_{\text{carb}}$  excursions (Hoffman and Lamothe, 2019). In their model,  
549 Hoffman & Lamothe (2019) propose that the observed multimodal  $\delta^{13}\text{C}_{\text{carb}}$  expression between  
550 inner platform, basin margin and upper foreslope carbonates may be associated with significant  
551 facies-dependent distinction relating to seawater vs sediment-buffered diagenesis. They note that

552 this may significantly complicate the utility of  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphic studies throughout  
553 geological time, especially where radiometric anchor-points are absent or sparse. Anomalously  
554 positive  $\delta^{13}\text{C}_{\text{carb}}$  values of the middle Bambuí Group of Brazil, stratigraphically above *Cloudina*-  
555 bearing carbonates, also clearly demonstrate offset from global seawater composition (Uhlein et  
556 al., 2019). This offset is interpreted to reflect local effects of unusual water column chemistry that  
557 likely result from partial restriction (Cui et al., 2020b; Uhlein et al., 2019).

558 In our models, a number of regions show a degree of scatter in  $\delta^{13}\text{C}_{\text{carb}}$ , with possible evidence  
559 for deviation from the idealized seawater  $\delta^{13}\text{C}_{\text{carb}}$  curve. Examples include the Zuun-Arts and  
560 Salaany Gol formations (Mongolia), and potential  $\delta^{13}\text{C}_{\text{carb}}$  bimodality between different facies  
561 across the Yangtze Block (South China). In particular, the negative excursions at ca. 546.5 Ma  
562 (A0) and 541 Ma (A4), which may be globally widespread, are significantly muted in sections of  
563 the Yangtze Block. Whether the excursions themselves, or the muted record in South China, best  
564 reflect true changes in seawater composition as opposed to degrees of diagenetic alteration or  
565 restriction, remains uncertain.

566 Resolving the possible multimodal nature of Ediacaran and lower Cambrian  $\delta^{13}\text{C}_{\text{carb}}$  records  
567 will benefit from future radiometric calibration, in addition to high-resolution studies of integrated  
568 stratigraphic, petrographic,  $\delta^{44/40}\text{Ca}$  and  $\delta^{26}\text{Mg}$  analyses (e.g. Ahm et al., 2021; Bold et al., 2020).  
569 Whilst this frustrates the utility of the proposed global  $\delta^{13}\text{C}_{\text{carb}}$  correlation for regional  
570 chemostratigraphic studies of unfossiliferous strata with limited radiometric constraints  
571 throughout this time interval, we note that it does not alter proposed FADs and LADs of key taxa.  
572 We tentatively suggest that the broad trends observed in  $\delta^{13}\text{C}_{\text{carb}}$  represented by gradual,  
573 unidirectional shifts in  $\delta^{13}\text{C}_{\text{carb}}$ , are consistent between sections but that the absolute magnitude of

574 positive and negative excursions may differ depending on the specifics of local diagenetic  
575 alteration and/or steepness of the local isotopic gradient of seawater during organic carbon  
576 remineralisation. We note that this assumption holds true even for the Cryogenian interglacial  
577 interval, with the possible exception of the interval recording the Taishir anomaly (Hoffman and  
578 Lamothe, 2019). In this regard, and given the stratigraphic alternatives considered herein (Fig. 2),  
579 we do not consider the stable, positive  $\delta^{13}\text{C}_{\text{carb}}$  data of the Swartpunt section to necessarily correlate  
580 with the nadir of the BACE, as has previously been suggested (e.g. Hodgin et al., 2020).

## 581 *5.2 Age of the base of the Dengying Formation*

582 In models A to C, the shape of the global composite  $\delta^{13}\text{C}_{\text{carb}}$  curve between ~547 Ma and 543  
583 Ma is dictated in large part by the age of the base of the Dengying Fm of the Yangtze Platform,  
584 South China, and the shape of the Dengying Fm  $\delta^{13}\text{C}_{\text{carb}}$  profile. Detailed litho-, chemo-, and  
585 sequence stratigraphic studies of the Ediacaran Yangtze Platform are numerous (e.g. An et al.,  
586 2015; Condon et al., 2005; Cui et al., 2016; Cui et al., 2019; Ishikawa et al., 2008; Li et al., 2013;  
587 Lu et al., 2013; Tahata et al., 2013; Wang et al., 2014, 2017; Yang et al., 2021; C. Zhou et al.,  
588 2017b; Zhu et al., 2007, 2013). A summary description of the Dengying Fm, and detailed section  
589 correlation figures (Figs. S3 and S4) are provided herein for reference.

590 The Dengying Fm is lithostratigraphically subdivided into three members, each of which have  
591 differing names that correspond to geographic position on the Yangtze Platform (Fig. S3). The  
592 lower Member is dominated by dolostone that was deposited during a sea level highstand atop  
593 black shale of Member IV of the Doushantuo Formation (Zhu et al., 2007). This unit corresponds  
594 to the Algal Dolomite and Donglongtan members on the shallow Yangtze platform to the north  
595 and west, respectively, where it reaches thicknesses of >280m. In the Yangtze Gorges area to the  
596 east, the equivalent Hamajing Member ranges in thickness from 3-60m in sections measured for



597  $\delta^{13}\text{C}_{\text{carb}}$  (Fig. S3), but may reach a maximum thickness of 200m (Jiang et al., 2007; Zhu et al.,  
598 2007).

599 A sequence boundary separates dolostone of the lower Dengying Fm from overlying  
600 fossiliferous deeper marine deposits of the middle Dengying Fm across the Yangtze Platform (Zhu  
601 et al., 2007). In the north, this unit corresponds to fossiliferous transgressive siliciclastics and  
602 limestones of the Gaojiashan Member (20-45m) (Cui et al., 2016; Cui et al., 2019; Zhu et al.,  
603 2007). Equivalent transgressive deposits of the middle Dengying Fm correspond to shale of the  
604 Jiucheng Member (20-45m) in the west, and bituminous limestone of the richly fossiliferous  
605 Shibantan Member (up to >100m) in the Yangtze Gorges area to the east (Duda et al., 2016; Xiao  
606 et al., 2020; Zhu et al., 2007).

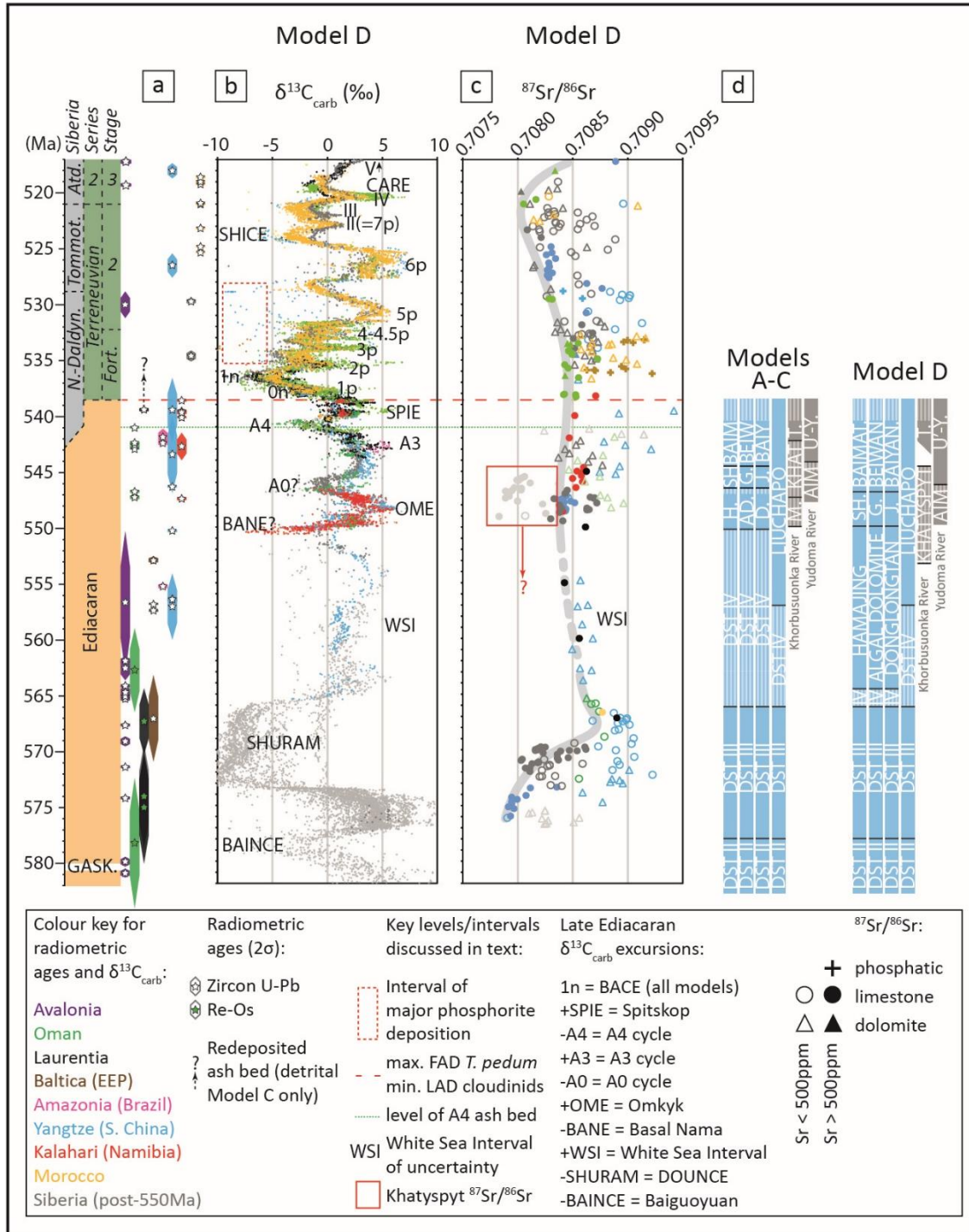
607 The third and topmost Member of the Dengying Fm is composed of highstand systems tract  
608 dolostones, which are frequently capped by a sequence boundary that shows evidence for  
609 exposure. In the north and west, this unit corresponds to the Beiwan (25-370m) and Baiyanshao  
610 ( $\leq 120\text{m}$ ) members, respectively, which correlate with the Baimatuo Member ( $\leq 400\text{m}$ ) in the  
611 Yangtze Gorges area (Zhu et al., 2007). Zircons within an ash layer 45m above the base of the  
612 Baimatuo Member at the Zhoujiaao section (central south Huangling anticline, Fig. S1) have been  
613 dated by U-Pb SIMS to  $543.40 \pm 3.5$  Ma (Huang et al., 2020).

614 A zircon U-Pb CA-ID-TIMS age of  $550.14 \pm 0.63$  Ma (Yang et al., 2021) from an ash bed at  
615 the top of Member IV (Miaohe Member) of the Doushantuo Fm at Jiuqunao section of the western  
616 Huangling anticline (Fig. S3) is classically considered to constrain a maximum age for the base of  
617 the Dengying Fm (Condon et al., 2005). The Dengying Fm in the Jiuqunao section records  
618 recovery from a negative  $\delta^{13}\text{C}_{\text{carb}}$  excursion characterised by increasing  $\delta^{13}\text{C}_{\text{carb}}$  from  $-4.05\text{‰}$  to  
619  $+3.56\text{‰}$  in  $<3\text{m}$  of dolostone (Fig. S3) (Condon et al., 2005; Yang et al., 2021; Zhu et al., 2007).

620 Unfortunately, lithostratigraphic and chemostratigraphic correlation between sections of the  
621 western Huangling anticline at the boundary between the Doushantuo and Dengying formations is  
622 complicated by slumping and associated stratigraphic repetition (Fig. S3) (An et al., 2015; Vernhet,  
623 2007; Yang et al., 2021; Zhou et al., 2017b). Furthermore, the ~550 Ma ash layer at Jiuqunao  
624 section has not been reported at the top of Doushantuo Member IV, or elsewhere, from any other  
625 section on the Yangtze Platform to date.

626 Here we consider a further alternative model (Model D) that explores the implications of  
627 correlating the  $\delta^{13}\text{C}_{\text{carb}}$  data above the 550 Ma ash bed at Jiuqunao with the upper Hamajing Mb,  
628 rather than the basal Hamajing Mb (Fig. S4). In this model, the 550 Ma ash layer represents the  
629 age of slumping in the western Huangling anticline, and was deposited at the top of the disrupted  
630 unit, thereby permitting a conformable contact between the ash horizon and the overlying  
631 Dengying Fm at Jiuqunao section. The sequence stratigraphic framework for the entire Dengying  
632 Fm in sections across the Yangtze Platform and slope presented by Zhu et al. (2007) is maintained  
633 in Model D. However, this model implies that the thick Algal Dolomite and Donglongtan  
634 members, and the Hamajing Mb in many sections of the central and eastern Huangling anticline,  
635 were deposited between  $\leq 565$  Ma and ~550 Ma, rather than  $< 550$  Ma.

636 The alternative correlation presented in Model D greatly simplifies the global  $\delta^{13}\text{C}_{\text{carb}}$  curve  
637 between 546 Ma and 543 Ma and, by extension, between 550 Ma and 541 Ma (Fig. 7). In models  
638 A-C, the  $\delta^{13}\text{C}_{\text{carb}}$  profile from the (e.g.) Gaojiashan Member occupies the interval from 546 Ma to  
639 543 Ma, however in Model D the middle Member of the Dengying Fm across the Yangtze Platform  
640 correlates well with the  $\delta^{13}\text{C}_{\text{carb}}$  profile of the Kuibis Subgroup of the Nama Group, between 550



641

642 **Fig. 7. Model D output resulting from correlation of the ~550 Ma ash layer at the Jiuqunao**

643 **section with the upper Hamajing Mb and equivalent units of the lower Dengying Fm (see**

644 **Fig. S4). Age model from 541-517 Ma is consistent with Model C, and age model for 582–550**

645 **Ma interval in grey after Yang et al. (2021).** **A)** Radiometric ages with associated  $2\sigma$  uncertainty,  
646 **B)** Global  $\delta^{13}\text{C}_{\text{carb}}$  profile resulting from Model D correlation, **C)** Global  $^{87}\text{Sr}/^{86}\text{Sr}$  profile resulting  
647 from Model D correlation, **D)** Summary of differences in stratigraphic correlation between models  
648 A-C and Model D for stratigraphy of South China (blue) and Siberia (grey). SH = Shibantan, G =  
649 Gaojiashan, J = Jiucheng, BAIMAT = Baimatuo, BAIYAN = Baiyanshao, M = Mastakh, T =  
650 Turkut, U'-Y = Ust'-Yudoma.

651  
652 Ma and 546 Ma. Model D also implies that the Aim and Khatyspyt formations of the Siberian  
653 Platform may similarly occupy the interval from 550 Ma to 546 Ma based on best fit with the  
654 resulting global  $\delta^{13}\text{C}_{\text{carb}}$  curve (Fig. 7d). In Model D, the global  $\delta^{13}\text{C}_{\text{carb}}$  curve between 546.5 Ma  
655 and 541 Ma is characterised by a simple increase and decrease (Fig. 7b), from A0 to A3 and  
656 culminating in the A4 excursion (which may or may not correspond with the BACE).

### 657 5.3 Age of the Khatyspyt Formation

658 The temporal placement of the Khatyspyt Formation of the Olenek Uplift is key to  
659 understanding the degree of assemblage overlap between the Avalon, White Sea and Nama  
660 assemblages, as it contains typical Avalon assemblage fossils including the rangeomorphs *Charnia*  
661 *masoni* and *Khatyspytia grandis* (e.g. Cui et al., 2016). The age of the Khatyspyt Formation also  
662 has significant implications for the evolution and morphological changes in macroalgae during the  
663 late Ediacaran (Bykova et al., 2020). The Khatyspyt Formation has long been assumed to record  
664 deposition between ca. 560 and 550 Ma, approximately contemporaneously with the Miaohé  
665 Member and fossiliferous deposits of the White Sea area (e.g. Cui et al., 2016). In fact, the only  
666 radiometric constraint available is a maximum age for intrusion of the volcanic breccia of the Tas-

667 Yuryakh volcanic complex within the lower part of the Syhargalakh Formation (lower Kessyusa  
668 Group), which unconformably overlies the Khatyspyt and overlying Turkut formations. The  
669 maximum age for intrusion of this unit is  $542.8 \pm 1.30$  Ma, provided by zircon U-Pb air abrasion  
670 ID-TIMS (Table S1) (Bowring et al., 1993; Maloof et al., 2010; Rogov et al., 2015).  
671 Notwithstanding uncertainties in this age (Table S1), the Turkut Formation, which overlies the  
672 Khatyspyt Formation, contains the local FAD of the anabaritid *Cambrotubulus decurvatus* and the  
673 onset of a negative excursion which may be equivalent either to the A4 anomaly or the BACE  
674 (depending on the preferred model, Figs. 3 and 4). Screened  $^{87}\text{Sr}/^{86}\text{Sr}$  data for the Khatyspyt  
675 Formation (boxed data in Fig. 4b-d) are notably depleted (mean = 0.708038, n = 19, Cui et al.,  
676 2016; Vishnevskaya et al., 2017, 2013) relative to all screened data prior to the nadir in upper  
677 Cambrian Stage 2 (Table S2). Recent efforts to produce a global late Ediacaran  $^{87}\text{Sr}/^{86}\text{Sr}$   
678 compilation suggest that the low  $^{87}\text{Sr}/^{86}\text{Sr}$  data recorded by the Khatyspyt Formation are supportive  
679 of a temporal placement approximately coincident with and postdating data from the Nama Group  
680 (Cui et al., 2020a). Potential issues with this correlation are outlined below.

681 Carbon isotope data from the Nama Group are anchored at various levels to high precision  
682 radiometric ages (e.g. Bowring et al., 2007; Linnemann et al., 2019), and reveal trends in  $\delta^{13}\text{C}_{\text{carb}}$   
683 that are correlatable in other, globally distributed and similarly temporally well-constrained  
684 sections (e.g. Ara Group, Oman, Amthor et al., 2003; Bowring et al., 2007). Robust  $^{87}\text{Sr}/^{86}\text{Sr}$  data  
685 from the Nama Group are recorded from samples spanning the Omkyk Member (Zaris Formation)  
686 to the Nomtsas Formation, with relatively invariable  $^{87}\text{Sr}/^{86}\text{Sr}$  values (mean = 0.708538, n = 11)  
687 (Kaufman et al., 1993). Furthermore, high Sr limestones from the Shibantan Member, South China  
688 and the Zuun-Arts and overlying Bayan-Gol formations of the Zavkhan Terrane, Mongolia, show  
689 robust  $^{87}\text{Sr}/^{86}\text{Sr}$  values and  $\delta^{13}\text{C}_{\text{carb}}$  trends consistent with the record from the Nama Group, with

690 the latter extending relatively stable values of  $\sim 0.708500$  into the lower Fortunian (Fig. 4b-d, Table  
691 S2, Brasier et al., 1996). In light of available robust  $\delta^{13}\text{C}_{\text{carb}}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  data from radiometrically  
692 well-constrained sections, our compilation suggests either: 1) that low  $^{87}\text{Sr}/^{86}\text{Sr}$  values and an  
693 Avalon-type biotic assemblage support an older temporal placement for the Khatyspyt Formation  
694 than that shown in our compilation ( $>551$  Ma and possibly as old as  $\sim 575$  Ma), or 2) that the  
695  $^{87}\text{Sr}/^{86}\text{Sr}$  data recorded by the Khatyspyt Formation are not representative of global seawater  
696 composition. The nature of the contact between the Khatyspyt and Turkut formations along the  
697 Khorbusuonka River is key to determining the true placement of the Khatyspyt Formation, and  
698 reports vary considerably. For example, Cui et al. (2016) report that the boundary between the  
699 Khatyspyt and Turkut formations is conformable, whereas Vishnevskaya et al. (2017) suggest that  
700 this is an unconformable contact. However, neither publication provides figured evidence of the  
701 nature of the contact.

702 In our correlation, we tentatively assume that the hiatus (if any) at the boundary between these  
703 two formations along the Khorbusuonka River is relatively minor ( $<500$  kyrs). This is justified in  
704 part by the consistency in  $\delta^{13}\text{C}_{\text{carb}}$  and lithostratigraphy between late Ediacaran sections of the  
705 Olenek uplift and the Nama and Ara groups (Figs. 3 and 5). However, we stress that this requires  
706 future clarification due to the unusually low  $^{87}\text{Sr}/^{86}\text{Sr}$  data of the Khatyspyt Formation in this time  
707 interval. If the boundary is conformable, the presence of Avalon-type fossils in the Khatyspyt  
708 Formation, in addition to *Charniodiscus* noted from the Shibantan Member (Chen et al., 2014),  
709 together suggest that rare remnants of the Avalon assemblage remained until possibly as late as  
710 ca. 545.5 Ma. It is noteworthy that ordination plots of the overall late Ediacaran fossil assemblages  
711 have not placed the Khatyspyt assemblage within the Avalon-type biotas and instead place it with  
712 the younger White Sea biota (Boag et al., 2016). The temporal overlap between the Avalon and

713 Nama assemblages also holds true regardless of the age of the Khatyspyt Formation, as the age of  
714 the Shibantan Member is confidently constrained (< ca. 551 Ma) by the aforementioned  
715 radiometric age of the volcanic tuff deposit in the underlying upper Miaohe Member (Condon et  
716 al., 2005; Schmitz, 2012; Yang et al., 2021).

