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1 A Bayesian astrochronology for the Cambrian first occurrence of
2 trilobites in West Gondwana (Morocco)

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8

9 **ABSTRACT**

10 The first occurrence of trilobites ~520 million years ago is an iconic feature of the
11 Cambrian Explosion. Developing a robust evolutionary view on early Cambrian life is generally
12 hindered by large uncertainties in the ages of fossil finds, and their global stratigraphic correlation.
13 Here, we develop an astrochronological interpretation for the Tiout section in Morocco that
14 features some of the oldest trilobite fossils. Our novel approach to incorporating individual
15 astronomical cycle durations in an integrated radio-isotopic and astrochronological Bayesian age-
16 depth model results in an age estimate of 519.62 Ma (519.70–519.54 Ma 95% highest posterior
17 distribution) for the first occurrence of trilobites in West Gondwana. This level of precise age
18 estimation is exceptional for biological events in deep time and demonstrates the power of our
19 novel approach.

20

21 **INTRODUCTION**

22 Lower Cambrian (~540–520 million years ago, Ma) strata are marked by a prominent
23 increase in abundance and diversity in the fossil record. Whether this increase reflects a fast
24 evolutionary event, also known as the ‘Cambrian Explosion’ (Gould, 1989), or a more gradual
25 mode of evolution (Wood et al., 2019) is an open question. The main challenges in resolving this
26 question are large uncertainties in the stratigraphic framework and a lack of direct radioisotopic
27 age control of fossil finds (Bowyer et al., 2022). Given the limitations of classical stratigraphic
28 tools like biostratigraphy and magnetostratigraphy for lower Cambrian stratigraphy, carbon
29 isotope ratio chemostratigraphy ($\delta^{13}\text{C}$) has become the main tool for global correlations (Tucker,
30 1986; Magaritz et al., 1991; Bowyer et al., 2022).

31 An iconic feature of the early Cambrian evolutionary transition is the first occurrence (FO)
32 of trilobites. Some of the oldest trilobite fossils can be found in West Gondwana, corresponding
33 to present-day southern Morocco (Landing et al., 2021). These Moroccan sections are also crucial
34 for lower Cambrian stratigraphy due to extensive $\delta^{13}\text{C}$ chemostratigraphic and geochronological
35 studies (Tucker, 1986; Compston et al., 1992; Maloof et al., 2005, 2010; Hay et al., 2019; Landing
36 et al., 2021). While radio-isotope geochronology provides anchored numerical age information for
37 individual horizons, astrochronology – i.e. the estimation of time based on the identification of
38 astronomical cycles in the sedimentary record – has the complementary advantage of providing
39 floating but continuous duration estimates (Laskar, 2020). Combining absolute age estimates of
40 discrete beds with this continuous record of the passage of time across strata can further constrain
41 temporal frameworks and correlations. Existing Bayesian age-depth models only use total
42 astrochronological duration estimates for specific stratigraphic intervals (Meyers et al., 2012; De
43 Vleeschouwer and Parnell, 2014). In this study, we present a high-resolution astrochronological
44 age model for the FO of trilobites in Morocco, in the well-studied Tiout section. In addition, we

45 suggest a novel way to improve both precision and accuracy of integrated age-depth models by
46 explicitly using individual astronomical cycles in an astrochronological Bayesian age-depth
47 model.

48

49 **MATERIALS AND METHODS**

50 The Tiout section consists of a series of clearly exposed lower Cambrian strata in a gorge
51 south of Tiout village (30°23' N, 8°42' W; see Fig. 1 in [Maloof et al. \(2005\)](#) for a regional
52 geological map). We digitized the quantified lithofacies and cyclothem identification reported in
53 [Monninger \(1979\)](#). Chemical abrasion isotope-dilution thermal ionization mass spectrometry (CA-
54 ID-TIMS) radio-isotopic dates and analytical uncertainty estimates are taken from [Landing et al.](#)
55 [\(2021\)](#) as input for our age-depth models. All dates come from bentonite volcanic zircon samples,
56 except for detrital zircons from a thin sandstone layer (Ti I-neg 8.5) near the base of the Tiout
57 Member some 30 m above the level of first trilobite fragments that offer a maximal depositional
58 age constraint ([Landing et al., 2021](#)).