#### 717 *5.4 Age of the Turkut Formation:*

718 A maximum age for intrusion of the Tas-Yuryakh volcanic breccia within the lower  
719 Syhargalakh Formation (lower Kessyusa Group) along the Khorbusuonka River is suggested by a  
720 zircon U-Pb air abrasion ID-TIMS age of  $542.8 \pm 1.30$  Ma (Table S1) (Bowring et al., 1993;  
721 Maloof et al., 2010; Rogov et al., 2015). The intrusive Tas-Yuryakh volcanic breccia  
722 unconformably overlies the Turkut Formation. The FAD of the anabaritid *Cambrotubulus*  
723 *decurvatus* is recorded from the lower Turkut Formation in this section (Rogov et al., 2015), which  
724 supports a late Ediacaran lower boundary for the regional Nemakit-Daldynian Stage of Siberia,  
725 consistent with biostratigraphy and  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphy in sections along the Yudoma River  
726 of SE Siberia (Zhu et al., 2017).  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphic and sequence stratigraphic studies  
727 support temporal placement of the Turkut Formation of the Khorbusuonka River correlative with  
728 the middle – upper Ust'-Yudoma Formation in sections along the Yudoma River (Knoll et al.,  
729 1995; Pelechaty, 1998; Pelechaty et al., 1996b, 1996a; Zhu et al., 2017). Indeed, if the age of the  
730 Tas-Yuryakh volcanic breccia is close to the minimum age within analytical uncertainty, then the  
731 negative excursion recorded at the top of the Turkut Formation (Knoll et al., 1995) is equivalent  
732 to the A4 anomaly, and either corresponds with (Model A) or precedes (models B and C) the  
733 BACE. In both scenarios, the lower Turkut Formation and middle Ust'-Yudoma Formation at  
734 Kyra-Ytyga contain the earliest known FADs of anabaritids globally ( $\geq 541$  Ma, Fig. 8). It is likely

735 that future high precision CA-ID-TIMS analyses significantly alter the temporal position of the  
736 Tas-Yuryakh volcanic breccia, and by extension the minimum age of the underlying Turkut  
737 Formation. In the age models presented herein, a maximum age for the FAD of SSFs of the  
738 *Anabarites trisulcatus* – *Protohertzina anabarica* Zone (and by extension the Nemakit-Daldynian  
739 lower boundary) is therefore set at ca. 541–542 Ma across the Siberian Platform (Fig. 8). This  
740 temporal placement is most consistent with the dominant  $\delta^{13}\text{C}_{\text{carb}}$  trends observed pre-BACE,  
741 whereby positive  $\delta^{13}\text{C}_{\text{carb}}$  values are interrupted by short-lived negative excursions (Fig. 3e).

#### 742 *5.5 Integrated geochronology of the Ara Group*

743 A complication inherent in the chemostratigraphic assessment of the Ara Group is the nature  
744 of the carbonate units themselves, which are found as ‘stringers’, frequently interbedded by  
745 evaporite (Amthor et al., 2003; Bowring et al., 2007). We note that whilst the high precision  
746 radiometric ages provided by Bowring et al. (2007) confidently place these carbonate units in  
747 relative stratigraphic order, the analysed tuffaceous material and  $\delta^{13}\text{C}_{\text{carb}}$  datasets do not always  
748 derive from the same core. For example, the A0  $\delta^{13}\text{C}_{\text{carb}}$  excursion is recorded within the Sabsab-  
749 1 well, whereas the radiometric constraint of ~546.72 Ma derives from a tuff bed in the Asala-1  
750 well.  $\delta^{13}\text{C}_{\text{carb}}$  data for the Asala-1 well remain unpublished, precluding confident calibration of this  
751  $\delta^{13}\text{C}_{\text{carb}}$  excursion. Indeed, the only two wells for which both radiometric and  $\delta^{13}\text{C}_{\text{carb}}$  data are  
752 available are BB-5 and Minha-1. Whilst BB-5 constrains the A4 anomaly, Minha-1 captures  
753 positive  $\delta^{13}\text{C}_{\text{carb}}$  values in the A3 Member that are in agreement with radiometrically constrained  
754  $\delta^{13}\text{C}_{\text{carb}}$  data from Brazil (Parry et al., 2017) and South China (Huang et al., 2020).



755 We note that some other globally-distributed sections record an excursion that is demonstrably  
756 pre-BACE (e.g. Zuun-Arts Formation), which may be more consistent with an earlier, distinct ‘A4’  
757 anomaly. The A5 Member of the Ara Group also records a  $\delta^{13}\text{C}_{\text{carb}}$  plateau of similar magnitude  
758 to that recorded at Swartpunt (Figs. 5a, b), followed by a gradual decrease in  $\delta^{13}\text{C}_{\text{carb}}$  that mirrors  
759 the decrease seen above the level of the ca. 539.6 Ma horizon at Swartpunt (Figs. 2 and 5a, b).  
760 These features may add credence to a pre-BACE ‘A4’ anomaly (models B and C).

#### 761 5.6 $\delta^{13}\text{C}_{\text{carb}}$ correlation of the lower Fortunian

762 Recent biostratigraphic and  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphic assessment of Ediacaran – Cambrian  
763 transitional strata of the Yangtze Platform, South China have shown a previously underappreciated  
764 level of  $\delta^{13}\text{C}_{\text{carb}}$  variability in the post-BACE, pre-ZHUCE (Zhujiaping positive  $\delta^{13}\text{C}_{\text{carb}}$  excursion)  
765 interval (Steiner et al., 2020). In age models A and B, the BACE is constrained to be late Ediacaran  
766 in age, with a nadir either at ca. 541 (Model A) or ca. 539 Ma (Model B, Figs. 3 and 9, Table S2).  
767 In Model C, the BACE is within the basal Cambrian based on correlation with the radiometric age  
768 and inferred maximum FAD of *T. pedum* in the Nomtsas Fm (Fig. 10). However, as noted above,  
769 the FAD of *T. pedum* is constrained to be post-BACE in all successions that host the BACE, which  
770 may also support an Ediacaran age for the BACE in Model C. The BACE is well-recorded in  
771 sections across the Yangtze Platform, South China, in the lower Zhujiaping Formation (Daibu  
772 Member) and Yanjiahe Formation, and is commonly overlain by phosphorus-rich carbonates of  
773 the middle Zhujiaping Formation (Zhongyicun Member) and equivalent units (Brasier et al., 1990;  
774 Steiner et al., 2020). Phosphorite deposition is globally widespread in lower Fortunian strata (e.g.  
775 Tarim, Yangtze Platform, Malyi Karatau of Kazakhstan, northern Mongolia, some sections of  
776 Laurentia), with carbonate substituted in the phosphorite lattice commonly recording very

777 negative, or highly variable  $\delta^{13}\text{C}_{\text{carb}}$  values that diverge from global seawater composition. The  
778 upper Yanjiahe Formation, above the level of the BACE, yields highly variable  $\delta^{13}\text{C}_{\text{carb}}$  values  
779 alongside SSFs of the *A. trisulcatus* – *P. anabarica* assemblage Zone (Steiner et al., 2020). The  
780 Kuanchuanpu Formation yields similarly variable  $\delta^{13}\text{C}_{\text{carb}}$  values and SSFs (Steiner et al., 2020; B.  
781 Yang et al., 2016). Crucially, the lower Kuanchuanpu Formation records the co-occurrence of  
782 *Cloudina* with SSFs of the *A. trisulcatus* – *P. anabarica* Zone (B. Yang et al., 2016), however the  
783 exact position of this mixed assemblage relative to the BACE nadir remains uncertain.

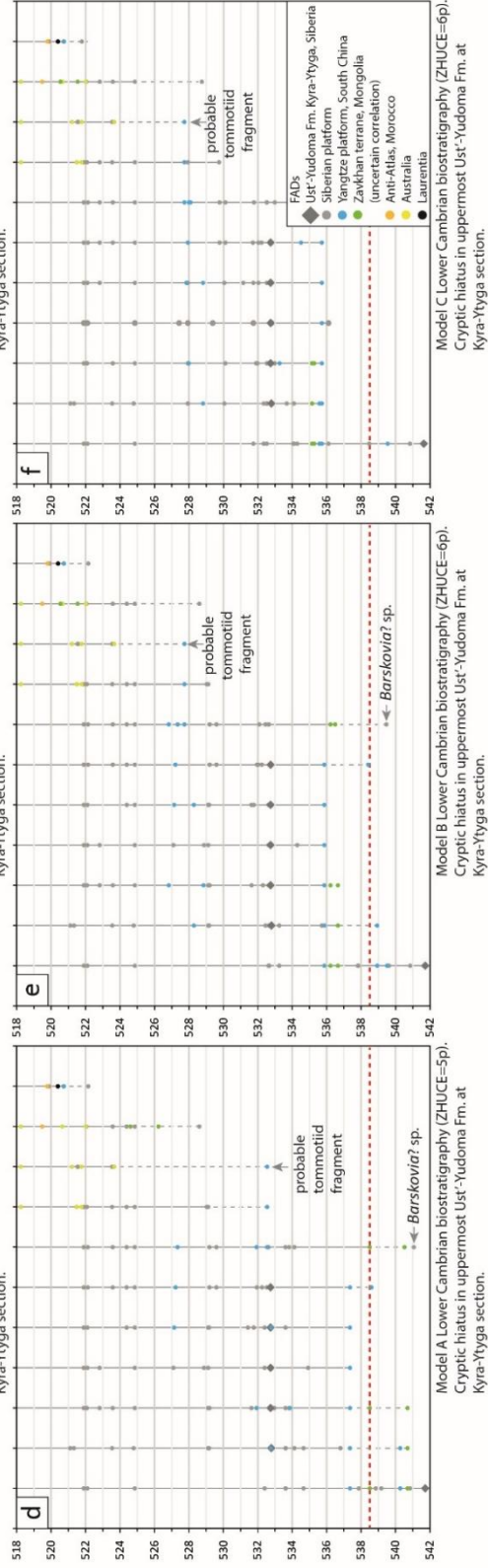
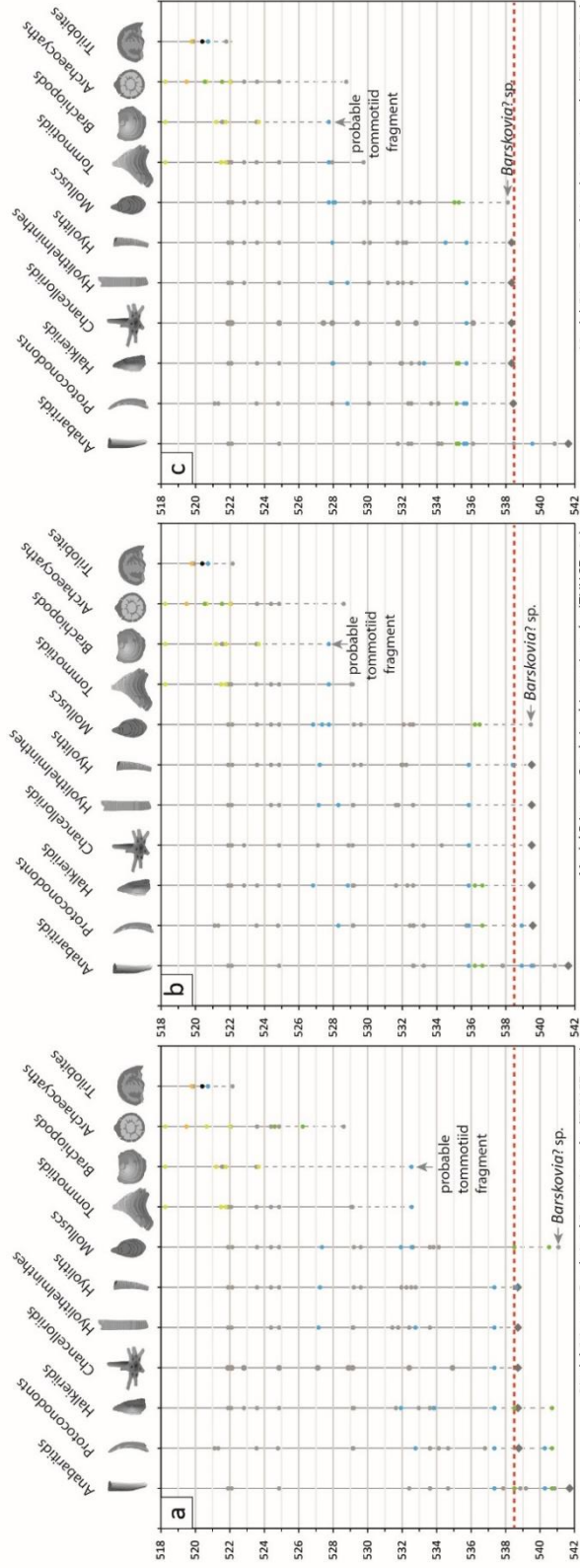
784 In areas where phosphorite deposition is limited, the  $\delta^{13}\text{C}_{\text{carb}}$  composition of Fortunian-age  
785 global seawater is more faithfully recorded (e.g. Siberia, Morocco, Mongolia), and appears to show  
786 high frequency excursions (including peaks 2p-4p) that record a gradual increase in  $\delta^{13}\text{C}_{\text{carb}}$   
787 towards a large positive excursion (5p) (Figs. 3b-d, 5d-f) (Kouchinsky et al., 2007; Maloof et al.,  
788 2010; Smith et al., 2015). Crucially, however, this interval of high frequency  $\delta^{13}\text{C}_{\text{carb}}$  variability  
789 suffers from a significant dearth of radiometric anchor-points, robust differentiation in SSF  
790 zonation, or differentiation of  $\delta^{13}\text{C}_{\text{carb}}$  peaks of distinct magnitude. Sections of the Anti-Atlas  
791 Mountains in Morocco and along the Sukharikha River of northwest Siberia have been proposed  
792 as continuous reference sections for correlative trends in Fortunian global seawater  $\delta^{13}\text{C}$   
793 (Kouchinsky et al., 2007; Maloof et al., 2010). However, the absolute magnitude and number of  
794 peaks are thought to vary between and within regions (e.g. Smith et al., 2015). At present, the  
795 published section information in both of these areas is insufficiently detailed to accurately  
796 constrain the position of individual exposure surfaces. We note that the Fortunian remains the  
797 interval of greatest uncertainty in our correlation and demands future targeted study, integrating  
798 high resolution chemostratigraphic data with detailed sedimentological, biostratigraphic and  
799 sequence stratigraphic information and, where possible, high resolution radiometric age

800 constraints. Higher resolution  $\delta^{13}\text{C}_{\text{carb}}$  datasets may also permit more statistically significant peak  
801 correlation through use of dynamic programming algorithms, as has been demonstrated for  
802 Atdabanian successions of Morocco (Hay et al., 2019).

### 803 *5.7 The position of the ZHUCE relative to peaks 5p and 6p*

804 Below we consider alternative temporal positions for the ZHUCE and the excursion recorded  
805 in the Salaany Gol Formation. For ease of reference, alternative correlations are incorporated into  
806 Model A relative to models B and C, however their relative positions and uncertainties should be  
807 considered in isolation.

808 The upper Zhujiqing Formation (Dahai Member) of the Yangtze Platform records a prominent  
809 positive  $\delta^{13}\text{C}_{\text{carb}}$  excursion with an onset approximately coincident with the FADs of the mollusks  
810 *Aldanella attleborensis* and *Watsonella crosbyi* (Figs. 8-10, Table S3, Li et al., 2011; Parkhaev  
811 and Karlova, 2011; Steiner et al., 2020). The FAD of *Watsonella crosbyi* occurs prior to the apex  
812 of 5p, or immediately following recovery from 5p in sections of the western Anabar Shield, and  
813 may be approximately contemporaneous in the Bayangol Fm of the Zavkhan Terrane, Mongolia  
814 (Kouchinsky et al., 2017; Smith et al., 2015) (but see section 5.8). Peak 5p is followed by 6p in  
815 Cambrian Stage 2 strata of Siberia and Morocco, but the relative position of the singular excursion  
816 recorded in the Dahai Member has been problematic (Steiner et al., 2020). Possible regional  
817 variability in the magnitude of the ZHUCE in South China, in addition to widespread phosphorite  
818 deposition of the underlying Zhongyicun Member in some areas of the Yangtze Platform,  
819 complicates the utility of  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphy for accurately determining the correct  
820 correlation of the peak recorded in the Dahai Member (Steiner et al., 2020).



822 **Fig. 8. High-resolution Cambrian biostratigraphy resulting from models A to C.** Note that  
823 first occurrences are pinned only within sections that have high-resolution  $\delta^{13}\text{C}_{\text{carb}}$  data. As such,  
824 first appearances within siliciclastic-dominated successions remain uncalibrated. The single  
825 specimen of *Aldanotreta* sp. (brachiopod) reported from the upper Zhongyicun Member (Table  
826 S2) may instead represent a tommotiid fragment; however, this cannot be confirmed due to the  
827 poor quality of the specimen.

828

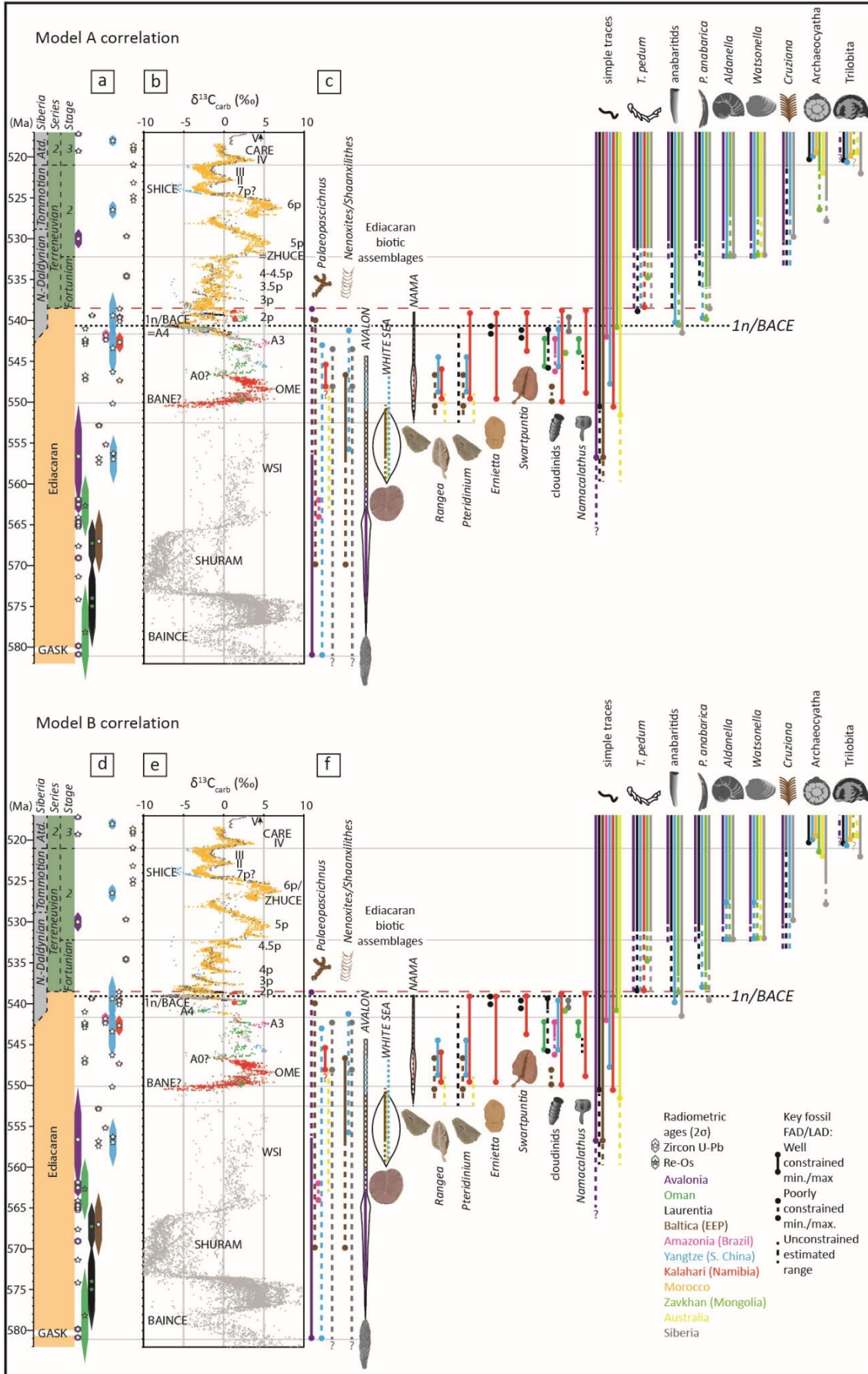
829 Model A (Figs. 3b, 8a, 9b,c) shows the result of correlating the ZHUCE with 5p, which may be  
830 more consistent with a depositional hiatus of longer duration that separates the Dahai Member  
831 from the overlying Shiyantou Formation. In this correlation, the FAD of tommotiids in South  
832 China significantly predates Siberia (Fig. 8a), and maximum  $\delta^{13}\text{C}_{\text{carb}}$  values of the Dahai Member  
833 are greater than 5p in the Siberian and Moroccan profiles. However, Model A results in a relatively  
834 consistent (possibly slightly earlier) FAD of the mollusks *Watsonella* and *Aldanella* relative to  
835 Siberia (Fig. 9c), whereas Model B results in a slightly delayed FAD of these genera in South  
836 China (Figs. 8b and 9f). The correlation of ZHUCE with 5p is also supported by SSF  
837 biostratigraphy of the Yanjiahe Fm, where peak values in Unit 3 occur within the SSF Zone 2  
838 (*Purella antiqua*), which would be consistent with a pre-5p excursion in other localities.

839 In models B and C, the ZHUCE is correlated with peak 6p (Figs. 3c,d, 8b,c, 9f, 10c) and  
840 negative  $\delta^{13}\text{C}_{\text{carb}}$  values associated with phosphatic lithologies of the Zhongyicun Member are not  
841 considered useful for global chemostratigraphic correlation. Correlation of the ZHUCE with 6p  
842 may be justified by the best fit of  $\delta^{13}\text{C}_{\text{carb}}$  data (particularly maximum values at Xiaotan section),  
843 but also by recognition of the more consistent age for the resulting FAD of tommotiids in South

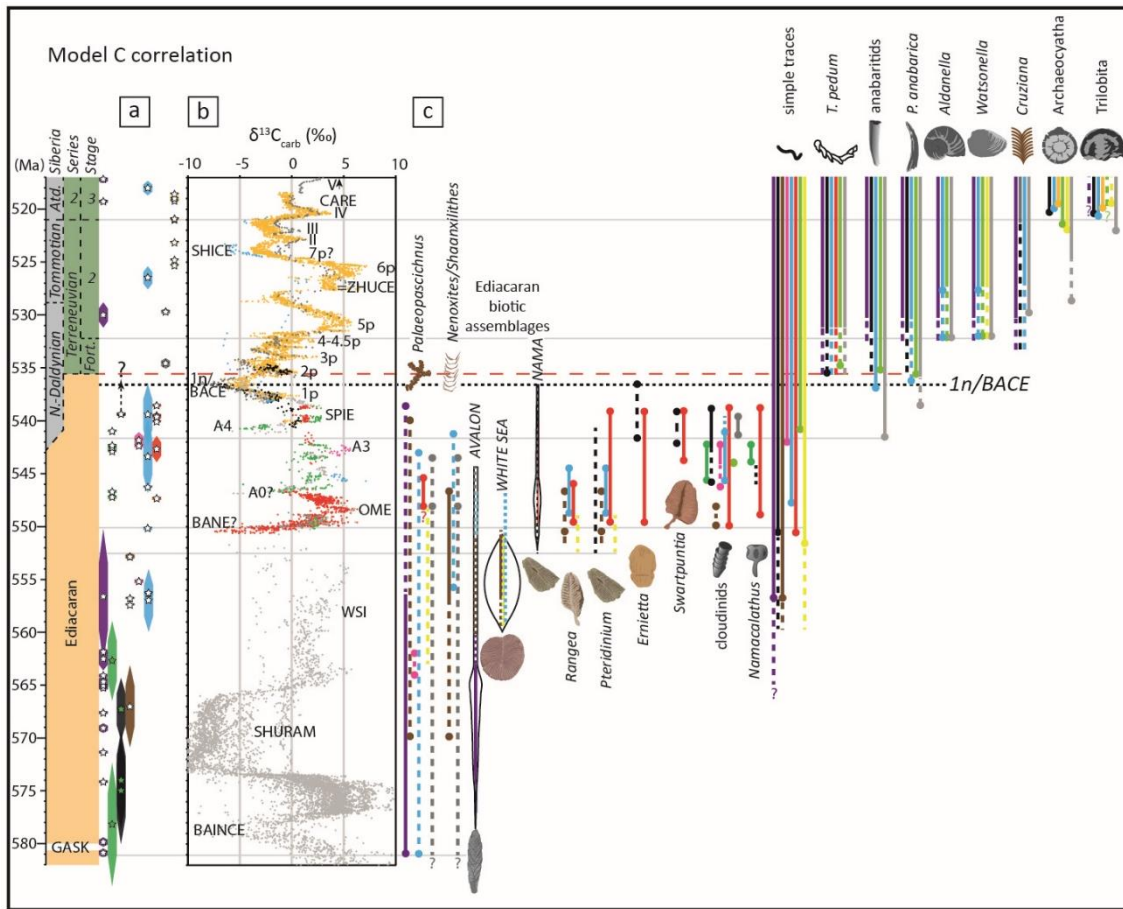
844 China relative to Siberia (Fig. 8b,c). In Model B, positive  $\delta^{13}\text{C}_{\text{carb}}$  in Yanjiahe Unit 3 are correlated  
845 with peak 5p, and peak 6p is absent from this formation in recognition of the depositional hiatus  
846 separating the Yanjiahe Formation from the overlying Shuijingtuo Formation (Steiner et al., 2020).  
847 Robust differentiation between these correlations is currently hampered by a lack of radiometric  
848 data and discontinuous carbonate sections from this interval in South China.

849 *5.8 Correlation of the Salaany Gol Formation (Zavkhan Terrane, Mongolia) with peak 6p vs peak*  
850 *IV*

851 A basal Tommotian (Stage 2) age for the lower Salaany Gol (Salaagol) Formation of SW  
852 Mongolia was justified by Smith et al. (2015) on the basis of an absence of trilobites in this unit,  
853 which in their view makes the excursion equivalent to positive peak 6p of the Siberian scale (shown  
854 in Model A of Figs 3a, 8a, 9b). However, the archaeocyathan assemblage of the lower Salaany Gol  
855 Formation includes approximately 30 distinct species (up to 16 species per single reef; Zhuravlev  
856 and Naimark, 2005), which are widespread throughout Mongolian, Altay-Sayan and  
857 Transbaikalian terranes and occur permanently below the first trilobites in each area (Debrenne et  
858 al., 2015; Dyatlova and Sycheva, 1999; Osadchaya and Kotel'nikov, 1998; Zhuravleva et al.,  
859 1997). In turn, this first trilobite species assemblage is also the same and belongs to the *Resimopsis*  
860 trilobite Zone, which contains species of the middle Atdabanian (Stage 3) *Repinaella* trilobite Zone  
861 of the Siberian Platform and lacks any earlier trilobite elements (Astashkin et al., 1995; Korobov,  
862 1989, 1980). Landing and Kruse (2017) noted these inconsistencies and suggested that the positive  
863  $\delta^{13}\text{C}_{\text{carb}}$  excursion in the lower Salaany Gol Formation is rather an equivalent of the middle  
864 Atdabanian  $\delta^{13}\text{C}_{\text{carb}}$  excursion IV of the Siberian Platform, which fits better to both archaeocyath  
865 and trilobite biostratigraphies. The other suggestion of Smith et al. (2015) concerning the absence



867 **Fig. 9. Biostratigraphic output resulting from Model A (a–c) and Model B (d–f) for the**  
 868 **interval ~551–517 Ma. Includes (a,d) radiometric constraints, (b,e)  $\delta^{13}\text{C}_{\text{carb}}$ , and (c,f) First**  
 869 **Appearance Datum (FAD) and Last Appearance Datum (LAD) of key Ediacaran-Cambrian fossils**  
 870 **(Table S3). Black dotted line marks the temporal position of the 1n/BACE nadir. Red dashed line**  
 871 **marks the Ediacaran-Cambrian boundary as defined by the maximum age for the first appearance**  
 872 **datum of *Treptichnus pedum*. Note that uncertainty remains in ichnofossil assignment of the traces**  
 873 **in the Mistaken Point Formation of Avalonia (Warren et al., 2020).**



874

875 **Fig. 10. Biostratigraphic output resulting from Model C (a–c) for the interval ~551–517 Ma.**  
 876 **Includes (a) radiometric constraints, (b)  $\delta^{13}\text{C}_{\text{carb}}$ , and (c) First Appearance Datum (FAD) and Last**  
 877 **Appearance Datum (LAD) of key Ediacaran-Cambrian fossils (Table S3). Black dotted line marks**



878 the temporal position of the 1n/BACE nadir. Red dashed line marks the Ediacaran-Cambrian  
879 boundary as defined by the maximum age for the first appearance datum of *Treptichnus pedum*. In  
880 this figure, the FAD of *T. pedum* is interpreted to post-date the BACE nadir in all regions (max.  
881 FAD in upper Esmeralda Mb, Nevada, Fig. 5c), and the age of the lower Nomtsas Fm at  
882 Swartkloofberg section does not anchor the FAD of *T. pedum* in Namibia (see discussion in Section  
883 4). Key provided in Fig. 9.

884  
885 of upper Atdabanian and Botoman (stages 3 and 4) faunal elements from the Salaany Gol  
886 Formation is correct and supported by the restudy of archaeocyath species assemblage, which is  
887 the same through the entire formation (Cordie et al., 2019; Debrenne et al., 2015; Zhuravlev, 1998).

888 We agree with Smith et al. (2015) that the magnitude of the positive  $\delta^{13}\text{C}_{\text{carb}}$  excursion reported  
889 from the Salaany Gol Formation fits well with peak 6p on the reference scale, but greatly exceeds  
890 the magnitude of peak IV (Figs. 3, 5f, Table S2). However, we also note that the regional  $\delta^{13}\text{C}_{\text{carb}}$   
891 record from the Zavkhan terrane throughout the underlying Zuun-Arts and Bayangol formations  
892 frequently exhibits more extreme values (positive and negative) relative to other late Ediacaran  
893 and lower Cambrian records from Siberia, Morocco and elsewhere. Models B and C (Figs. 3c,d,  
894 8b,c, 9e,f, 10b,c) reposition the Salaany Gol Formation to the Atdabanian, with the uppermost  
895 Bayan Gol Formation occupying a position relative to peak 6p, and implies poor expression of  
896 peak 5p, possibly within lower Member BG5 of Smith et al. (2015) (Fig. 5f). We stress, however,  
897 that peak correlation throughout the Fortunian and Stage 2 of Mongolia, and globally, remains  
898 poorly constrained.

900 The Arrowie and Stansbury basins contain a rich assemblage of lower Cambrian fossils,  
901 including the regional first appearance of archaeocyaths, trilobites, bradoriids and tommotiids.  
902 Betts et al. (2019, 2018, 2017a, 2017b, 2016) and Jago et al. (2020) refined the lower Cambrian  
903 biostratigraphy for South Australia developed by Daily (1990, 1972), Laurie (1986), Gravestock  
904 (1984), Bengtson et al. (1990), Zhuravlev and Gravestock (1994), and Gravestock et al. (2001)  
905 and added  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphy. Contrary to previous workers, Betts et al. (2019, 2018,  
906 2017a, 2017b, 2016) and Jago et al. (2020) suggested that lower units of fossiliferous strata of the  
907 Arrowie and Stansbury basins be repositioned to stages 2 and 3 instead of stages 3 and 4,  
908 respectively. These justifications were mostly based on tommotiid biostratigraphy, with little  
909 reference to other biostratigraphic constraints. However, Australian tommotiids are highly  
910 endemic species and some genera are unknown even beyond the Australian-Antarctic faunal  
911 province of Gondwana, while other faunal elements, including archaeocyaths, trilobites,  
912 bradoriids, mollusks and brachiopods are much more widespread, although at the generic level  
913 (Bengtson et al., 1990; Betts et al., 2017b; Brock et al., 2000; Gravestock et al., 2001; Laurie,  
914 1986). In dismissing the biostratigraphic value of archaeocyaths, for instance, these authors arrive  
915 at a correlation of their *Kulparina rostrata* tommotiid Zone and the regionally pre-trilobitic portion  
916 of their succeeding *Micrina etheridgei* Zone with the Cambrian Stage 2, even though these zones  
917 collectively coincide with the *Warriootacyathus wilkawillinensis*, *Spirillicyathus tenuis* and  
918 *Jugalicyathus tardus* archaeocyath zones (Zhuravlev and Gravestock, 1994), dated as Atdabanian  
919 in Siberian terms (Stage 3). Likewise, comparison of archaeocyath genera in common with South  
920 China indicates a correlation with trilobite-bearing upper Qiongzhusian-lower Canglangpuan  
921 (Stage 3) strata in that region (A. Yang et al., 2016). The same conclusions contradicting the

922 correlations of Betts et al. (2018, 2017a) follow from analysis of the biostratigraphic distribution  
923 of any other fossil group present in these tommotiid-based zones, including bradoriids,  
924 brachiopods (Kruse et al., 2017) and mollusks (Parkhaev, 2019a). In general, tommotiids and  
925 coeval early small shelly fossils in South Australia are not indicative of the Terreneuvian because  
926 representatives of all other co-occurring fossil groups (archaeocyaths, bradoriids, brachiopods,  
927 mollusks) are restricted to post-Terreneuvian strata in Siberia, South China, Laurentia and other  
928 regions, and more precisely to global stages 3 and 4 (Kruse et al., 2017; Parkhaev, 2019a), which  
929 suggests different, younger ages for some of the  $\delta^{13}\text{C}_{\text{carb}}$  peaks, rather than those accepted by Betts  
930 et al. (2018). In our correlation, we have repositioned some of these Australian  $\delta^{13}\text{C}_{\text{carb}}$  data to  
931 maintain consistency with both the regional stratigraphic correlation of Betts et al. (2018) and  
932 biostratigraphic constraints that are more globally applicable (Figs. 9 and 10, Table S2).

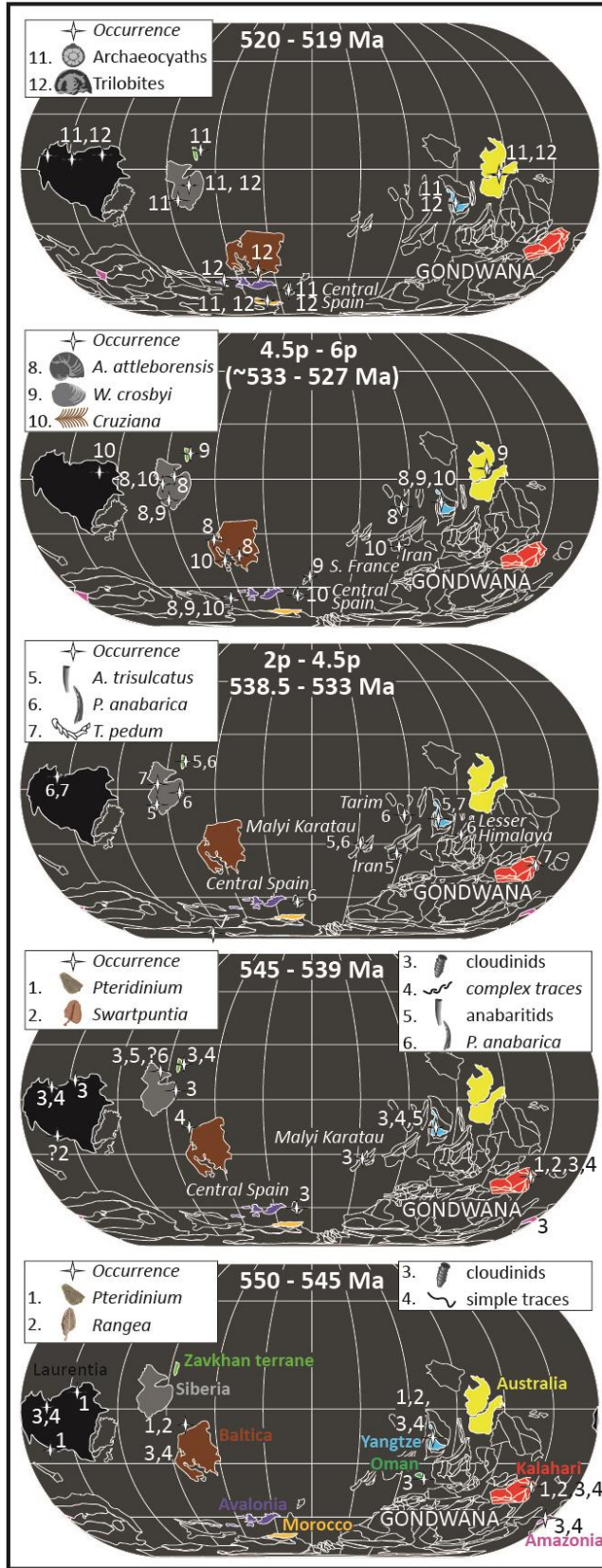
933

## 934 **6. Implications for macroevolutionary dynamics**

935 Our revised correlations have important implications both for the late Ediacaran global  $\delta^{13}\text{C}_{\text{carb}}$   
936 profile and for macroevolutionary dynamics across the BACE interval. Combining the temporal  
937 and spatial distribution of major Ediacaran-Cambrian shelly and trace fossils into these new global  
938  $\delta^{13}\text{C}_{\text{carb}}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$  and geochronological records, together with older Ediacaran radiometric dates,  
939 allows us to establish temporal and spatial paleobiogeographic trends that significantly diverge  
940 from the accepted consensus (Figs. 8-11; Table S3). These trends are robust despite remaining  
941 uncertainties, and crucially, all age models show the same macroevolutionary trends across the  
942 Ediacaran-Cambrian boundary interval (Figs. 8-10). Namely, that multiple negative  
943  $\delta^{13}\text{C}_{\text{carb}}$  excursions are present in the late Ediacaran record, which do not clearly correlate with

944 extinction events and that SSFs of the *A. trisulcatus* – *P. anabarica* Zone appeared below the  
945 BACE.

946 The available radiometric age constraints for the interval of ~580–538 Ma confirm the temporal  
947 overlap of elements of the Avalon, White Sea and Nama assemblages of the Ediacaran biota, rather  
948 than forming discrete successive assemblages, with the White Sea assemblage being entirely  
949 transitional (Grazhdankin, 2014; Yang et al., 2021). Consistent with previous models, the  
950 Ediacaran biota show a marked decline in diversity ~550, and again ~545 Ma (Boag et al., 2016;  
951 Grazhdankin, 2014; Muscente et al., 2019). Elements of the Avalon and White Sea assemblages  
952 inhabited different basins contemporaneously in the White Sea and Podolia regions of Baltica, and  
953 Australia, until ~552 Ma (Gehling and Droser, 2013; Grazhdankin, 2014), although the age range  
954 of fossiliferous strata of the Ediacara Member remains poorly constrained. Both the Avalon and  
955 White Sea assemblages largely disappeared by ~550 Ma, however some elements of the Avalon  
956 assemblage (e.g. *Charniodiscus*) and White Sea assemblage (e.g. possible *Dickinsonia* sp.) were  
957 likely present until as late as ~545.5 Ma in South China and possibly northern Siberia (e.g. Xiao  
958 et al., 2020). After this time, taxa of the Nama assemblage remained present in the Nama Basin,  
959 Namibia, the Erga Formation of the White Sea region, the Shibantan Member of the Yangtze  
960 Block, South China, and the Wood Canyon Formation of Laurentia. Successions of Armorica  
961 (Spain) and SW Gondwana (Brazil and Paraguay) also host skeletal assemblages of *Cloudina*,  
962 *Namacalathus* and *Corumbella* (Adôrno et al., 2017; Cortijo et al., 2010; Warren et al., 2011),  
963 however these successions remain poorly constrained in time <550 Ma due to a dearth of high  
964 resolution  $\delta^{13}\text{C}_{\text{carb}}$  data. Fossils of the *Palaeopascichnus* group may have extended below ~560  
965 Ma in the Shuram-Wonoka negative excursion interval in South Australia. However, these taxa  
966 are known from ~547–545 Ma in Siberia (Aim Formation), South China (Gaojiashan and



**Fig. 11. Global paleobiogeography at intervals between ~551 and 517 Ma consistent with all age models with paleogeography after (Merdith et al., 2021). Note that the positions of the Zavkhan terrane of Mongolia (bright green), Malyi Karatau of Kazakhstan, and Avalonian microcontinent in this interval remain uncertain (e.g. Landing et al., 2020). Craton coloring is consistent with stratigraphic and biostratigraphic ranges in Figs. 3-5, and 7-10.**

986 Shibantan members, and Liuchapo Formation) and Namibia (Schwarzrand Subgroup), and may  
987 show their greatest range in eastern Newfoundland, where they are found below a Gaskiers age  
988 diamictite (>580 Ma) and even co-occur with *T. pedum* above the basal Cambrian GSSP (Table  
989 S3).

990 Treptichnid trace fossils pre-date the inferred nadir of the BACE in Namibia, and Cambrian-  
991 type shelly fossils of the *Anabarites trisulcatus* – *Protohertzina anabarica* Zone predate the nadir  
992 of the BACE in Siberia and predate or co-occur with the nadir of the BACE in South China (Cai  
993 et al., 2019; Jensen et al., 2000; Zhu et al., 2017). Diverse and complex ichnofossils also predate  
994 the *T. pedum* FAD in a number of sections (e.g. Chen et al., 2019; Gozalo et al., 2003; Jensen et  
995 al., 2000; Zhu et al., 2017). At least three soft-bodied genera of the Nama assemblage are present  
996 in the Nama Basin, Namibia, post-dating (Model A), coeval with (Model B), or pre-dating (Model  
997 C) the inferred position of the BACE, and both *Cloudina* and *Namacalathus* occur above the  
998 inferred recovery from the A4 anomaly in the same section in all models (Fig. 2, Darroch et al.,  
999 2015; Narbonne et al., 1997; Wood et al., 2015). There are currently no environments that show  
1000 unequivocal co-occurrence of the Cambrian ichnospecies *T. pedum* and Ediacaran skeletal fossils  
1001 *Cloudina* or *Namacalathus*. These taxa, as well as *Nenoxites* (= *Shaanxilithes* in South China)  
1002 became extinct at or before the Ediacaran-Cambrian boundary, as defined by the FAD of *T. pedum*,  
1003 but significantly these extinctions were regional, rather than global events (e.g. *Cloudina* LAD  
1004 may be as early as ~542.3 Ma in Oman (Bowring et al., 2007), but occurred after ~539.6 Ma in  
1005 Namibia (Linnemann et al., 2019)).

1006 Model C may support a range extension for erniettomorphs in *Laurentia* associated with the  
1007 BACE nadir, to an age that is within the lower Cambrian as presently defined (Figs. 5 and 10).

1008 However, Model C may also imply a younger age for the FAD of *T. pedum* (and hence the  
1009 Ediacaran-Cambrian boundary) if this ichnospecies is restricted to a position above the BACE  
1010 recovery as suggested in multiple regions (Figs. 5 and 10, Table S3). The *T. pedum* FAD may  
1011 show broadly synchronous origination at the boundary above recovery from the BACE, with a  
1012 maximum radiometric age constraint of ~538.8 Ma (Linnemann et al., 2019). However, the first  
1013 appearance of this ichnospecies is delayed in the Zavkhan terrane, and is not well constrained  
1014 within the interval 538.8–532 Ma in Siberia, South China or the lower Cambrian boundary type  
1015 section in Avalonia (Table S3). This pattern may be a consequence of local ecological, taphonomic  
1016 and/or lithological controls.

1017 The FADs of Ediacaran and Cambrian shelly fossils are also highly variable temporally and  
1018 spatially (Figs. 8-10). The *Cloudina* – *Namacalathus* assemblage appeared ~550 Ma in the Nama  
1019 Basin and became globally widespread, but asynchronously, thereafter. *Anabarites trisulcatus* and  
1020 *Protohertzina anabarica* FADs, which are commonly recognized as the index fossils of the basal  
1021 Cambrian strata, are in fact oldest in Siberia, where *Anabarites* co-occurs with *Cloudina* at a level  
1022 below the BACE (Figs. 8-10) (Zhu et al., 2017), followed closely by the appearance of these taxa  
1023 in South China (Cai et al., 2019). Cambrian-type skeletal fossils (halkieriids, chancelloriids,  
1024 hyolithelminthes, hyoliths, archaeocyaths and many others) also appear highly asynchronously in  
1025 different basins (Fig. 8).

1026 By contrast, our compilation suggests that the appearance of *Watsonella* and *Aldanella* at  
1027 ~532–531 Ma may have had a broadly synchronous appearance during the same interval on the  
1028 global  $\delta^{13}\text{C}_{\text{carb}}$  profile, however this remains dependent upon the correlation of the ZHUCE in  
1029 South China (Figs. 8-10). The probability of a trilobite biomineralisation event at ~521–518 Ma

1030 is supported by the stratigraphic and paleogeographic distribution of arthropod scratch marks (e.g.  
1031 *Rusophycus*, *Cruziana* and *Diplichnites*), which occur from ~531–525 Ma and pre-date the  
1032 appearance of trilobites and other arthropods in almost every basin by several million years  
1033 (Landing et al., 2020; Paterson et al., 2019). This biomineralisation event may have been driven  
1034 by changing seawater chemistry (e.g. Mg/Ca ratios,  $p\text{CO}_2$ ), causing a shift from aragonite to calcite  
1035 seas (Porter, 2007).

1036 These observations may imply two patterns of first appearance. In the first case, an animal or a  
1037 group of animals appeared first in a single area and became globally widespread much later (e.g.  
1038 Namibian shelly fossils including *Cloudina* and *Namacalathus*, Siberian archaeocyaths). The  
1039 appearance of such organisms probably reflects local conditions most advantageous for their  
1040 oxygen, calcium and other essential requirements. The second type of FADs embraces a broadly  
1041 synchronous global appearance of the same group in remote regions (e.g. mollusks, trilobites).  
1042 Such events can be attributed to global changes of environmental factors (e.g.  $p\text{CO}_2$ , Mg:Ca ion  
1043 ratio) facilitating almost simultaneous biomineralisation of hitherto soft-bodied representatives of  
1044 these groups in different basins, as noted in trilobites (Paterson et al., 2019).

1045 We conclude that the Cambrian Explosion was in fact a protracted Ediacaran-Cambrian  
1046 radiation. All models reveal widespread and correlatable late Ediacaran negative and positive  
1047  $\delta^{13}\text{C}_{\text{carb}}$  excursions between ~550 Ma and the onset of the BACE. In contrast to previous studies  
1048 (Amthor et al., 2003), our correlation demonstrates no significant extinction or faunal turnover  
1049 coincident with the A4 anomaly, or any older negative carbon  $\delta^{13}\text{C}_{\text{carb}}$  perturbation between 550  
1050 Ma and 540 Ma, but rather a series of successive, often regional, originations and minor  
1051 extinctions. The canonical model (Model A) also implies that the disappearance of the Nama



1052 assemblage post-dated the BACE, whereas Model C may be compatible with a coincident  
1053 disappearance of this assemblage with the BACE nadir. Regardless, the pre-BACE appearance of  
1054 anabaritids and treptichnid traces in all models also argues against a mass extinction event  
1055 coincident with the BACE.

1056 While the near synchronous global appearance of trilobites may support a calcification  
1057 (biomineralisation) event in this group (Landing et al., 2020; Paterson et al., 2019), the radiation  
1058 of other skeletal biota was generally highly asynchronous, with varying tempos in different basins  
1059 (Figs. 8-11). This may reflect both a diversity gradient formed by clade origination in low  
1060 latitudinal basins (Siberia, Mongolia, Chinese and Namibian Gondwana) and then migration to  
1061 higher latitudes (e.g. Avalonia, Morocco) (Fig. 11, e.g. Jablonski et al., 2006, but see Landing et  
1062 al., 2020), and also a highly heterogeneous local landscape of redox and/or nutrient regimes. The  
1063 origination of many skeletal groups, including cloudinids, mollusks and trilobites, as well as the  
1064 Ediacaran-Cambrian boundary itself, all seem to coincide with the succession of marked positive  
1065  $\delta^{13}\text{C}_{\text{carb}}$  excursions (Figs. 9 and 10). Peak  $\delta^{13}\text{C}_{\text{carb}}$  values during positive excursions during  
1066 Cambrian stages 2–4 on the Siberian Platform have been proposed to record pulses of nutrients  
1067 and oxygen into shallow marine seas that promoted biodiversification (He et al., 2019). By  
1068 contrast, global  $\delta^{13}\text{C}_{\text{carb}}$  excursions of regionally variable magnitude, from the level of the BACE  
1069 to 6p, may reflect a combination of changes in glacioeustatic sea level overprinted by regional  
1070 palaeomarine redox and nutrient heterogeneity. The age model framework constructed herein  
1071 provides a comprehensive and editable template by which the operation of these, and other driving  
1072 forces, in shaping the Ediacaran-Cambrian radiation of early animals may be explored.

1073

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1088 the help of AZ, GS, RW, CY and MZ. FB constructed the age model with insight from all authors.  
1089 FB, AC, and RW collected and analyzed Namibian samples. All authors contributed to writing the  
1090 paper. **Competing interests:** Authors declare no competing interests; **Data and materials**  
1091 **availability:** All data, including expanded geological information and full age models are available  
1092 in the Supplementary Information.

1093

1094

1095

## Supplementary Materials for

1096

1097

## **Calibrating the temporal and spatial dynamics of the Ediacaran - Cambrian**

1098

## **radiation of animals**

1099

1100

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### **This file includes:**

1107

Supplementary Text

1108

Tables S1, S3

1109

1110

### **Other Supplementary Materials for this manuscript include the following:**

1111

Supplementary Figures S1 to S4 [separate pdf document: FigsS1-S4\_high\_resolution\_section\_correlation]

1112

Data S2 [TableS2\_AgeModels.xlsx]

1113 **Supplementary Text**

1114

1115 *Geological setting and sampling strategy of upper Nama Group sections, southern Namibia*

1116

1117       Sampling was undertaken at two stratigraphic sections in southern Namibia in July 2018 by  
1118 FB, AC and RW. Sampled sections are located on Farms Nord Witputz (base of section  
1119 27°34'3.66"S, 16°42'12.60"E, section measured due north) and Swartpunt (base of section  
1120 27°28'21.88"S, 16°41'46.37"E) (Fig. 2). These two sections constitute carbonate-dominated  
1121 members of the Urusis Formation (Schwarzrand Subgroup) that are separated by approximately  
1122 50-60 m of transgressive outer ramp to slope, green and purple shale of the Feldschuhhorn  
1123 Member, and interbedded carbonate-siliciclastic units of the lower and middle Spitskop Member  
1124 (e.g. Saylor, 2003; Saylor and Grotzinger, 1996; Wood et al., 2015).

1125       The Huns Member on Farm Nord Witputz overlies fossiliferous sandstone and siltstone of the  
1126 Nasep Member and is composed of shallow marine limestone and subordinate dolostone. Here,  
1127 strata of the Huns Member have an average dip of 20° to northwest, exposing a continuous section  
1128 bounded by the conformably underlying Nasep Member to the southeast, and the conformably  
1129 overlying Feldschuhhorn Member to the northwest. Packstones and ooid grainstones of the Huns  
1130 Member at this locality contain occasional well-developed cross-bedding accentuated by floating  
1131 grains of quartz sand indicating deposition in a high energy, shallow marine, inner to mid-ramp  
1132 environment above fair weather wave base. Intervals of thinly-bedded limestone with little  
1133 evidence for wave activity are interpreted as reflecting deposition in a mid-shelf environment and  
1134 correspond to minor transgressive parasequences, consistent with the sequence stratigraphic model  
1135 of Saylor (2003).

1136 We also compile data from a composite section noted as ‘near Swartkloofberg’(Saylor et al.,  
1137 1998) (Fig. 2). The ‘near Swartkloofberg’ section corresponds to a section incorporating the  
1138 Feldschuhhorn and lower Spitskop members (medium scale sequences D11- E16 of Saylor, 2003)  
1139 to the southeast of Swartpunt and the upper Spitskop Member at Swartpunt (section 14 of Saylor,  
1140 1996, position of section noted in Fig. 1 of Saylor and Grotzinger, 1996). An alternative  
1141 stratigraphic correlation of the section incorporating the lower Spitskop Member would reject the  
1142 lower Spitskop radiometric constraint of  $542.68 \pm 1.25$  Ma (Grotzinger et al., 1995, recalculated  
1143 in Schmitz, 2012), and directly correlate the lower Spitskop succession as an expanded shallow  
1144 shelf equivalent to the Swartpunt section. This stratigraphic reassessment would significantly  
1145 reduce the thickness of the Spitskop Member, constraining a maximum age for the Spitskop  
1146 Member of ca. 540 Ma and repositioning the BACE/A4 to the siliciclastic Feldschuhhorn Member.  
1147 It would also permit a longer duration for deposition of the underlying shale-dominated Nudaus  
1148 Formation in the Witputs Sub-basin. In this alternative correlation, the downturn from positive  
1149 values recorded in the Huns Member at Nord Witputz (this study) would correlate with the  
1150 downturn from the A3 excursion. This alternative correlation is incorporated into Model D (Table  
1151 S2).

1152 The stratigraphy, sedimentology and palaeontology of the Swartpunt section have been  
1153 described in detail in previous publications (e.g. Darroch et al., 2015; Linnemann et al., 2019;  
1154 Narbonne et al., 1997; Saylor, 2003; Wood et al., 2015). Sampling began 1 m above the lowermost  
1155 ash layer dated at  $540.095 \pm 0.099$  Ma (Table S1) (Linnemann et al., 2019), and continued to the  
1156 summit of the koppe.

1157

1158

1159 *Reviewing the co-occurrence of Cloudina, Namacalathus and T. pedum*

1160 According to published information, *T. pedum* and *Cloudina* sensu stricto do not occur at the  
1161 same level, and the *T. pedum* FAD occurs after the BACE nadir. We review these occurrences  
1162 briefly below:

1163 **Nama Group, southern Namibia:** The published LAD of clouidinids and *Namacalathus* occurs  
1164 in the uppermost beds of the Swartpunt section, dated by CA-ID-TIMS to between ~539.6 Ma and  
1165 ~538.6 Ma. There is no evidence from  $\delta^{13}\text{C}_{\text{carb}}$  for the BACE at Swartpunt, and this interval is  
1166 therefore most parsimoniously interpreted to be immediately pre-BACE (Model C). Though  
1167 simple ichnofossils, including treptichnids, appear lower in the Nama succession, the FAD of *T.*  
1168 *pedum* occurs in siliciclastic valley fill deposits on farms Vergelee and Sonntagsbrunn, >100km  
1169 to the east of farms Swartpunt and Swartkloofberg (Wilson et al., 2012; Darroch et al., 2021). The  
1170 maximum age for the *T. pedum* FAD is currently very loosely constrained by inferred lateral  
1171 equivalence between the Swartkloofberg section (basal Nomtsas maximum age of ~538.6 Ma,  
1172 Linnemann et al., 2019) and the valley fill deposits on farms Vergelee and Sonntagsbrunn.  
1173 However, it has been noted that the tuff bed from the Nomtsas Fm at Swartkloofberg may be  
1174 reworked (Linnemann et al., 2019).

1175 **South China** (please see Figs. S3 and S4): Both *Cloudina* and tubicolous calcifiers of ‘Cambrian’-  
1176 type are at inferred-pre-BACE levels in the Lijiagou section of the shallow Yangtze Platform (see  
1177 Figs. S2 and S3, Cai et al., 2019). This is the lowest published occurrence of Cambrian-type small  
1178 skeletal fossils (SSFs) in South China, however accurate correlation of the  $\delta^{13}\text{C}_{\text{carb}}$  profile in this  
1179 section remains problematic. In South China, the FAD of *T. pedum* occurs in the phosphatic  
1180 Zhongyicun Mb of the Zhujiqing Fm in multiple sections of the shallow platform. The underlying  
1181 (Daibu) Member and correlative units across the Yangtze Platform host the BACE nadir.

1182 **Kazakhstan:** The FAD of protoconodonts occurs in the lower Aksai Mb of the Chulaktau Fm  
1183 (Yang et al., 2016). The Aksai Mb is an extremely condensed phosphatic unit (~5m thick). The  
1184 cloudinid *Rajatubulus* occurs in the overlying Karatau Mb (5-10m thick unit) (Yang et al., 2016),  
1185 which is entirely phosphatic. It remains possible that these phosphatic units correspond to the  
1186 Zhongyicun Mb, thereby implying a post-BACE LAD of cloudinids in the Maly Karatau of  
1187 Kazakhstan. Given the uncertainty in accurate age determination of these members brought on by  
1188 the unsuitable (phosphatic) lithology for robust  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphy, we do not place undue  
1189 weight on these occurrences. However, we do note in Table S3 that the Chulaktau Fm may host  
1190 the global LAD of cloudinids in the lowermost Fortunian (citing Yang et al., 2016). *T. pedum* has  
1191 not been recovered from the Chulaktau Fm of underlying units, implying that the regional FAD of  
1192 this ichnospecies is most likely post-BACE in age.

1193 **Siberia:** The FAD of anabaritids occurs in the upper Ust'-Yudoma Fm at the Kyra-Ytyga section  
1194 on the Yudoma River of SE Siberia (Zhu et al., 2017). In this section, anabaritids co-occur with  
1195 cloudinids during a positive  $\delta^{13}\text{C}_{\text{carb}}$  plateau and below a downturn that is inferred to be the BACE  
1196 onset. Anabaritids also occur in a pre-BACE position in the lower Turkut Fm of the Khorbusuonka  
1197 River of NE Siberia (Rogov et al., 2015; Knoll et al., 1995; Pelechaty et al., 1996). The LAD of  
1198 cloudinids is also within this pre-BACE interval throughout sections of the Siberian Platform. The  
1199 FAD of *T. pedum* occurs in the upper Syhargalakh Fm along the Khorbusuonka River of the  
1200 Olenek Uplift. The Syhargalakh Fm is a condensed siliciclastic unit, and the *T. pedum* FAD occurs  
1201 above a poorly calibrated maximum age derived from air-abrasion ID-TIMS U-Pb dating of the  
1202 Tas-Yuryakh volcanic breccia (Bowring et al., 1993) (Table S1). The *T. pedum* FAD in this section  
1203 occurs beneath carbonates of the Mattaia Fm that host *Aldanella* and a CA-ID-TIMS U-Pb age of  
1204 ~529.70 Ma (Kaufman et al., 2012; Grazhdankin et al., 2019). In sections of the SW Siberian

1205 Platform, *T. pedum* occurs within a bed with a maximum detrital zircon age of  $531.1 \pm 5.20$  Ma  
1206 (weighted mean  $530.6 \pm 5.30$  Ma) in the Irkut Formation (Marusin et al., 2020, their Fig. 4e).  
1207 However, this trace fossil does not display a clear regular probing pattern typical of *T. pedum* and  
1208 can be rather interpreted as a treptichnid s.l. The FAD of *T. pedum* across the Siberian Platform  
1209 therefore remains poorly constrained but most likely above the nadir of the BACE.

1210 **Spain:** According to Álvaro et al. (2019), the lowest occurrence of *T. pedum* is within the lower  
1211 Arrocampo Fm of the Ibor and Navalpino anticlines, below a regional unconformity. The LAD of  
1212 in situ *Cloudina* is noted from the underlying Villarta Fm in the same succession. Allochthonous  
1213 broken fragments of reworked *Cloudina* are noted from megabreccia blocks in the neighbouring  
1214 Valdelacasa anticline. Given the absence of a robust  $\delta^{13}\text{C}_{\text{carb}}$  framework and the complexity of the  
1215 fragmentary record, it is not possible to assign the Valdelacasa cloudinids to the lower Cambrian.

1216 **Brazil:** The Tamengo Fm hosts cloudinids from an interval with positive  $\delta^{13}\text{C}_{\text{carb}}$  (Boggiani et al.,  
1217 2010). High precision radiometric dating constrains this interval as Ediacaran ( $>541$  Ma) (Parry et  
1218 al., 2017). Unfortunately, the succession transitions to siliciclastics of the Guaicurus Fm, and the  
1219 age of this transition is poorly constrained in time pre-BACE.

1220 **Paraguay:** Cloudinids and other Ediacaran skeletal fossils in Paraguay occur in a positive  $\delta^{13}\text{C}_{\text{carb}}$   
1221 plateau as demonstrated in numerous publications (e.g. Warren et al., 2019, 2017, 2011). These  
1222  $\delta^{13}\text{C}_{\text{carb}}$  records, and an associated U-Pb SHRIMP age of  $545 \pm 4.5$  Ma (Warren et al., 2019),  
1223 correlate most readily with the late Ediacaran  $\delta^{13}\text{C}_{\text{carb}}$  record. We are not familiar with any  
1224 published reports that show *T. pedum* co-occurring with *Cloudina* in sections of the Itapucumi  
1225 Group, and to our knowledge, the FAD of *T. pedum* is therefore most likely higher in the  
1226 succession, in accordance with the global record.

1227



1228 *Carbon isotope analyses*

1229 Carefully selected micritic carbonate was microdrilled from hand samples and simultaneously  
1230 analysed for  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{18}\text{O}_{\text{carb}}$  on an Elementar PRECISION stable isotope ratio mass  
1231 spectrometer following reaction with 100% orthophosphoric acid at 75°C, using an Elementar iso  
1232 FLOW system at the Wolfson Laboratory, School of Geosciences, Grant Institute, University of  
1233 Edinburgh. New  $\delta^{13}\text{C}_{\text{carb}}$  data from the upper Nama Group are reported in per mil (‰) notation  
1234 relative to the Vienna Pee Dee Belemnite standard (VPDB) alongside compiled global  $\delta^{13}\text{C}_{\text{carb}}$   
1235 data for the interval ca. 551-517 Ma in Table S2 (Supplementary xlsx file). The standard deviation  
1236 for replicate analyses (n=7) of an in-house coral standard (Reference COR1D) measured alongside  
1237 samples (standard-sample bracketing) was better than  $\pm 0.02\text{‰}$  for  $\delta^{13}\text{C}_{\text{carb}}$  and  $\pm 0.08\text{‰}$  for  
1238  $\delta^{18}\text{O}_{\text{carb}}$ .

1239 *Sr isotope screening criteria*

1240 The long mean residence time of Sr (3–5 Myrs) relative to the mixing time of the global ocean  
1241 (~1500 yrs) results in a globally homogeneous seawater Sr isotopic composition (Elderfield,  
1242 1986). Long term changes in oceanic  $^{87}\text{Sr}/^{86}\text{Sr}$  reflect the balance between radiogenic (high  
1243  $^{87}\text{Sr}/^{86}\text{Sr}$ ) input derived from continental weathering versus non-radiogenic (low  $^{87}\text{Sr}/^{86}\text{Sr}$ ) input  
1244 from hydrothermal alteration of oceanic crust (Brass, 1976). Unlike the majority of Phanerozoic  
1245 studies that benefit from targeted analyses of Sr retained with high fidelity in carbonate  
1246 biominerals, strontium isotope stratigraphy in pre-Cambrian and lower Cambrian sections relies  
1247 upon identifying primary marine Sr isotopic compositions from bulk (often micritic) carbonate  
1248 (e.g. Halverson et al., 2007). Post-depositional diagenetic exchange and contamination of bulk  
1249 carbonate by silicate-bound phases commonly result in deviation towards more radiogenic values  
1250 (Veizer and Compston, 1976), however late diagenesis may also skew  $^{87}\text{Sr}/^{86}\text{Sr}$  to lower values

1251 (Brand et al., 2010). Furthermore, identifying the most robust estimates of seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  from  
1252 legacy datasets is often hampered by the limited geochemical information necessary for adequate  
1253 screening, and the lack of a standardized methodology for chemical pre-treatment and dissolution  
1254 over the past 30 years of Sr isotope research.

1255 Due to the specific complications noted above, in addition to sample-specific carbonate  
1256 mineralogy and differential diagenesis, a universal screening procedure to determine primary  
1257 seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  from bulk carbonate data has proven elusive. A number of criteria are classically  
1258 used to identify the most isotopically altered samples, including Mn/Sr, Mg/Ca,  $\delta^{18}\text{O}$  and  
1259  $^{87}\text{Rb}/^{86}\text{Sr}$ . However, applying cut-off values for these parameters to determine degrees of  
1260 diagenetic alteration is often an unsuitable oversimplification, especially in the case of Mn/Sr,  
1261 where some primary marine carbonates may have precipitated from manganoous seawater (e.g.  
1262 Halverson et al., 2007).

1263 We compiled an updated dataset of published  $^{87}\text{Sr}/^{86}\text{Sr}$  from stratigraphic sections covering the  
1264 Ediacaran-Cambrian transition interval (Table S2), and employed a liberal screening procedure  
1265 using available geochemical data in an attempt to filter out values considered least likely to  
1266 represent seawater composition. Samples with  $^{87}\text{Sr}/^{86}\text{Sr} > 0.7095$  and  $>20\%$  insoluble residue  
1267 (where this information is available) were automatically discounted, and the remaining data were  
1268 screened on a section by section basis in order to identify trends suggestive of diagenetic alteration,  
1269 including cross-plotting  $^{87}\text{Sr}/^{86}\text{Sr}$  against Mn/Sr, [Sr], [Rb], and  $\delta^{18}\text{O}$ . In most cases, clear  
1270 covariations between these parameters was not observed, with the exception of [Sr] (see  
1271 Supplementary Information for details). We then discounted all data with Mn/Sr  $> 1$  and [Rb]  $>$   
1272 1ppm, as a final test. A critical evaluation of the screening criteria used, and implications for the

1273 resulting  $^{87}\text{Sr}/^{86}\text{Sr}$  correlation, are provided in the supplementary information. All data were  
1274 normalized to NIST SRM987 = 0.710250. The resulting compilation, including data that did not  
1275 pass our screening procedure, is provided in Table S2, and shown graphically by lithology and [Sr]  
1276 in Figure 4. We consider the lowest values throughout the studied interval to best represent  
1277 seawater  $^{87}\text{Sr}/^{86}\text{Sr}$ , with the exception of the values reported from the Mastakh and Khatyspyt  
1278 formations (red boxes in Fig 4c,g, see Supplementary Information).

1279 Our screening procedure removed ~50% of the data compiled from the published literature,  
1280 most of which tended towards radiogenic values. The remaining  $^{87}\text{Sr}/^{86}\text{Sr}$  dataset (Fig 4) shows  
1281 significant variability, likely due to the effects of diagenesis or contamination that are  
1282 indecipherable using only the published geochemical information. We consider the lowest values  
1283 throughout the studied interval to best represent seawater  $^{87}\text{Sr}/^{86}\text{Sr}$ , with the exception of the values  
1284 reported from the Mastakh and Khatyspyt formations (red boxes in Fig. 4c and 4g, see below).  
1285 Low  $^{87}\text{Sr}/^{86}\text{Sr}$  values are commonly retained in high [Sr] (>500ppm) limestone and dolomite  
1286 samples, whereas samples with low [Sr] tend to deviate towards more radiogenic values, consistent  
1287 with the findings of Halverson et al. (2007). However, of the 208 samples that were removed by  
1288 the final screening criteria ( $\text{Mn}/\text{Sr} > 1$ ,  $[\text{Rb}] > 1\text{ppm}$ ), 25 closely follow the trend captured by the  
1289 ‘most reliable’ data, which attests to the complications inherent in assigning cut-off thresholds for  
1290 sample screening of legacy datasets. The resulting seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  curves (grey lines in Fig. 4)  
1291 show trends consistent with previous correlations (e.g. Halverson et al., 2007; Maloof et al., 2010),  
1292 whereby latest Ediacaran to Fortunian values remain relatively constant in the range 0.70840 –  
1293 0.70850 before beginning to decrease in lower Cambrian Stage 2 and reaching a nadir of ~0.70806  
1294 at the boundary between stages 2 and 3, followed by increasing values during Stage 3.

**Table S1.***Radiometric ages*

<b>Ages in red are not included in the compilation for the reasons provided.</b>		
<b><u>Age (Ma)</u></b>	<b><u>Details</u></b>	<b><u>Reference</u></b>
<b>515.56 ± 1.03 (1.16)</b>	Zircon U-Pb age from the upper Lemdad Fm (equivalent to Lower Issafen Fm) of the Lemdad syncline, Morocco (section Le-XI). Five single grain analyses, originally processed via air abrasion in Landing et al. (1998), and recalculated by Maloof et al. (2010) using updated U decay constant (see Maloof et al. (2010) for details). Lower Botoman based on trilobite biostratigraphy. Marks onset of peak V? in Morocco.	(Landing et al., 1998; Maloof et al., 2010)
<b>517.22 ± 0.31 (0.40) [0.66]</b>	Zircon U-Pb CA-ID-TIMS age of bentonite 7m above the base of the Purley Shale Fm, Woodlands Quarry, Warwickshire, England (Avalon terrane). Five of nine single grain analyses (samples z1-4, z12), MSWD = 0.67.	(Williams et al., 2013)
<b>518.03 ± 0.69 (0.71)</b>	Youngest zircon U-Pb CA-ID-TIMS age (incorporating U-Pb tracer calibration uncertainty) of five single grain analyses of detrital zircons from the Maotianshan shale immediately underlying Chengjiang biota. Taken as maximum depositional age for the Chengjiang biota.	(Yang et al., 2018)
<b>518.59 ± 0.20 (0.32) [0.63]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed in the upper Amouslek Formation, Timoulaye Izder section, Morocco (sample Tim-269.5). (MSWD = 0.22, n = 3). Within the upper <i>Choubertella</i> or possibly lower <i>Daguinaspis</i> Zone.	(Landing et al., 2020)

<b>518.99 ± 0.14 (0.20) [0.58]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed in lower Amouslek Formation correlated to neighbouring section at Tazemmourt to upper <i>Choubertella</i> Zone. Sample Ti-Am-34.0 (MSWD = 0.38, n = 6).	(Landing et al., 2020)
<b>519.30 ± 0.23 (0.57) [0.77]</b>	Zircon U-Pb CA-ID-TIMS age of the Caerfai Bay Shales Fm at Cwm Bach, Pembrokeshire, South Wales (Avalon terrane). Six of seven fractions (single grains or fragments) from sample Cwm Bach 1 (MSWD = 1.1, n = 6).	(Harvey et al., 2011)
<b>519.23 ± 0.14 (0.21) [0.58]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed that rests unconformably atop the Tiout Member, in the basal Amouslek Formation (sample Ti-Am-0.0). Transition between upper <i>Fallotaspis plana</i> and lower <i>Choubertella</i> zones. Approximate zero-crossing point of recovery from peak IV.	(Landing et al., 2020)
<b>519.87 ± 0.24 (0.35) [0.64]</b>	Zircon U-Pb CA-ID-TIMS age of brown-weathering dolomitic feldspathic sandstone 8.5m below trilobite horizon T1 (sample Ti-I-neg8.5). Within lower member of the Igoudine Formation. Interpreted as a maximum depositional age. <b>Large relative uncertainty</b> (MSWD = 2.60, n = 2).	(Landing et al., 2020)
<b>520.93 ± 0.14 (0.28) [0.61]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed in the upper Lie de vin Formation, Tiout section, Anti Atlas Mountains, Morocco (sample M236). Six single grain analyses (MSWD = 0.42, n = 6). Ash bed at base of rising limb of peak IV.	(Maloof et al., 2010)
<b>521.06 ± 0.12 (0.28) [0.61]</b>	Zircon U-Pb CA-ID-TIMS age of tuff deposit 210m below top of Lie de vin Formation in the Tiout section, 500m below base of the Tiout Member, 310m below peak IV (sample	(Landing et al., 2020)

	Tiout-566). (MSWD = 0.61, n = 7)	
<b>523.17 ± 0.16 (0.42) [1.0]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed in the lower Lie de vin Formation at Oued Sdas section, Anti Atlas Mountains, Morocco (sample M234). Ten single grain analyses (MSWD = 1.2, n = 10) Ash bed at level immediately prior to peak II.	(Maloof et al., 2010)
<b>524.837 ± 0.092 (0.35) [0.93]</b>	Zircon U-Pb ID-TIMS age from tuff bed in the upper Tifnout Member (Adoudou Formation) at Oued Sdas section, Anti Atlas Mountains, Morocco (sample M231). Mixture of 5 air abraded and 3 chemically abraded single grain analyses (MSWD = 0.72, n = 8) Ash bed within falling limb of peak 6p.	(Maloof et al., 2010)
<b>525.343 ± 0.088 (0.35) [0.93]</b>	Zircon U-Pb ID-TIMS age from a tuff bed in the middle Tifnout Member (Adoudou Formation) at Oued Sdas section, Anti Atlas Mountains, Morocco (sample M223). Mixture of 6 air abraded and 6 chemically abraded single grain analyses (MSWD = 0.33, n = 11). Ash bed at/immediately after max values of peak 6p.	(Maloof et al., 2005), updated in (Maloof et al., 2010)
<b>526.5 ± 1.1</b>	SHRIMP U-Pb age of the base of the Badaowan (Shiyantou-equivalent) Formation, bed 9 at Meishucun section, Yunnan Province, South China. Note that the ZHUCE excursion in models B and C is curtailed early at Meishucun, consistent with this age. However, the ZHUCE excursion at Xiaotan section is considered to correlate with the entirety of 6p in these models.	(Compston et al., 2008)
<b>530.02 ± 1.2</b>	Zircon ID-TIMS (air abrasion) age for tuff bed 24.32 – 24.58m above the base of the Chapel Island Formation, Ratcliffe Brook Group, Somerset Street, Saint	(Isachsen et al., 1994), recalculated in (Schmitz, 2012)

	<p>John, southern New Brunswick (sample SoS-24.4). Three multigrain fractions. Approximate age of the Chapel Island Formation lithofacies association (Member 5 (Mystery Lake Member) after regional litho- and biostratigraphic correlation with sections in Saint John, New Brunswick (Landing, 1994, 1991). Middle part of trace fossil zone <i>Rusophycus avalonensis</i>, Placentian Series.</p>	
<p><b>529.7 ± 0.3</b></p>	<p>Zircon U-Pb CA-ID-TIMS age for tuff deposit in upper Mattaia Formation, Mattaia Creek mouth (above FAD <i>Aldanella attleborensis</i>). <b>No detailed information available on the number of single grain analyses, concordance or MSWD for this age, as it was published in abstract form only.</b> However, if correct, this places a minimum age constraint on the FAD of <i>A. attleborensis</i> which is consistent with a first appearance approximately contemporaneous with peak 5p in Siberia, as previously suggested.</p>	<p>(Grazhdankin et al., 2019; Kaufman et al., 2012)</p>
<p><b>533 Ma</b></p>	<p><b>Zircon U-Pb ID-TIMS age from bed 5 of Meishucun section (Zhongyicun Member). Age in abstract form only and no information pertaining to uncertainty or procedural laboratory techniques (including number of single grain analyses, air vs chemical abrasion, tracer etc.) exist in published form to our knowledge. Likely CA-ID-TIMS. Whilst we do not include this age in our model, we note that the age model remains entirely consistent with this age.</b> Unfortunately, the phosphorite interval of the Zhongyicun Member at</p>	<p>Age provided in (Maloof et al., 2010) citing (Brooks et al., 2006)</p>

	Meishucun does not afford any useful, detailed chemostratigraphic correlation potential at present.	
<b>534.6 ± 0.5</b>	Zircon air-abrasion ID-TIMS age for ultra-potassic trachyrhyolite porphyry cobbles in a fluvial conglomerate of the lower Tyuser Formation in the Kharaulakh ranges, lower Lena River. Age not adjusted for updated U decay constant.	(Bowring et al., 1993)
<b>538.58 ± 0.19 (0.24) [0.62]</b>	Zircon U-Pb CA-ID-TIMS age of a tuff bed in the lower Nomtsas Formation exposed on Farm Swartkloofberg, west of Swartpunt (sample 17SWART7, ash 6, equivalent to 92-N-1 of Grotzinger et al. (1995). Three single grain analyses (MSWD = 0.10, n = 3)	(Grotzinger et al., 1995; Linnemann et al., 2019)
<b>538.99 ± 0.21 (0.25) [0.63]</b>	Zircon U-Pb CA-ID-TIMS age of the highest ash bed exposed in the upper Spitskop Member of the section on Farm Swartpunt (sample 15UNA20, ash 5). Three single grain analyses (MSWD = 2.2, n = 3). This age appears too young when considering the lack of observed hiatus (or facies change) above the preceding 3 dated tuff deposits (15UNA17-19, see below) in this section, all of which give ages of ca. 539.6 Ma. The ages of 15UNA22 and 15UNA19 yield a depositional rate of 94.41m/Myrs, whereas the ages of 15UNA19 and 15UNA20 yield a depositional rate for identical lithofacies of 11.86m/Myrs. MSWD for 15UNA20 is also high. For these reasons, this age is not included in our correlation.	(Linnemann et al., 2019)
<b>539.40 ± 0.23 (0.35) [0.66]</b>	Zircon U-Pb CA-ID-TIMS age of a 10cm-thick bed of sandy, hematite-rich	(Hodgin et al., 2020)



	<p>dolostone interpreted as a diagenetically altered tuffaceous horizon in the upper La Ciénega Formation (top of Unit 3 at Cerro Clemente), above a laterally reproducible negative excursion correlated with the global BACE (sample CC1801-138). Interpreted conservatively as a maximum depositional age. Six single grain zircon fragments (of 10) (MSWD = 1.05, n = 6). We consider this level to be slightly younger than the age itself, to maintain consistency with ages and carbon isotope profile of the Swartpunt section.</p>	
<p><b>539.4 ± 2.9</b></p>	<p>SHRIMP U-Pb age of bentonites, Zhongyicun Member of the Zhujiaping Formation, bed 5 at Meishucun section, Yunnan Province, South China. <b>Note, age updated by ID-TIMS (Brooks et al., 2006, see above), but data in abstract form only. We prefer the younger age provided by Brooks et al. (2006) for this age model in agreement with Maloof et al. (2010), however uncertainty in this age (noted above) precludes inclusion in age model figures.</b></p>	<p>(Compston et al., 2008)</p>
<p><b>539.64 ± 0.19 (0.23) [0.62]</b></p>	<p>Zircon U-Pb CA-ID-TIMS age of tuff bed in upper Spitskop Member in middle of section on Farm Swartpunt (sample 15UNA19, ash 4). Four single grain analyses (MSWD = 0.46, n = 4).</p>	<p>(Linnemann et al., 2019)</p>
<p><b>539.52 ± 0.14 (0.20) [0.61]</b></p>	<p>Zircon U-Pb CA-ID-TIMS age of tuff bed in upper Spitskop Member in middle of section on Farm Swartpunt (sample 15UNA18, ash 3). Five single grain analyses (MSWD = 1.4, n = 5).</p>	<p>(Linnemann et al., 2019)</p>
<p><b>539.58 ± 0.34 (0.37) [0.68]</b></p>	<p>Zircon U-Pb CA-ID-TIMS age of tuff bed in upper Spitskop Member in middle of section on Farm Swartpunt</p>	<p>(Linnemann et al., 2019)</p>

	(sample 15UNA17, ash 2). Six single grain analyses (MSWD = 0.44, n = 6)	
<b>540.095 ± 0.099 (0.17) [0.60]</b>	Zircon U-Pb CA-ID-TIMS age of an ash bed in the upper Spitskop Member at the base of the section on Farm Swartpunt (sample 15UNA22, ash 1, equivalent to 94-N-11 of (Grotzinger et al., 1995)). Five single grain analyses (MSWD = 1.7, n = 5).	(Grotzinger et al., 1995; Linnemann et al., 2019)
<b>541.00 ± 0.13 (0.21) [0.81]</b>	Zircon U-Pb CA-ID-TIMS age from Ara Group (A4 Member, 3045m depth in Birba-5 well, SOSB), Oman (sample BB-5). 8 concordant single grain analyses of 18 total (MSWD = 1.0, n = 8)	(Bowring et al., 2007)
<b>541.85 ± 0.75 (0.77) [0.97]</b>	Zircon U-Pb age for ash bed at top of Tamengo Formation, Brazil. Dated via U-Pb CA-ID-TIMS using the ET535 tracer. Cluster of the five youngest concordant analyses (MSWD = 3.3, n = 5 out of 11)	(Parry et al., 2017)
<b>542.33 ± 0.11 (0.19) [0.79]</b>	Zircon U-Pb CA-ID-TIMS age from Ara Group (A3 Member, 9m below top of A3 carbonate unit, 2194.4m depth in Mukhaizna-11 well), Oman (sample MKZ-11B). 8 concordant single grain analyses of 16 total (MSWD = 0.50, n = 8)	(Bowring et al., 2007)
<b>542.37 ± 0.28 (0.32) [0.68]</b>	Zircon U-Pb age for ash bed at top of Tamengo Formation, Brazil. Dated via U-Pb CA-ID-TIMS using the ET535 tracer. Cluster of four concordant analyses (MSWD = 0.68, n = 4 out of 8)	(Parry et al., 2017)
<b>542.54 ± 0.45 (0.53) [1.13]</b>	Zircon U-Pb CA-ID-TIMS age from top of Fara Formation (Ara A2-A3 equivalent), Oman (sample WB.01.1). 4 concordant single grain analyses of 10 total (MSWD = 2.6, n = 4)	(Bowring et al., 2007)
<b>542.68 ± 1.25 (2.80)</b>	Zircon Pb-Pb ID-TIMS age of an ash bed in the lower Spitskop Member on Farm Witputs (sample 91-N-1 or,	(Grotzinger et al., 1995), recalculated in (Schmitz, 2012)

	<p>alternatively, BZS-7). Air abrasion age of eight single grain and small multigrain fractions. Grotzinger et al. (1995) originally reported a weighted mean <math>^{207}\text{Pb}/^{206}\text{Pb}</math> crystallization age of <math>545.1 \pm 0.70</math> Ma (MSWD = 0.22, n = 8).</p>	
<p><b><math>542.90 \pm 0.12</math> (0.20) [0.80]</b></p>	<p>Zircon U-Pb CA-ID-TIMS age from Ara Group (A3 Member, 3m above base of A3 carbonate unit, 3988.3m depth in Minha-1 well), Oman (sample Minha-1A). 8 concordant single grain analyses of 17 total (MSWD = 0.62, n = 8)</p>	<p>(Bowring et al., 2007)</p>
<p><b><math>543.40 \pm 3.5</math></b></p>	<p>SIMS zircon U-Pb age from an ash bed 45m above the base of the Baimatuo Member, Zhoujiaao section, southern margin of the Huangling anticline, 3 Gorges Area. Age constrains plateau in <math>\delta^{13}\text{C}_{\text{carb}}</math> at <math>\sim 3\text{‰}</math>.</p>	<p>(Huang et al., 2020)</p>
<p><b><math>543.9 \pm 0.24</math> Recalculated to <math>542.8 \pm 1.30</math> Ma by Maloof et al. (2010) and interpreted as the maximum age of the unit by Maloof et al. (2010)</b></p>	<p>Zircon U-Pb ID-TIMS (air abrasion), Kessyusa Group (Syhargalakh Formation) volcanic breccia of the Tas-Yuryakh volcanic complex (Khorbusuonka River). We stress that these zircons have not been re-analysed using the updated chemical abrasion methodology and, as stated in Maloof et al. (2010), have lost Pb. We anticipate substantial modification to this age after future re-analysis. If taken as a minimum age for the top of the Turkut Formation, this may imply correlation of the negative excursion at the top of the Turkut Formation (e.g. at the Olenek River section) with the either the A0 excursion, or the more minor negative excursion in the lowermost part of the upper Dengying Fm (Beiwan and equivalent members). We prefer to correlate the Turkut negative excursion with the A4 onset, which is also</p>	<p>(Bowring et al., 1993)</p>

	<p>consistent with the interpretation of Maloof et al. (2010) for a maximum age of <math>542.8 \pm 1.30</math> Ma for the Tas-Yuryakh volcanic complex, and a minimal hiatus separating the Syhargalakh Fm from the underlying Turkut Formation.</p>	
<p><b><math>546.25 \pm 0.19</math> (0.27) [0.64]</b></p>	<p>Ash bed in the Jiucheng Member, 471m above the base of the Dengying Formation at Yinchangpo section (sample 14YCP02). Zircon U-Pb CA-ID-TIMS age (n = 5 of 12). Originally dated via SIMS with weighted mean <math>^{207}\text{Pb}/^{206}\text{Pb}</math> age of <math>546.3 \pm 2.70</math> (3.80) (MSWD = 0.58, n = 44 of 50). Constrains a maximum depositional age for the base of the overlying Baiyanshao Member at Yinchangpo section.</p>	<p>CA-ID-TIMS age (Yang et al., 2021) updated from (Yang et al., 2017)</p>
<p><b><math>546.72 \pm 0.21</math> (0.29) [0.89]</b></p>	<p>Zircon U-Pb CA-ID-TIMS age of tuff bed from Ara Group (middle of A0 Member, 3847m depth in Asala-1 well), Oman (sample Asala-1 c21). 8 concordant single grain analyses of 12 total (MSWD = 0.92, n = 8).</p>	<p>(Bowring et al., 2007)</p>
<p><b><math>547.23 \pm 0.28</math> (0.36) [0.96]</b></p>	<p>Zircon U-Pb CA-ID-TIMS age of tuff bed from the Fara Formation (200m above the base of the formation), Oman (sample WB.01.2). Considered to predate A0 Member. 8 concordant single grain analyses of 17 total (MSWD = 1.3, n = 8)</p>	<p>(Bowring et al., 2007)</p>
<p><b><math>547.36 \pm 0.23</math> (0.31) [0.91]</b></p>	<p>Zircon U-Pb CA-ID-TIMS age from 8 single grain analyses (sample 94-N-10B). Lower Hoogland Member, Zaris Formation, Kuibis Subgroup, Nama Group, Namibia. 8 single grain analyses (MSWD = 1.4, n = 8).</p>	<p>(Bowring et al., 2007). (Schmitz, 2012) report age of <math>547.32 \pm 0.31</math> (0.65) Ma.</p>
<p><b><math>550.14 \pm 0.16</math> (0.24) [0.63]</b></p>	<p>Zircon U-Pb CA-ID-TIMS age of an ash in Doushantuo Member IV (Miaohu Member) at Jijiawan section, Hubei Province (Yangtze</p>	<p>Age updated in (Yang et al., 2021) from initial age of (Condon et al., 2005).</p>

	<p>Gorges area), South China (sample 16JJW-3). Ash bed is 85cm below base of Dengying Formation (Hamajing Member). Six concordant (of 14) single grain analyses (MSWD = 1.9).</p> <p>Original ages in (Condon et al., 2005) for same ash bed (sample JIN04-2): U-Pb concordia age of <math>551.07 \pm 0.61</math> Ma (MSWD = 0.48), and weighted mean <math>^{207}\text{Pb}/^{206}\text{Pb}</math> 550.55 <math>\pm</math> 0.75 Ma (MSWD = 0.48). Age recalculated in (Schmitz, 2012) using two concordant (of ten total) single grain analyses. All ten zircons yield weighted mean <math>^{207}\text{Pb}/^{206}\text{Pb}</math> age of <math>548.09 \pm 2.61</math> Ma.</p>	
<b>552.96 <math>\pm</math> 0.19 (0.30) [0.66]</b>	<p>Zircon U-Pb CA-ID-TIMS age of a tuff bed in the lower part of the Zimnegory Formation, Valdai Group, White Sea area (sample WhiteSeaAsh). Five concordant (of 11) single grain analyses. Sample previously dated at <math>555.3 \pm 0.3</math> Ma (Martin et al., 2000), recalculated to <math>552.85 \pm 0.77</math> (2.62) (<math>^{207}\text{Pb}/^{206}\text{Pb}</math>) by (Schmitz, 2012).</p>	(Yang et al., 2021)
<b>554.29 <math>\pm</math> 0.14 (0.22) [0.63]</b>	<p>Zircon U-Pb CA-ID-TIMS age for an ash bed 3.8m above the phosphorite layer at the base of the Jiucheng Member at Xiaolantian section, eastern Yunnan (sample 14CJ07, MSWD = 0.8, n = 7 of 10). Age implies highly condensed sedimentation, cryptic hiatus within lower Jiucheng member, reworking during deposition, or incorporation of xenocrystic materials in the magmatic environment (see age of sample 14YCP02). See discussion in (Yang et al., 2021).</p>	Updated from original SIMS age of (Yang et al., 2017) by (Yang et al., 2021)

<b>555.18 ± 0.3 (0.34) [0.70]</b>	Zircon U-Pb age for ash bed in the upper Bocaina Formation, Brazil. Dated via U-Pb CA-ID-TIMS using the ET535 tracer. (MSWD = 1.6, n = 8 out of 8)	(Parry et al., 2017)
<b>556.26 ± 0.21 (0.25) [0.65]</b>	Zircon U-Pb CA-ID-TIMS age of the dolostone/chert boundary of the basal Liuchapo Formation, Nangao section (samples 17WA05). Five concordant (of 9 total) single grain analyses (MSWD = 0.2, n = 9).	(Yang et al., 2021)
<b>556.38 ± 0.14 (0.27) [0.65]</b>	Zircon U-Pb CA-ID-TIMS age of the dolostone/chert boundary of the basal Liuchapo Formation, Wengxiu section (samples 17GZWX01). Eight concordant (of 10 total) single grain analyses (MSWD = 1.8, n = 8).	(Yang et al., 2021)
<b>556.6 ± 6.4</b>	Zircon U-Pb CA-ID-TIMS age from 4 single grain analyses (sample 846). Hanging Rocks Formation (Maplewell Group, Charnian Supergroup).	(Noble et al., 2015)
<b>556.78 ± 0.10 (0.18) [0.62]</b>	Zircon U-Pb CA-ID-TIMS age from bentonite bed in middle Mohylivska Formation, Podolia, Ukraine (sample B1b). All five zircons from bentonite B1 are concordant, yielding a statistically equivalent weighted mean age (MSWD = 2.2, n = 5)	(Soldatenko et al., 2019)
<b>557 ± 3</b>	SHRIMP zircon U-Pb age for ash bed in dolostone of the Liuchapo Fm at Fanglong section, Guizhou province. Immediately above recovery from a negative $\delta^{13}\text{C}_{\text{carb}}$ excursion.	(Zhou et al., 2018)
<b>557.28 ± 0.14 (0.22) [0.63]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed at the base of the Verkhovka Formation, Valdai Group, White Sea area (sample 9607-1601). Six concordant (of 9 total) single grain analyses (MSWD = 1.6).	(Yang et al., 2021)

<b>561.85 ± 0.34 (0.66) [0.89]</b>	Zircon U-Pb CA-ID-TIMS age from 7 concordant (of 12) single grain analyses (sample 912). Bradgate Formation (Maplewell Group, Charnian Supergroup). (MSWD = 1.2)	(Noble et al., 2015)
<b>562.5 ± 1.1</b>	Zircon U-Pb CA-ID-TIMS age from 7 concordant single grain analyses (MSWD = 0.34). 27m below the top of the Trepassey Formation, Shingle Head, Mistaken Point ecological reserve, Newfoundland (sample N10-SH6B). <b>Detailed stratigraphic mapping and reassessment by (Matthews et al., 2020) places this ash bed in the lower Fermeuse Formation. See (Matthews et al., 2020) for discussion of additional uncertainties associated with the age of sample N10-SH6B. The maximum age of the lower Fermeuse Formation suggested by sample SH-2 of (Matthews et al., 2020) (see below) is 564.13 ± 0.20 Ma.</b>	(Canfield et al., 2020)
<b>562.7 ± 3.8</b>	Re-Os age lower Buah Fm, Well M. Initial $^{187}\text{Os}/^{188}\text{Os} = 0.68 \pm 0.01$ . ( $2\sigma$ age, MSWD = 1.40, n = 7)	(Rooney et al., 2020)
<b>564.13 ± 0.20 (0.25) [0.65]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed in the lower Fermeuse Formation (Shingle Head surface), Mistaken Point Ecological Reserve, Newfoundland (sample SH-2). Six single grain analyses (MSWD = 1.5, n = 6)	(Matthews et al., 2020)
<b>564.71 ± 0.63 (0.65) [0.88]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed immediately atop the 'Pizzeria' in the Trepassey Formation, Long Cove, Mistaken Point Ecological Reserve, Newfoundland (sample LC-1). Two single grain analyses (MSWD = 0.69, n = 2 of 11)	(Matthews et al., 2020)
<b>565.00 ± 0.16 (0.22) [0.64]</b>	Zircon U-Pb CA-ID-TIMS age of tuff deposit immediately above 'E' surface of upper Mistaken Point Formation (~60m	(Matthews et al., 2020)

	below top of Formation), Mistaken Point Ecological Reserve, Newfoundland (sample MP-14). Four concordant single grain analyses (MSWD = 1.2, n = 4)	
<b>565.22 ± 0.33 (0.65) [0.89]</b>	Zircon U-Pb CA-ID-TIMS age from 2 concordant (of 5) single grain analyses (sample 907). Beacon Hill Formation (Maplewell Group, Charnian Supergroup). (MSWD = 0.42, n = 2)	(Noble et al., 2015)
<b>566.25 ± 0.35 (0.48) [0.77]</b>	<b>Zircon U-Pb CA-ID-TIMS age of Mistaken Point Formation, Newfoundland (sample MPMP33.56). Five single grain analyses (MSWD = 1.3, n = 5). Analyses show degree of discordance, and the age of the same ash horizon has been updated in (Matthews et al., 2020) (their sample MP-14, see above). We favour the concordant age of (Matthews et al., 2020) sample MP-14.</b>	(Pu et al., 2016)
<b>567 ± 3.9</b>	Zircon U-Pb age of volcanic tuff from Sylvitsa Group (Perevalok Formation), Krutaya Gora section, Us'va River, central Urals (sample 09-03-15). (MSWD = 1.14, n = 16). <b>Age shown in figures but lack of detailed analytical methods provided in original publication.</b>	(Grazhdankin et al., 2011)
<b>567.3 ± 3.0</b>	Re-Os age upper Unit PH4, inferred equivalent to Blueflower Fm (sample A1707). 16m above contact with Gametrail Fm, Coal Creek Section, Ogilvie Mountains. Initial $^{187}\text{Os}/^{188}\text{Os}$ = 0.61 ± 0.04. (2σ age, MSWD = 0.81, n = 6)	(Rooney et al., 2020)
<b>567.63 ± 0.21 (0.26) [0.66]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed in the middle Briscal Formation (~110m above the base of the Formation) overlying the 'Brasier Surface', Mistaken Point Ecological Reserve, Newfoundland (sample BRS-	(Matthews et al., 2020)



	1). Five single grain analyses (MSWD = 2.1, n = 5)	
<b>569.08 ± 0.45 (0.73) [0.94]</b>	Zircon U-Pb CA-ID-TIMS age from 2 concordant (of 12) single grain analyses (sample 918). Benniscliffe Breccia between Blackbrook Reservoir Formation and Beacon Hill Formation (Charnian Supergroup). (MSWD = 0.8, n = 2).	(Noble et al., 2015)
<b>570.94 ± 0.38 (0.46) [0.77]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed in upper Drook Formation, Newfoundland (sample Drook-2). Five single grain analyses (MSWD = 0.33, n = 5). Despite ongoing uncertainty in the age of this ash layer, we favour the model of (Matthews et al., 2020) based on maintenance of stratigraphic superposition using new ages from the upper Drook Formation (their sample DRK-10) and overlying lower Briscal Formation (their sample DRK-1). Accordingly, the age of sample Drook-2 is not included in our age model despite concordant single grain analyses and low uncertainty.	(Pu et al., 2016)
<b>571.38 ± 0.16 (0.25) [0.66]</b>	Zircon U-Pb CA-ID-TIMS age of tuff bed in the basal Briscal Formation (~20m above top of Drook Formation), Daley's Cove, Mistaken Point Ecological Reserve, Newfoundland (sample DRK-1). Eight single grain analyses (MSWD = 2.0, n = 8)	(Matthews et al., 2020)
<b>574.0 ± 4.7</b>	Re-Os age upper Nadaleen Fm, J1719. Initial $^{187}\text{Os}/^{188}\text{Os}$ = 0.60 ± 0.01. (2σ age, MSWD = 0.75, n = 8)	(Rooney et al., 2020)
<b>574.17 ± 0.19 (0.24) [0.66]</b>	Zircon U-Pb CA-ID-TIMS age of Drook Formation (~25m below top of Formation), 'Pizza Disc Bed', Pigeon Cove, Mistaken Point Ecological Reserve, Newfoundland (sample DRK-10). Nine single grain	(Matthews et al., 2020)

	analyses (MSWD = 2.8, n = 9)	
<b>575.0 ± 5.1</b>	Re-Os age Nadaleen Fm, J1443. Initial $^{187}\text{Os}/^{188}\text{Os} = 0.60 \pm 0.01$ . ( $2\sigma$ age, MSWD = 1.20, n = 5)	(Rooney et al., 2020)
<b>578.2 ± 5.9</b>	Re-Os age middle Khufai Fm, Well L. Initial $^{187}\text{Os}/^{188}\text{Os} = 1.15 \pm 0.05$ . ( $2\sigma$ age, MSWD = 0.97, n = 7)	(Rooney et al., 2020)
<b>579.88 ± 0.44 Ma (0.52) [0.81]</b>	Zircon U-Pb CA-ID-TIMS age of lower Drook Formation (sample NoP-0.9). Five single grain analyses (MSWD = 0.82, n = 5)	(Pu et al., 2016)
<b>580.90 ± 0.40 (0.53) [0.82]</b>	Zircon U-Pb CA-ID-TIMS age of Upper Mall Bay Formation (sample GCI-neg6.55). Nine single grain analyses (MSWD = 1.1, n = 9)	(Pu et al., 2016)
<b>585.7 ± 2.6 [2.8]</b>	Re-Os age on sample (A1606) 1m below 'Carbonate B' of the Doushantuo Formation at Wenghui section, Yangtze Gorges, South China (sample A1606). Initial $^{187}\text{Os}/^{186}\text{Os} = 1.81 \pm 0.02$ . (n = 9)	(Yang et al., 2021)
<b>587.2 ± 3.3 [3.6]</b>	Re-Os age on sample (F1404) 58m above the base of the Doushantuo Formation at Jiulongwan section, Yangtze Gorges, South China (sample F1404). Initial $^{187}\text{Os}/^{186}\text{Os} = 0.90 \pm 0.02$ . ( $2\sigma$ age, MSWD = 1.1, n = 6)	(Yang et al., 2021)
<b>612.46 ± 0.62 (0.67) [0.94]</b>	Zircon U-Pb CA-ID-TIMS age (re-interpreted as a maximum deposition age for detrital zircons in a mudstone layer) at the Unit 4/5 contact of the Doushantuo Fm at Zhangcunping section, Hubei. Carbonate below the dated horizon records a negative $\delta^{13}\text{C}_{\text{carb}}$ excursion.	Original SIMS age of (Zhou et al., 2017a) updated by (Yang et al., 2021)
<b>614 ± 7.6</b>	Zircon U-Pb SHRIMP age of a tuff bed in the Doushantuo Formation at Wangjiagou section, Zhangcunping, Hubei (sample 7527). Tuff bed occurs between beds 3 and 4, below an erosional unconformity in the middle	(Liu et al., 2009), updated by (Schmitz, 2012)

	Doushantuo Fm (Member II). Eighteen single grain analyses. Liu et al. (2009) initially reported an age of $614 \pm 7.6$ Ma (MSWD = 2.3, n = 18).	
<b>632.48 ± 1.02</b>	Zircon U-Pb CA-ID-TIMS age of a tuff bed in the lower Doushantuo Formation (at top of black shale unit, ~9m above the Nantuo-Doushantuo contact) at Jijiawan (Jiuqunao) section (sample YG-04-2). Three concordant (of 9 total) single grain analyses. Condon et al. (2005) initially reported an age of $632.50 \pm 0.48$ Ma (MSWD = 0.38, n = 3).	(Condon et al., 2005) updated by (Schmitz, 2012)
<b>634.57 ± 0.88 (0.90) [1.61]</b>	Zircon U-Pb CA-ID-TIMS of an ~20cm thick grey tuffaceous mudstone within the top of the Nantuo diamictite at Eshan section, eastern Yunnan (sample ES-1). Four concordant analyses (MSWD = 1.4, n = 4 of 7).	(Zhou et al., 2019)
<b>635.21 ± 0.59 (0.61) [0.92]</b>	Zircon U-Pb CA-ID-TIMS age of a tuff deposit (~30m below the contact with the Keilberg cap dolostone) interbedded with the basinal equivalent of the Ghaub Formation glacial diamictite, Navachab section, norther Namibia (sample NAV-00-2B). Five single grain analyses (MSWD = 3.4, n = 5).	(Prave et al., 2016)
<b>635.26 ± 1.07</b>	Zircon U-b CA-ID-TIMS age of a tuff bed at the contact surface between the lower and upper part of the cap dolomite, overlying the Nantuo glacial diamictite at the Wuhe-Gaojiayi section, Yangtze Gorges (sample YG-04-15). Three concordant (of 18) single grain analyses. (Condon et al., 2005) initially reported an age of $635.23 \pm 0.57$ Ma (MSWD = 0.28, n = 3).	(Condon et al., 2005) recalculated by (Schmitz, 2012)
<b>639.29 ± 0.26 (0.31) [0.75]</b>	Zircon U-Pb CA-ID-TIMS age of tuff deposit interbedded with the Ghaub	(Prave et al., 2016)

	glacial diamictite (~15m below the base of the Keilberg cap carbonate), Duurwater section, northern Namibia (sample DW-1). Middle of three ash beds. Nine single grain analyses (MSWD = 2.6, n = 9)	
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**Table S3.**

Key fossil First Appearance Datums (FADs) and stratigraphic distributions [including FADs and Last Appearance Datums (LADs)].

Entries highlighted in grey indicate siliciclastic units that lack  $\delta^{13}\text{C}_{\text{carb}}$  chemostratigraphic control.

<b><u>Region</u></b>	<b><u>Formation</u></b>	<b><u>Details</u></b>	<b><u>Reference</u></b>
<i>Palaeopascichnus</i> spp. stratigraphic distribution			
Siberia, Yudoma-Maya Confluence	Aim Fm	middle siliciclastic part	(Ivantsov, 2017)
Siberia, Khorbusuonka River	Khatyspyt Fm	upper Mb3, Mb 4	(Kolesnikov et al., 2018)
Gondwana, South Australia	Wonoka Fm	50m below the top, Unit 8	(Haines, 2000)
Gondwana, South Australia	Pound sGr, Rawnsley Quartzite, Ediacara Mb		(Droser et al., 2019)
Gondwana, Namibia	Schwarzrand sGr	middle part	(Darroch et al., 2016) ( <i>Shaanxilithes</i> ) but see (Darroch et al., 2021) for alternative interpretation.
Gondwana, Namibia	Upper Omkyk Mb	middle part	(Macdonald et al., 2014) ( <i>Zoophycos</i> ) but see (Darroch et al., 2021) for alternative interpretation.
Gondwana, Brazil, Itajaí Basin	Depositional sequence 1	about level 563±0.3 Ma	(Becker-Kerber et al., 2020)
Avalonia, Newfoundland, Burin Peninsula	Chapel Island Fm	lower Mb 2A	(Gehling et al., 2001)
Avalonia, Newfoundland, Avalon Peninsula	Fermeuse Fm	upper part	(Gehling et al., 2000)
Avalonia, Newfoundland, Bonavista Peninsula	Rocky Harbour Fm	Pre-date Gaskiers-equivalent Trinity 'facies' diamictite	(Liu and Tindal, 2021)
Avalonia, UK, South Wales, Dyfed	Coomb Volcanic Fm		(Cope, 1983)
South China, Anhui, Xiuning & Yixian counties	Lantian Fm	Mb 2	(Wan et al., 2014; Yuan et al., 2011)
Baltica, Central Urals, Sylvitsa River	Sylvitsa Gr (Perevalok & Chernyi Kamen fms)		(Kolesnikov et al., 2018)
Baltica, South Urals	Basa & Zigan fms		(Becker, 2010; Kolesnikov et al., 2015)
Baltica, White Sea	Valday Gr (Lyamtsa, Verkhovka, Zimnie Gory & Erga fms)	uppermost Lyamtsa Fm; above 559 Ma	(Fedonkin, 1990, 1976; Fedonkin et al., 2007; Grazhdankin, 2014)
Baltica, Ukraine, Podolia	Mogiliv-Podilsky Gr (Mogiliv Fm)		(Fedonkin, 1990; Palij, 1976)
Baltica, Moldova	Kanilovka Gr	Komarovo beds	(Ivantsov et al., 2015; Palij, 1976)

Baltica, Norway, Finmark, Digermulen Peninsula	Stáhpogieddi Fm	Indreelva & Mannrapselva mbs	(Jensen et al., 2018; McIlroy and Brasier, 2017)
? Baltica, Poland, Lublin	Lublin Fm		(Paczeńska, 1986)

<i>Nenoxites (=Shaanxilithes) spp.</i> stratigraphic distribution			
Siberia, Yudoma River, Nuuchchalakh	Aim Fm	middle calcareous siltstone part	(Zhuravlev et al., 2009) ( <i>Gaojiashania</i> )
Siberia, Khorbusuonka River	Khatyspyt Fm	upper part	(Rogov et al., 2012)
South China, Shaanxi (Gaojiashan & Lijiagou sections)	Dengying Fm	Gaojiashan Mb, lower part	(Cai et al., 2011) ( <i>Shaanxilithes</i> )
South China, Yunnan, Chengjiang & Jinning counties	Yuhucun Fm	basal Yuhucun Fm, Jiucheng Mb	(Zhang et al., 2015) ( <i>Shaanxilithes</i> ); AZ field 2018
South China, Guizhou	Taozichong Fm		(Cai et al., 2011) ( <i>Shaanxilithes</i> )
South China, Hunan (Ganziping & Liujiata sections), Guizhou (Jiumen & Sifangjing sections)	Liuchapo Fm		(Luo and Miao, 2020)
South China, Guangxi (Silikou section)	Laobao Fm	lower part	(Luo and Miao, 2020)
South China, Anhui (southern)	Piyuancun Fm	upper part	(Luo and Miao, 2020)
North China, Ningxia Hui AR (Helanshan area, Suyukou section)	Zhengmuguan Fm	Slate Mb, upper part	(Shen et al., 2007) ( <i>Shaanxilithes</i> , <i>Palaeopascichnus</i> )
North China, Qinghai (Chaidam Basin, Quanjishan section)	Zhoujieshan Fm	middle part	(Shen et al., 2007) ( <i>Shaanxilithes</i> )
India, Lesser Himalaya, Nigali Dhar Syncline	Krol Gr, Earthy Dolomite Mb & Tal Gr, Shaliyan Fm, Earthy Siltstone Mb	basal Tal Gr	(Tarhan et al., 2014) ( <i>Shaanxilithes</i> )
Baltica, White Sea	Valday Gr (Lyamtsa, Verkhovka, Zimmie Gory & Erga fms)	uppermost Lyamtsa Fm, basal Erga Fm; 559-550 Ma	(Fedonkin, 1990, 1976; Grazhdankin, 2014; Grazhdankin and Krayushkin, 2007)

<i>Pteridinium spp.</i> stratigraphic distribution			
Baltica, White Sea	Upper Erga Fm	upper part, above 550.2±4.6 Ma. Radiometric age not incorporated into model due to large uncertainty.	(Ivantsov, 2011)
Laurentia, North Carolina, Carolina Slate Belt	Lower Floyd Church Fm	above ash bed dated at 540.6 ± 1.2 Ma (multigrain fraction air abrasion Pb/Pb age) (Ingle et al., 2003). This age is not included in our age model as it has not been corrected for the updated U decay constant or updated laboratory and analytical methodology. Analysis of an andesite at the base of the underlying Flat Swamp Member (immediately overlying the unnamed mudstone Member of the upper Cid Fm)	(Weaver et al., 2006)

		yields a zircon U-Pb ID-TIMS age of $547 \pm 2$ Ma (sample #00CT-03, MSWD = 0.55, n = 6) (Hibbard et al., 2009). Temporal placement of this fossil occurrence is poorly constrained.	
Laurentia, Mackenzie Mountains, Northwest Territories	Blueflower Formation	Sekwi Brook section. Age range poorly constrained due to sparse distribution of carbonate beds for chemostratigraphy (see Macdonald et al., 2013). Age constrained by lower Blueflower Re-Os age of $567.3 \pm 3.0$ Ma (Rooney et al., 2020) and unconformably overlying terminal Ediacaran Risky Fm, which records the BACE.	(Narbonne and Aitken, 1990; Sperling et al., 2016)
Gondwana, Namibia, Witputs Subbasin	Spitskop Member, Vingerbreek Member, Niederhagen Member, Upper Kliphoek (Aar) Member.	Farm Swartpunt, 25km north of Farm Helmeringhausen (Kosos?), Farm Aar. Temporal range spans $>547.32$ Ma (Bowring et al., 2007), to fossiliferous horizon in upper Spitskop Member at Swartpunt constrained between ca. 539.6 and 538.58 Ma (Linnemann et al., 2019), within interval interpreted as coincident with the BACE nadir.	(Darroch et al., 2021; Gürich, 1933, 1930), full reference list in SI of (Bowyer et al., 2020)
South China, 3 Gorges area, Hubei	Dengying Fm, Shibantan Mb	$\delta^{13}\text{C}$ positive excursion	(Chen et al., 2014)
Gondwana, South Australia, Flinders Ranges	Ediacara Member, Rawnsley Quartzite	Poor temporal constraint on Rawnsley Quartzite. However, mixed Nama/White Sea assemblage may indicate pre-550 Ma age.	(Gehling and Droser, 2013)

*Rangaea* spp. stratigraphic distribution

Baltica, White Sea	Upper Erga Fm	upper part, above $550.2 \pm 4.6$ Ma. Radiometric age not incorporated into model due to large uncertainty.	(Ivantsov, 2011)
Gondwana, Namibia, Witputs subbasin	Niederhagen Member, Kliphoek Member.	Farms Kuibis, Vrede, Aar and Chamis. $>547.32$ Ma (Bowring et al., 2007), to $>542.68 \pm 2.8$ (59).	(full reference list in SI of (Bowyer et al., 2020)
South China, 3 Gorges area, Hubei	Dengying Fm, Shibantan Member	$\delta^{13}\text{C}$ positive excursion	(Chen et al., 2014)
Gondwana, South Australia, Flinders Ranges	Ediacara Member, Rawnsley Quartzite	Poor temporal constraint on Rawnsley Quartzite. However, mixed Nama/White Sea assemblage may support pre-550 Ma age.	(Gehling and Droser, 2013)

*Ernietta* spp. stratigraphic distribution

Gondwana, Namibia, Witputs subbasin	Upper Kliphoek (Aar) Member (reassignment of Farm Hansburg samples to Kliphoek Member after (Gibson et al., 2019; Maloney et al., 2020), Spitskop Member	Farms Plateau, Aar, Wegkruip, Hansburg and Swartpunt $>547.32$ Ma (Bowring et al., 2007), potentially to fossiliferous horizon in Spitskop Member constrained between ca. 539.6 Ma and 538.58 Ma (Linnemann et al., 2019). Putative <i>Ernietta</i> sample at Farm Swartpunt	(Darroch et al., 2021, 2015; Elliott et al., 2016; Gibson et al., 2019; Maloney et al., 2020; Pflug, 1966), full reference list in SI of (Bowyer et al., 2020)
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		(Darroch et al., 2015) tentatively defines LAD of this form.	
Laurentia, Montgomery Mountains, near Johnnie townsite	Lower Wood Canyon Formation	Erniettomorph fossils recovered from sandstones that underly and are interbedded with ooidal dolostone unit that records the onset of the BACE (Smith et al., 2017).	(Smith et al., 2017)

<i>Swartpuntia</i> spp. stratigraphic distribution			
Laurentia, North Carolina	Cid Fm, unnamed mudstone member.	Putative (?) <i>Swartpuntia</i> occurrence below ash bed dated at $540.6 \pm 1.2$ Ma (multigrain fraction air abrasion Pb/Pb age) (Ingle et al., 2003). This age is not included in our age model as it has not been corrected for the updated U decay constant or updated laboratory and analytical methodology. Furthermore, analysis of an andesite at the base of the Flat Swamp Member (immediately overlying the unnamed mudstone Member of the Cid Fm) yields a zircon U-Pb ID-TIMS age of $547 \pm 2$ Ma (sample #00CT-03, MSWD = 0.55, n = 6) (Hibbard et al., 2009). Temporal placement of this fossil occurrence is poorly constrained.	(Weaver et al., 2006)
Laurentia, Kelso Mountains, California	Upper Member of Lower Wood Canyon Fm	LACMIP 12726. Uncertain precise temporal placement within the Wood Canyon Fm. Approximately coeval with or immediately preceding BACE, based on $\delta^{13}\text{C}_{\text{carb}}$ chemostratigraphy of (Smith et al., 2017). Putative <i>Swartpuntia</i> affinity questioned by (Smith et al., 2017) based on lack of preserved stalk or figured full specimens.	(Hagadorn et al., 2000; Hagadorn and Waggoner, 2000)
Laurentia, White Mountains, California	Middle Member of Poleta Fm	UCMP 37450. Uncertain precise temporal placement relative to the Wood Canyon Fm. Approximately coeval with or immediately preceding BACE, based on $\delta^{13}\text{C}_{\text{carb}}$ chemostratigraphy of (Smith et al., 2017). Putative <i>Swartpuntia</i> affinity questioned by (Smith et al., 2017) based on lack of preserved stalk or figured full specimens.	(Hagadorn et al., 2000)
Laurentia, Montgomery Mountains, Nevada	Wood Canyon Fm	lower member, above cloudinids occurring in the Stirling Quartzite	(Hall et al., 2020)
Gondwana, Namibia, Witputs subbasin	Spitskop Member, Feldschuhhorn Member.	Farm Swartpunt. Occurrence in Feldschuhhorn Member (Jensen et al., 2000) suggests range > ca. 540.095 Ma extending to fossiliferous horizon in Spitskop Member constrained between ca. 539.6 Ma and 538.58 Ma (Linnemann et al., 2019).	(Darroch et al., 2015; Jensen et al., 2000; Narbonne et al., 1997)

<i>Cloudina</i> spp. and other cloudinid stratigraphic distribution			
Siberia, Yudoma River, Kyra-Ytyga River mouth	Yudoma Gr, Ust'-Yudoma Fm	upper part /upper $\delta^{13}\text{C}$ plateau/inferred to be below BACE excursion	<i>Cloudina</i> ex gr. <i>C. riemkeae</i> (Zhu et al., 2017; Zhuravlev et al., 2012)



West Siberian Plate	Kotodzha and Raiga fms	uppermost Katadzha Fm to middle Raiga Fm. Uncertain temporal placement due to lack of associated $\delta^{13}\text{C}$ data.	<i>Cloudina hartmanae</i> (Kontorovich et al., 2008)
Altay Sayan Foldbelt, Eastern Sayan	Anastas'ino Fm	Upper part of mb 3. Uncertain temporal placement due to lack of associated $\delta^{13}\text{C}$ data.	<i>Cloudina</i> sp. (Kheraskova and Samygin, 1992; Terleev et al., 2011)
Altay Sayan Foldbelt, Mountain Shoria	West Siberia & Belka fms	Uncertain temporal placement due to lack of associated $\delta^{13}\text{C}$ data.	<i>Cloudina</i> sp. (Bagmet, 1994; Terleev et al., 2011)
Altay Sayan Foldbelt, Kuznetsk Alatau	Tarzbul' Fm	Middle part. Uncertain temporal placement due to lack of associated $\delta^{13}\text{C}$ data.	<i>Cloudina</i> sp. (Terleev et al., 2011)
Mongolia, Zavkhan Terrane	Zuun-Arts Fm	Basal part. Uncertain temporal placement due to lack of associated $\delta^{13}\text{C}$ data, but within interval ca. 540 – 539 Ma according to Model C.	<i>Zuunia chimidtsereni</i> (Yang et al., 2020)
Kazakhstan, Karatau-Naryn Terrane	Chulaktau Fm	Aksai & Karatau mbs with <i>Anabarites</i> and <i>Protohertzina</i> . May post-date the BACE, however this is difficult to confirm due to the unsuitable lithology of the Chulukatau Fm for robust use in $\delta^{13}\text{C}$ chemostratigraphy.	<i>Rajatubus costatus</i> (B. Yang et al., 2016)
Gondwana, Namibia, Zaris & Witputs subbasins	Nama Gr, Kuibus & Schwarzrand sgrs	Zaris Fm, upper Omkyk & lower Hoogland mbs, Urusis Fm, Feldschuhhorn & Spitskop mbs, Dabis Fm, Mara Mb />547.32 Ma – 538.58±0.19 Ma/	<i>Cloudina hartmanae</i> , <i>C. riemkeae</i> (Bowring et al., 2007; Bowyer et al., 2017; Grotzinger et al., 2005, 1995; Linnemann et al., 2019; Wood et al., 2017; Wood and Curtis, 2015); full references in SI of (Bowyer et al., 2020)
Gondwana, Brazil, Mato Grosso do Sul	Corumbá Gr	middle & upper Tamengo Fm	<i>Cloudina lucianoii</i> , <i>C. carinata</i> (Adôrmo et al., 2019, 2017; Becker-Kerber et al., 2017)
Gondwana, Paraguay	Itapucumí Gr, Tagatiya Guazú Fm	Available low-resolution $\delta^{13}\text{C}$ data suggest placement in interval between 547 and 543 Ma.	<i>Cloudina</i> sp. (Warren et al., 2017)
Gondwana, Uruguay, Rio de la Plata Craton	Arroyo del Soldado Gr	upper Yermal Fm. Note ongoing uncertainties in the age of the Arroyo del Soldado Group (e.g. Pecoits et al., 2016)	<i>Cloudina</i> sp.? (Gaucher, 2000; Gaucher et al., 2003). Ongoing uncertainty in affinity due to a dearth of figured material at high resolution.
Gondwana, Oman	Huqf Supergr, Ara Gr	A1-A3, 546.72±0.21 Ma – 542.33±0.12 Ma	<i>Cloudina</i> cf. <i>C. hartmanae</i> (Amthor et al., 2003; Bowring et al., 2007; Conway Morris et al., 1990)
Gondwana, South China, southern Shaanxi, Ningqiang County	Dengying Fm	upper part of the middle Gaojiashan Mb / $\delta^{13}\text{C}$ positive excursion/ – Beiwan Mb /at plateau, below $\delta^{13}\text{C}$ BACE negative excursion/ above 548±8 Ma (detrital) – 538.8 Ma	<i>Cloudina hartmanae</i> , <i>C. ningqiangensis</i> , <i>C. xuanjiangpingensis</i> (Cai et al., 2010; Cui et al., 2019; Hua et al., 2005)

Gondwana, South China, Hubei, Yichang County	Kuanchuanpu Fm	basal part with <i>Anabarites</i> and <i>Protohertzina</i> . Occurs below a large negative $\delta^{13}\text{C}$ excursion thought to postdate the BACE. No raw $\delta^{13}\text{C}$ data have been published to incorporate into our age model but see $\delta^{13}\text{C}$ profile in (Steiner et al., 2020) (their figure 11). According to the model of (Steiner et al., 2020) and (B. Yang et al., 2016), cloudinids occur coincident with, or slightly above the BACE in the lowermost Kuanchuanpu Fm, with a minimum age LAD equivalent to the upper Spitskop Member, Swartpunt section (Nama Group, Namibia). Alternatively, the negative excursion at the top of the Kuanchuanpu Fm may represent the BACE, with SSFs of the <i>Anabarites trisulcatus</i> – <i>Protohertzina anabarica</i> Zone extending down into the late Ediacaran, similar to the record from SE Siberia. To be confirmed.	<i>Cloudina hartmanae</i> (Steiner et al., 2020; B. Yang et al., 2016)
Gondwana, Spain, East Galician-Castilian Zone, Valdelacasa Anticline	Río Huso Gr	Membrillar olistostrome (mostly siliciclastic with a few carbonate olistoliths and silicified <i>Cloudina</i> )	<i>Cloudina carinata</i> (Cortijo et al., 2010; Vidal et al., 1994)
Gondwana, Spain East Lusitanian-Alcudian Zone, Abenójar & Navalpino anticlines	Ibor Gr	Villarta Formation	<i>Cloudina hartmanae</i> , <i>C. carinata</i> (Álvaro et al., 2019; Zhuravlev et al., 2012)
Laurentia, W Canada, British Columbia, Rocky Mts	Windermere Supergr, Miette Gr, Byng Fm	Uppermost part	<i>Cloudina</i> sp. (Hofmann and Mountjoy, 2001)
Laurentia, Nevada & California	Deep Spring Fm	Lower part	<i>Cloudina dunfeeii</i> (Signor et al., 1987)
Laurentia, Nevada	Wood Canyon & Deep Spring fms	Esmeralda Mb (Deep Spring Fm), lower mb (Wood Canyon Fm)	<i>Saarina hagadorni</i> (Selly et al., 2020)
Laurentia, Mexico, Sonora	La Ciénega Fm	Unit 1 contains both <i>Cloudina</i> and <i>Sinotubulites</i> below the level dated at $539.40 \pm 0.23$ (0.35) Ma (Hodgin et al., 2020) (maximum depositional age)	<i>Cloudina</i> sp. (McMenamin, 1985; Sour-Tovar et al., 2007)
Baltica, White Sea area	Erga Fm	upper part, above $550.2 \pm 4.6$ Ma. Radiometric age not incorporated into model due to large uncertainty.	<i>Saarina</i> sp. (Grazhdankin and Maslov, 2015; Ivantsov, 2011)
Baltica, Leningrad region		Rovno Horizon, lowermost Cambrian?	<i>Saarina tenera</i> (Sokolov, 1967)

<i>Namacalathus hermanastes</i> stratigraphic distribution			
Gondwana, Namibia, Zaris & Witputs subbasins	Nama Gr, Kuibus & Schwarzrand sgrs	Zaris Fm, upper Omkyk & lower Hoogland mbs, Urusis Fm, Feldschuhhorn & Spitskop mbs />547.32 Ma – 538.58±0.19 Ma/	(Bowring et al., 2007; Bowyer et al., 2017; Grotzinger et al., 2000, 1995; Linnemann et al., 2019; Penny et al., 2017; Wood et al., 2015); see SI of (Bowyer et al., 2020) for full references. FB field observation <i>in situ</i> at summit of Swartpunt section (image available upon request).
Gondwana, Oman	Huqf Supergr, Ara Gr	A2-A3, above 546.72±0.21 Ma – 542.33±0.12 Ma / $\delta^{13}\text{C}$ positive excursion/	(Amthor et al., 2003; Bowring et al., 2007)
Gondwana, Paraguay	Itapucumí Gr, Tagatiya Guazú Fm	Available low-resolution $\delta^{13}\text{C}$ data suggest placement in interval between 547 and 543 Ma.	(Warren et al., 2017)
Laurentia, W Canada, British Columbia, Rocky Mts	Windermere Supergr, Miette Gr, Byng Fm	Uppermost part	(Hofmann and Mountjoy, 2001)

<i>Treptichnus pedum</i> FADs			
Mongolia, Zavkhan Terrane	Bayan-Gol Fm, contact between members BG3 and BG4	~275m above the nadir of the BACE. ~250m above the FAD of Anabaritids. Approximately coincident with peak 4p.	(Smith et al., 2015)
Avalonia, Burin Peninsula, Newfoundland	Lowest occurrence: 2m below lithofacies association ('member') 2 of the Chapel Island Formation at Fortune Head.	Largely unconstrained by $\delta^{13}\text{C}$ chemostratigraphy due to dominance of siliciclastic deposits (see Brasier et al. (1992) for available data). >>530.02 ± 1.2 Ma (Isachsen et al., 1994, recalculated in Schmitz, 2012) based on approximate age of Chapel Island Formation lithofacies association (Member) 5 (Mystery Lake Member) after regional litho- and biostratigraphic correlation (Landing, 1994, 1991) with sections in Saint John, New Brunswick.	(Brasier et al., 1994; Gehling et al., 2001; Geyer and Landing, 2017; Landing, 1991; Landing et al., 1988)
Gondwana, Namibia, Witputs subbasin	Nama Group, Schwarzrand Subgroup, Farm Sonntagsbrunn, Farm Vergelee (bordering	Nomtsas Fm. $\leq 538.58 \pm 0.19$ (0.24) [0.62] Ma. Maximum age based on radiometric dating of tuff bed in presumed-correlative lower Nomtsas deposits on Farm	(Germs, 1972; Geyer and Uchman, 1995; Grotzinger et al., 1995; Wilson et al., 2012), see updated ichnofossil biostratigraphy of (Darroch et al., 2021)

	Sonntagsbrunn to SE)	Swartkloofberg (Linnemann et al., 2019)	
South China, NE Yunnan	Meishucun section, near Jinning	Lower Zhongyicun Mbr (Zhujiqing Fm). Above the nadir of the BACE, within interval of highly variable $\delta^{13}\text{C}$ and widespread phosphorite deposition across the platform.	(Zhu et al., 2001)
Siberia, Northwestern slope of Olenek Uplift, Khorbusuonka River	Upper Syhargalakh Fm.	Upper Syhargalakh Fm. Above maximum age of $542.8 \pm 1.30$ Ma from volcanic breccia of the Tas-Yuryakh volcanic complex (Bowring et al., 1993; Maloof et al., 2010). Uncertainty in this age is noted in Table S1.	(Rogov et al., 2015)
Laurentia, California	Immediately above second dolomite marker bed in the lower member of the Wood Canyon Fm	Above nadir of the BACE recorded in the second dolomite marker bed of the lower member, Wood Canyon Fm.	(Smith et al., 2017)
Laurentia, Mexico, Sonora	Lowermost Cerro Rajón Formation.	Above sandy, hematite-rich dolostone bed dated at $539.40 \pm 0.23$ (0.35) Ma (interpreted as maximum depositional age). Above recovery from the BACE (Model A), within BACE interval (Model B), or eruption of tuffaceous material pre-BACE followed by bed re-deposition coincident with BACE at $\sim 536.25$ Ma (Model C).	(Hodgin et al., 2020)

<i>Anabarites trisulcatus</i> FADs			
Mongolia, Zavkhan Terrane	Lowermost Bayan-Gol Fm, BG2 Member	Lowermost phosphorite unit of Bayan-Gol Fm, positive $\delta^{13}\text{C}$ excursion 2p. Base of transitional recovery interval following BACE/'In'.	(Smith et al., 2015)
Avalonia, Burin Peninsula	Chapel Island Fm, Lithofacies association ('Member') 4	Largely unconstrained by $\delta^{13}\text{C}$ chemostratigraphy due to dominance of siliciclastic deposits (see ((Brasier et al., 1992)) for available data). $>>530.02 \pm 1.2$ Ma (Isachsen et al., 1994, recalculated in Schmitz, 2012) based on approximate age of Chapel Island Formation lithofacies association (Member) 5 (Mystery Lake Member) after regional litho- and biostratigraphic correlation (Landing, 1994, 1991) with sections in Saint John, New Brunswick.	<i>Tiksitheca korobovi</i> in (Landing, 1988)
Laurentia, Yukon	Uppermost Ingta Fm	Below FAD <i>T. pedum</i> in basal Vampire Fm, above recovery from BACE? Temporal position poorly constrained.	(Nowlan et al., 1985; Pyle et al., 2006)

Gondwana, South China, Hubei, Yichang County	Kuanchuanpu Fm	Basal part with <i>Protohertzina</i> and cloudinids. Occurs below a large negative $\delta^{13}\text{C}$ excursion thought to postdate the BACE. No raw $\delta^{13}\text{C}$ data have been published to incorporate into our age model but see $\delta^{13}\text{C}$ profile in (Steiner et al., 2020) (their figure 11). According to the model of (Steiner et al., 2020) and (B. Yang et al., 2016), cloudinids occur coincident with, or slightly above the BACE in the lowermost Kuanchuanpu Fm, with a minimum age LAD equivalent to the upper Spitskop Member, Swartpunt section (Nama Group, Namibia). Alternatively, the negative excursion at the top of the Kuanchuanpu Fm may represent the BACE, with SSFs of the <i>Anabarites trisulcatus</i> – <i>Protohertzina anabarica</i> zone extending down into the late Ediacaran, similar to the record from SE Siberia. To be confirmed.	(Steiner et al., 2020; B. Yang et al., 2016)
Gondwana, South China, Hubei	Middle – upper Yanjiahe Formation, Gunziao section	<i>Anabarites</i> occurs above nadir of BACE, but <i>Anabarites trisulcatus</i> – <i>Protohertzina anabarica</i> Zone begins below nadir of BACE.	(Steiner et al., 2020)
Gondwana, South China, Yunnan	Daibu Member	<i>Anabarites trisulcatus</i> – <i>Protohertzina anabarica</i> Zone begins below nadir of BACE	(Steiner et al., 2020; B. Yang et al., 2016)
Gondwana, South China, southern Shaanxi, Ningqiang County	Dengying Formation	Beiwan Mb /at plateau, below $\delta^{13}\text{C}$ BACE negative excursion/ above 548±8 Ma (detrital) – 538.8 Ma	(Cai et al., 2019)
Kazakhstan, Karatau-Naryn Terrane	Chulaktau Fm	Aksai & Karatau mbs	(B. Yang et al., 2016)
Siberia, Yudoma River, Kyyra-Ytyga River mouth	Yudoma Gr, Ust'-Yudoma Fm	upper part below BACE	(Zhu et al., 2017)
Siberia, western Anabar Uplift, Kotuykan River	Manykai Fm, Bed III	lower part / $\delta^{13}\text{C}$ positive excursion 2p	(Kaufman et al., 1996)

<i>Protohertzina anabarica</i> FAD			
Siberia, Yudoma River, Kyyra-Ytyga River mouth	Yudoma Gr, Ust'-Yudoma Fm	upper part below BACE	(Zhu et al., 2017)
Siberia, Uchur-Maya region, Dzhandara River	Yudoma Gr, Ust'-Yudoma Fm	25-30 m below the top	(Khomontovskiy et al., 1990)
Siberia, Uchur-Maya region, Nimnekey River	Yudoma Gr, Ust'-Yudoma Fm	80 m below the top	(Khomontovskiy and Karlova, 1991)
Siberia, western Anabar Uplift, Kotuykan River	Manykai/Nemakit-Daldyn Fm	lower part / $\delta^{13}\text{C}$ positive excursion 2p peak/	(Kaufman et al., 1996; Kouchinsky et al., 2017)
Siberia, eastern Anabar Uplift, Bol'shay and Malaya Kuonamka rivers	Manykay Fm	lower part /below $\delta^{13}\text{C}$ excursion 2p bottom ???/	(Kouchinsky et al., 2017)

Siberia, Olenek Uplift	Syhargalakh Fm (Kessyuse Gr)	upper part, above 543.9±0.24 Ma level. Uncertainty in this radiometric constraint noted in Table S1.	(Nagovitsin et al., 2015)
West Siberian Plate, Tomsk region	Churbiga Fm	lower part	(Novozhilova and Korovnikov, 2019)
Mongolia, Zavkhan Terrane	Bayan-Gol Fm	lower part / $\delta^{13}\text{C}$ positive excursion 2p peak ???/	(Esakova and Zhegallo, 1996; Smith et al., 2015)
Kazakhstan, Karatau-Naryn Terrane	Chulaktau Fm	Aksai & lower Karatau mbs with cloudinid <i>Rajatubus</i>	(Missarzhevsky, 1973; B. Yang et al., 2016)
Gondwana, South China, Yunnan, Huize County	Zhujiaping Fm	basal Zhongyicun Mb / $\delta^{13}\text{C}$ P2-P3 interval/	(Li et al., 2013; Yang et al., 2014)
Gondwana, South China, Shaanxi	Kuanchuanpu Fm	lower & middle part	(Steiner et al., 2007)
Gondwana, South China, Hubei, Yichang County, Yangtze Gorges	Yanjiahe Fm	Dolostone Unit 2 & Tianzhushan Mb / $\delta^{13}\text{C}$ positive excursion/	(Steiner et al., 2020)
Gondwana, South China, Sichuan	Maidiping Fm	lower part	(Steiner et al., 2020)
Gondwana, South China, Hunan	Hetang Fm	basal chert unit	(Yang et al., 2014)
Gondwana, South China, Anhui	Hetang Fm	basal part	(Steiner et al., 2003)
Gondwana, Tarim, Xinjiang	Yurtusu Fm		(Zhang et al., 2020)
Gondwana, India, Lesser Himalaia, Mussoorie Syncline	Tal Gr	Lower Tal Gr, basal part	(Brasier and Singh, 1987; Hughes, 2016)
Iran, Alborz Mts	Soltanieh Fm	Lower Shale Mb, lower part / $\delta^{13}\text{C}$ negative excursion above EPIP/	(Hamdi, 1995; Kimura et al., 1997)
Gondwana, Spain East Lusitanian-Alcudian Zone, Abenójar Anticline	Ibor Gr	Villarta Fm, with <i>Cloudina</i>	<i>Protohertzina</i> sp. (Simón, 2018)
Avalonia, Newfoundland, Burin Peninsula	Chapel Island Fm	mb 4	(Landing et al., 1989)
Baltica, Estonia	Lontova & coeval Voosi fms	Kestla Mb	<i>Protohertzina compressa</i> in (Slater et al., 2018) /organic compression/
Laurentia, W Canada, Mackenzie Mts	Backbone Ranges Fm	(former Map Unit 11) /above $\delta^{13}\text{C}$ negative excursion/	(Conway Morris and Fritz, 1980; Narbonne et al., 1994)
Laurentia, W Canada, Wernecke Mts	Ingta Fm	upper part	(Pyle et al., 2006)

<p><i>Aldanella attleborensis</i> FADs  [including its junior synonyms <i>A. kunda</i> (Öpik, 1926); <i>A. yanjiaheensis</i> (Chen, 1984); <i>A. costata</i> (Missarzhevsky, 1989); <i>A. patelliformis</i> (Bokova, 1990; B. Yang et al., 2016)].</p>			
Siberia, Aldan River, Dvortsy section	Pestrotsvet Fm	Bed 15, basal part of the formation /beginning of $\delta^{13}\text{C}$ Cycle II = -1‰/	(Brasier et al., 1994; Parkhaev and Karlova, 2011; Semikhatov et al., 1970)

Siberia, Selinde River	Pestrotsvet Fm	basal part / $\delta^{13}\text{C}$ excursion I'/	(Kouchinsky et al., 2005; Parkhaev and Karlova, 2011; Repina et al., 1988)
Siberia, Igarka region, Sukharikha River	Sukharikha Fm	uppermost part (occurs above in the lower Krasny Porog Fm) / $\delta^{13}\text{C}$ excursion 7p/	(Kouchinsky et al., 2007; Parkhaev and Karlova, 2011)
Siberia, western Anabar Uplift, Kotuy River	Medvezh'ya Fm	lower part / $\delta^{13}\text{C}$ excursion I'/	(Kouchinsky et al., 2017; Parkhaev and Karlova, 2011)
Siberia, eastern Anabar Uplift, Bol'shay and Malaya Kuonamka rivers	Manykay Fm	upper part (occurs above in the lower Emyaksin Fm) /below $\delta^{13}\text{C}$ excursion I'/	(Kouchinsky et al., 2017; Parkhaev and Karlova, 2011)
Siberia, Olenek Uplift	Mattaia Fm (Kessyuse Gr)	middle mb, below 529.7 $\pm$ 0.3 Ma level	(Sarsembaev and Marusin, 2019)
Siberia, Noril'sk area	Polba Fm	uppermost part	(Parkhaev, 2014)
Siberia, Kolyma Uplift	Kirpichnaya Fm	lower part	(Tkachenko et al., 1987)
Siberia, Taimyr Peninsula	Graviinorechenskaya Gr		(Parkhaev and Karlova, 2011)
Mongolia, Zavkhan Terrane	Khairkhan Fm	reworked material	(Missarzhevsky, 1973)
Gondwana, South China, Yunnan, Huize County	Zhujiaying Fm	Dahai Mb	(Parkhaev and Karlova, 2011)
Gondwana, South China, Hubei, Yichang County, Yangtze Gorges	Yanjiahe Fm	Unit 4 / $\delta^{13}\text{C}$ positive excursion/	(Steiner et al., 2020)
Gondwana, South China, Sichuan, Emei County	Maidiping Fm	upper part	(Parkhaev and Karlova, 2011)
Gondwana, Tarim, Xinjiang	Yurtusu Fm		(Parkhaev, 2019b)
Avalonia, Newfoundland, Burin Peninsula	Chapel Island Fm	upper mb 3 /and mb 4/	(Landing et al., 1989)
Avalonia, Massachusetts	Weymouth Fm	lower mb, below 530.7 $\pm$ 0.9 Ma level	(Landing, 1989, 1988; Landing et al., 1998)
Baltica, Estonia	Lontova Fm	Kestla Mb	<i>Aldanella kunda</i> (Öpik, 1926) in (Isakar and Peel, 2007)
Baltica, Norway, Troms	Dividal Gr	Mb D ( <i>Platysolenites antiquissimus</i> Zone)	(Føyn and Glaessner, 1979)

*Watsonella crosbyi* FADs

Siberia, Aldan River, Dvortsy section	Pestrotsvet Fm	Bed 15, basal part of the formation /beginning of $\delta^{13}\text{C}$ Cycle II = -1‰/ (occurs up to Bed 16, 34 m above the base)	(Brasier et al., 1994; Semikhatov et al., 1970)
Siberia, Selinde River	Pestrotsvet Fm	basal part / $\delta^{13}\text{C}$ excursion I'/	(Kouchinsky et al., 2005; Repina et al., 1988)
Siberia, Igarka region, Sukharikha River	Krasny Porog Fm	lower part /beginning of $\delta^{13}\text{C}$ Cycle II = -1‰/	(Kouchinsky et al., 2007; Rowland et al., 1998)

Siberia, western Anabar Uplift, Kotuy River	Medvezh'ya Fm	lower part / $\delta^{13}\text{C}$ excursion I'/	(Landing and Kouchinsky, 2016)
Siberia, Olenek Uplift	Mattaia Fm (Kessyuse Gr)	upper mb, right above 529.7 $\pm$ 0.3 Ma level	(Sarsembaev and Marusin, 2019)
Mongolia, Zavkhan Terrane	Bayan-Gol Fm	uppermost part /approximately $\delta^{13}\text{C}$ positive excursion 5p?/	(Esakova and Zhegallo, 1996; Smith et al., 2015)
Gondwana, South China, Yunnan, Yongshan, Xundian, Jinning & Huize counties	Zhujiaping Fm	upper Dahai Mb, above 536.7 $\pm$ 3.9 Ma level / $\delta^{13}\text{C}$ Cycle P or ZHUCE/	(Chen et al., 2015; Li et al., 2011; Steiner et al., 2020)
Gondwana, South China, Hubei, Yichang County, Yangtze Gorges	Yanjiahe Fm	bed 5 / $\delta^{13}\text{C}$ positive excursion/	(Guo et al., 2020; Steiner et al., 2020)
Gondwana, South China, Sichuan, Emei & Ganlu counties	Maidiping Fm	upper part / $\delta^{13}\text{C}$ positive excursion/	(Steiner et al., 2020, 2007)
Gondwana, North China, northern Shaanxi	Xinji Fm	Mb B, <i>Estangia</i> trilobite zone, Canglangpuan Stage /lower Stage 4/	(Parkhaev, 2019b)
Gondwana, South Australia, Stansbury Basin, Fleurieu Peninsula	Mount Terrible Fm	upper part of middle mb (occurs up to the Wangkonda and lower Selick Hill fms) /suggested below $\delta^{13}\text{C}$ ZHUCE/	(Bengtson et al., 1990; Betts et al., 2018; Jacquet et al., 2017)
Gondwana, France, Montagne Noir, Avène-Mendic parautochthon	Marcou Fm	Heraultia Mb	(Devaere et al., 2013)
Avalonia, Newfoundland, Burin Peninsula	Chapel Island Fm	upper mb 3 /and above including the Bonavista Gr/	(Landing et al., 2017)
Avalonia, Massachusetts	Weymouth Fm	lower mb, below 530.7 $\pm$ 0.9 Ma level	(Landing, 1989, 1988; Landing et al., 1998)

*Cruziana* ichnospp. FADs

Siberia, Olenek Uplift	Kessyuse Gr, Mattaia Fm	about 529.7 $\pm$ 0.3 Ma level	(Marusin et al., 2015; Nagovitsin et al., 2015)
Gondwana, South China, Yunnan, Jinning County	Zhujiaping Fm	Zhongyicun Mb, Upper Phosphorite bed	(Weber et al., 2007)
Iran, Alborz Mts	Soltanieh Fm	Lower Shale Mb, uppermost part	(Shahkarami et al., 2017)
Gondwana, Spain, Cantabrian Zone, Cadenas Ibéricas	Embid Fm	upper part	(Gámez Vintaned et al., 2009)
Laurentia, Canada, Wernecke Mts	Vampire Fm	basal part (above Ingta Fm with <i>Protohertzina</i> )	(Narbonne and Aitken, 1995)
Laurentia, USA, Great Basin	Deep Spring Fm	upper part (Gold Point Mb)	(Ahn et al., 2011; Corsetti and Hagadorn, 2003)
Laurentia, Mexico, Sonora (Cerro Rajón section)	Puerto Blanco Fm	Unit 2, basal part (with trilobite cf. <i>Fallotaspis</i> sp.)	(Stewart et al., 1984)
Avalonia, Newfoundland, Burin Peninsula	Chapel Island Fm	upper Member 2	(Landing et al., 2017)



Baltica, Norway, Finnmark	Breidvika & Duolbasgaissa fms	Lower Breidvika Mb to Lower Duolbasgaissa Mb (below trilobite <i>Kijerulfia</i> )	(Crimes and McIlroy, 1999; McIlroy and Brasier, 2017)
Baltica, South Sweden	Mickwitzia Sandstone Mb	upper part, Interval D (with <i>Volborthella</i> and below trilobite <i>Holmiella</i> ; Stage 4 ?)	(Jensen, 1997)

Archaeocyatha FADs			
(A1–B1) – archaeocyath zones equated with the Siberian lower Cambrian zonation. (? Cycle IV) – carbon-isotope cycles following the Siberian record.			
Siberia, Aldan River (Ulakan-Sulugur section)	Pestrotsvet Fm	basal Bed 12, $\delta^{13}\text{C} = 0\text{‰}$ pre-dating negative nadir at the beginning of Cycle II (T1); <i>Archaeolynthus polaris</i> , <i>Nochoroicyathus sunnaginicus</i> , <i>N. virgatus</i> , <i>N. belvederi</i> , <i>N. tkatschenkoi</i> , <i>Cryptoporocyathus junicanensis</i> , <i>Cambrocyathellus tschuranicus</i>	(Magaritz et al., 1991; Riding and Zhuravlev, 1995)
Siberia, Selinde River	Pestrotsvet Fm	2.7 m above the base of the formation, $\delta^{13}\text{C}$ positive excursion pre-dating I'n (?ND); <i>Nochoroicyathus</i> sp., <i>Cambrocyathellus</i> sp.	(Khomentovsky and Karlova, 2002; Kouchinsky et al., 2005)
Siberia, Sukharikha River	Sukharikha Fm	uppermost part, $\delta^{13}\text{C}$ positive excursion 7p (?ND); <i>Archaeolynthus polaris</i> , <i>Nochoroicyathus sunnaginicus</i> , <i>N. virgatus</i> , <i>N. dragunovi</i> , <i>N. igarcaensis</i> , <i>Cryptoporocyathus junicanensis</i>	(Kouchinsky et al., 2007; Rowland et al., 1998)
Mongolia, Zavkhan Terrane (Salaany-Gol section)	Salaany-Gol Fm	45 m above the base, $\delta^{13}\text{C}$ positive excursion (? Cycle IV), Mongolian archaeocyath zone 1 (A1); <i>Archaeolynthus solidimurus</i> , <i>Tumuliolynthus musatovi</i> , <i>Dokidocyathus bogradiensis</i> , <i>Nochoroicyathus howelli</i> , <i>N. misertumulus</i> , <i>Rotundocyathus floris</i> , <i>Urcyathus batenensis</i> , <i>Sclerocyathus floridus</i> , <i>Tumulocyathus exiguus</i> , <i>Plicocyathus stellatus</i> , <i>Pretiosocyathus subtilis</i> , <i>Agyrekocyathus shoriensis</i> , <i>Capsulocyathus irregularis</i> , <i>Alataucyathus jaroshevitschi</i> , <i>Cambrocyathellus minutus</i> , <i>C. tuberculatus</i> , <i>Okulitchicyathus communis</i> , <i>Dictyocyathus confertus</i> , <i>Archaeopharetra smolianinovae</i> , <i>Spinococyathus mongolicus</i> , <i>Tabulacyathellus bidzhaensis</i> , <i>Usloncyathus bipartita</i>	(Smith et al., 2015; Voronin et al., 1982)
Mongolia, Tuva-Mongolia Terrane, southern Khubsugul area	Egyin-Gol Fm	lower member (300-500 m thick), Mongolian archaeocyath zone 2 (A2); <i>Archaeolynthus solidimurus</i> , <i>Dokidocyathus bogradiensis</i> , <i>Nochoroicyathus howelli</i> , <i>Orbicyathellus bogradi</i> , <i>Gordonicyathus annulispinosus</i> , <i>Inessococyathus heterospinosus</i> , <i>Formosococyathus spinosus</i> , <i>Capsulocyathus irregularis</i> , <i>Loculicyathus cibus</i> , <i>Ardrossacyathus ornatus</i> , <i>Archaeopharetra smolianinovae</i> , <i>Usloncyathus serus</i>	AZ own observations
Gondwana, South China, Shaanxi (Fucheng section)	Xiannudong Fm	at the base, with trilobites of the upper <i>Wutingaspis-Eoredlichia</i> Zone ( <i>Yunnanocephalus</i> Subzone) (A1);	(B. Yang et al., 2016)

		<i>Dailycyathus xiuqiensis</i> , <i>Conannulofungia annuliformis</i> , <i>Erismacoscinus zhuyuanensis</i> , <i>Archaeopharetra? chengkouensis</i> , <i>Metacyathellus lepidus</i> , <i>Usloncyathus jindingshanensis</i>	
Gondwana, South Australia, Arrowie Basin, Wilkawillina Gorge	Wilkawillina Lm	c. 40 m above the base (A1); <i>Inessocyathus clarus</i> , <i>Erugatocyathus krusei</i> , <i>Archaeopharetra insculpta</i> , <i>Copleicyathus cymosus</i> , <i>Warriootacyathus wilkawillinensis</i> , <i>Usloncyathus obtusus</i>	(Gravestock, 1984)
Gondwana, South Australia, Arrowie Basin, Mount Scott Range	Ajax Lm	c. 80 m above the base, below $\delta^{13}\text{C}$ positive excursion (? Cycle IV) (A1); <i>Copleicyathus cymosus</i> , <i>Warriootacyathus wilkawillinensis</i>	(Betts et al., 2018; Gravestock, 1984)
Gondwana, Morocco, Anti-Atlas Mts	Igoudine Fm	Tiout Mb (15 m above the base), 519.71±0.26 Ma, $\delta^{13}\text{C}$ peak (? Cycle IV) (A1); <i>Nochoroicyathus cribratus</i> , <i>N. crassus</i> , <i>Rotundocyathus</i> sp., <i>Sibirecyathus compositus</i> , <i>Tumulifungia marocana</i> , <i>Retecoscinus minutus</i> , <i>Erismacoscinus fasciola</i> , <i>E. primus</i> , <i>Geyericoscinus equiporus</i> , <i>Neoloculicyathus magnus</i> , <i>Dictyocyathus stipatus</i> , <i>D. circulus</i> , <i>Protopharetra taissensis</i> , <i>Agastrocyathus gregarius</i>	(Debrenne and Debrenne, 1995; Landing et al., 2020)
Gondwana, Spain, Ossa-Morena Zone, Sierra de Córdoba (Las Ermitas section)	Pedroche Fm	Mb I, basal part, archaeocyath zone I (A1); <i>Archaeolynthus</i> sp., <i>Cordobicyathus deserti</i> , <i>Nochoroicyathus cabanasi</i> , <i>Urcyathus</i> sp., <i>Taylorocyathus carbonelli</i> , <i>Morenicyathus arruzafai</i> , <i>Retecoscinus gadalquivirensis</i> , <i>Neoloculicyathus magnus</i> , <i>Okulitchicyathus andalusicus</i>	(Perejón, 1994; Perejón et al., 2014; Perejón and Moreno-Eiris, 2006)
Gondwana, France, Montagne Noir, Minervois Nappe	Pardailhan Fm	basal HI interval (A4); <i>Inessocyathus levis</i> , <i>Retecoscinus boyeri</i> , <i>Anthomorpha margarita</i> , <i>Dictyocyathus circulus</i> , <i>Protopharetra</i> cf. <i>polymorpha</i>	(Debrenne et al., 2002)
Laurentia, Canada, Mackenzie Mts	Sekwi Fm	c. 200 m above the base, S0, post-dating $\delta^{13}\text{C}$ Cycle B peak (? = Cycle VI) (B1); <i>Robertiolynthus handfieldi</i> , <i>Sekwicyathus nahanniensis</i> , <i>Sanarkocyathus plurimus</i> , <i>Cordilleracyathus blussoni</i> , <i>Stephenicyathus rowlandi</i> , <i>Protopharetra junensis</i> , <i>Williamicyathus colvillensis</i>	(Dilliard et al., 2007; Voronova et al., 1987)
Laurentia, USA, Great Basin, Nevada	Campito Fm	Montenegro Mb (upper 50 m) (A4); <i>Robustocyathellus? weeksi</i> , <i>Cordilleracyathus blussoni</i> , <i>Ethmophyllum whitney</i> , <i>Metaldetes fischeri</i> , <i>Metacyathellus argenteus</i>	(Mansy et al., 1993)
Laurentia, Mexico, Sonora (Cerro Rajón section)	Puerto Blanco Fm	middle Unit 2, poorly preserved. Basal Unit 3 (B1); <i>Robustocyathellus? pusillus</i> , <i>Palmericyathus americanus</i> , <i>Loculicyathus polycladus</i> , <i>Graphoscypia ramosa</i> , <i>Spirocyathella spinosa</i> , <i>Metaldetes</i> cf. <i>meeki</i>	(Debrenne et al., 1989)

Trilobita FADs

Siberia, Lena River, Zhurinsky Mys sections	Pestrotsvet Fm	47 m above the base of the section (Bed 4), beginning of $\delta^{13}\text{C}$ Cycle IV = 0‰; <i>Profallotaspis</i> sp. 54 m above the base of the section (Bed 5), beginning of $\delta^{13}\text{C}$ Cycle IV = 0.5‰; <i>Profallotaspis jakutensis</i> . 57 m above the base of the section (Bed 6), beginning of $\delta^{13}\text{C}$ Cycle IV = 1‰; <i>Profallotaspis jakutensis</i> . 73 m above the base of the section (Bed 7), $\delta^{13}\text{C}$ Cycle IV peak = 1.5‰; <i>Repinaella explicata</i> .	(Astashkin et al., 1984; Kirschvink et al., 1991)
Siberia, Selinde River	Pestrotsvet Fm	Bed 37 (95 m above the base of the formation), $\delta^{13}\text{C}$ = 0.5‰ pre-dating Cycle IV peak; <i>Profallotaspis privica</i> . Beds 38–40 within the same cycle: <i>P. jakutensis</i> , <i>Repinaella sibirica</i> , <i>R. explicata</i> , <i>Bigotina malycanica</i> , <i>Nevadella</i> aff. <i>effusa</i>	(Kouchinsky et al., 2005; Repina et al., 1988)
Mongolia, Tuva-Mongolia Terrane, southern Khubsugul area	Egyin-Gol Fm	lower member (300-500 m thick), Mongolian archaeocyath zone 2; <i>Elganellus pensus</i> , <i>Bigotina malycanica</i> , <i>Malykania murenica</i>	(Korobov, 1989, 1980)
Gondwana, South China, Yunnan, Jinning County (Maotianshan & Xiaolantian sections)	Yu'an-shan Fm	basal “black shale member”, at the beginning of $\delta^{13}\text{C}$ MICE (? Cycle IV), below the Chengjiang Biota of 518.03±0.69/0.71 Ma; <i>Parabadiella huoi</i>	(Yang et al., 2018; Zhang et al., 2001; Zhu et al., 2001)
Gondwana, South Australia, Arrowie Basin, Wilkawillina Gorge	Wilkawillina Lm	uppermost part; <i>Eoredlichia</i> sp.	(Bengtson et al., 1990)
Gondwana, South Australia, Arrowie Basin, Mount Scott Range	Ajax Lm	140 m above the base, $\delta^{13}\text{C}$ positive excursions (? Cycle IV); <i>Parabadiella huoi</i> . 200 m above the base, between $\delta^{13}\text{C}$ positive excursions (? Cycles IV and V); <i>Pararaia tatei</i> , <i>Eoredlichia shensiensis</i>	(Bengtson et al., 1990; Betts et al., 2018)
Gondwana, Morocco, Anti-Atlas Mts	Igoudine Fm	Tiout Mb, 519.95±0.43, trilobite fragments. 519.78±0.78 – 518.99±0.14 Ma, $\delta^{13}\text{C}$ peak (? Cycle IV); <i>Hupetina antiqua</i> – <i>Eofallotaspis prima</i> , <i>Bigotina kelleri</i> , <i>Eladiolinania castor</i> – <i>Bigotina monningeri</i> – <i>Eofallotaspis tioutensis</i> – <i>Fallotaspis antecedens</i>	(Landing et al., 2020)
Gondwana, Spain, Galician-Castilian Zone, Salamanca (La Rinconada section)	Tamanes Ss	lower part; <i>Lunagraulos tamamensis</i>	(Liñán et al., 2015)
Gondwana, Spain, Ossa-Morena Zone, Sierra de Córdoba (Arroyo de Pedroche 1 section)	Pedroche Fm	Mb I, base, archaeocyath zone I; cf. <i>Bigotina</i> . Mb I, 140-160 m above the base, archaeocyath zone III; <i>Bigotina bivallata</i> , <i>Lemdadella</i> aff. <i>linaresae</i> .	(Liñán et al., 2005)

		Mb I, 180-190 m above the base, archaeocyath zone III; <i>Eoredlichia</i> cf. <i>ovetiensis</i> , <i>Lemdadella peregjoni</i>	
Laurentia, Canada, Mackenzie Mts	Sekwi Fm	basal part, S0, $\delta^{13}\text{C}$ Cycle A peak (? = Cycle IV); <i>Parafallotaspis grata</i>	(Dilliard et al., 2007; Fritz, 1972)
Laurentia, USA, Great Basin	Campito Fm	Gold Coin Mb; <i>Fritzaspis</i> sp. – <i>Profallotaspis?</i> sp. – <i>Fritzaspis generalis</i> – <i>F. ovalis</i> – <i>Amplifallotaspis keni</i> – <i>Repinaella</i> sp.	(Hollingsworth, 2011)
Laurentia, Mexico, Sonora (Cerro Rajón section)	Puerto Blanco Fm	Unit 2, basal part; cf. <i>Fallotaspis</i> sp.	(Stewart et al., 1984)
Avalonia, Newfoundland, Avalon Peninsula	Brigus Fm	St. Mary's Mb, middle part /cf. $517.22 \pm 0.31(0.40)$ [0.66] Ma (Williams et al., 2013) by correlation with Purley Sh, England/; <i>Callavia broeggeri</i>	(Landing et al., 2017, 2013; Williams et al., 2013)
Avalonia, Cwm Bach, South Wales	Caerfai Bay Fm	Zircon U-Pb age of $519.30 \pm 0.23$ (0.57) [0.77] Ma (Harvey et al., 2011) for the lowest Caerfai Bay Fm (see table S1), which contains the oldest unidentified trilobite fragments in Avalonia (Landing et al., 2020).	(Harvey et al., 2011; Landing et al., 2020)
Baltica, Sweden, Scåne	Læså Fm	Norretorp Mb, middle part; <i>Schmidtellus mickwitzii</i> , <i>Holmia mobergi</i>	(Nielsen and Schovsbo, 2011)

## Table S2.

(separate xlsx data file 'TableS2\_AgeModels.xlsx'). Alternative age models for the Ediacaran and lower Cambrian interval ca. 635-517 Ma. Includes new  $\delta^{13}\text{C}_{\text{carb}}$  data from sections of the Nama Group, Namibia, and compiled published data from globally-distributed sections, in addition to biostratigraphic information (Tab1\_Global\_Data\_550-517), published age model of Yang et al. (2021) (Tab2\_Yang\_635-550), output of lower Cambrian fossil first appearances within each stratigraphic section subdivided by family (Tab3\_CambrianFADs), biostratigraphic reference table (Tab4\_Biostratigraphy), full (and screened)  $^{87}\text{Sr}/^{86}\text{Sr}$  database (Tab5\_8786Sr), output of  $\delta^{13}\text{C}_{\text{carb}}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  data by region (Tab6\_Figured\_Correlations), output of block averaged sedimentation rates for interval 635-517 Ma (Tab7\_BlockAverageSedRate), and associated references (Tab8\_References).

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