59 We used the R package “astrochron” ([Meyers, 2014](#); [R core team, 2023](#)) to conduct
60 evolutive power spectral analysis ([Thomson, 1982](#)) and eTimeOpt analysis ([Meyers, 2015, 2019](#)).
61 TimeOpt is a statistical optimization method that can simultaneously consider spectra distributions
62 and amplitude modulation patterns to test for a precession-eccentricity origin in a signal. While
63 TimeOpt uses a constant accumulation rate for the entire investigated section, eTimeOpt allows
64 for changing accumulation rates using a moving window approach.

65 We built an integrated radio-isotopic plus astrochronological Bayesian age-depth model by
66 expressing depth in units of sedimentary cycles, which the astrochronological interpretation infers
67 are short eccentricity (SE) cycles (model A). This approach assumes constant accumulation rates

68 within a cycle, and the absence of substantial hiatuses. This depth scale was used for the positions
69 of the radio-isotopic constraints; interpreted SE cycles; and the FO of trilobites. Following [Landing](#)
70 [et al. \(2021\)](#), we used the lowest level of trilobite fragments, rather than the lowest level of
71 identifiable trilobite species, to denote the local FO of trilobites. To build the age-depth model we
72 used an Oxcal 4.4 ([Ramsey, 2009](#)) U-sequence assuming a fixed (but unknown) deposition rate
73 per unit of depth model to relate these units to time. A prior distribution for the duration of the
74 individual SE cycles with a mean of 96.5 k.y. ($\sigma = 2$ k.y.) was taken from [Lantink et al. \(2022\)](#),
75 who investigated the time differences between successive maxima in full eccentricity solution
76 curves, rather than considering only the duration of the SE cycle that has multiple components
77 around ~100 k.y.. To evaluate our new model, we also constructed two reference Oxcal age-depth
78 models that do not employ astrochronological data – conceptually similar to [Landing et al. \(2021\)](#),
79 [who](#) used the “modifiedBchron” package ([Trayler et al., 2020](#)). The first radio-isotopic age-depth
80 model (model B) only considers ages from volcanic zircons whose ages represents the date of
81 deposition (bentonites labelled as Ti566 – assumed to be equivalent with M236 from [Maloof et al.](#)
82 [\(2010\)](#), Am0.0 and Am34.0 in **Fig. 2A**) using an Oxcal P-sequence model ([Ramsey, 2008](#); [Ramsey](#)
83 [and Lee, 2013](#)). The Oxcal P-sequence models sediment deposition as a series of discrete deposits
84 of sediment, with the number of events per unit length of section following a Poisson distribution,
85 and the parameter of the distribution to be inferred. Our second radio-isotopic age-depth model
86 (model C) uses an additional date from detrital zircons (Ti I-neg 8.5) to contain the maximal
87 depositional age of its depth. The digitized lithofacies, R spectral analysis script and Oxcal age-
88 depth models are available in the **Supplemental Material**.

89

90 **RESULTS AND DISCUSSION**

91 Cyclostratigraphic Analysis

92 The lower Cambrian strata of Tiout are characterized by regular alternations of darker
93 limestones with lighter-colored marlstones that are clearly developed in the Lie de Vin and
94 Igoudine formations (Monninger, 1979; **Fig. 1A**). Individual beds and cycles can be traced for
95 many kilometres, whereas the lithological expression of cycles can vary slightly according to the
96 stratigraphic and regional position (Monninger, 1979; **Fig. 1**). Monninger (1979) constructed a
97 detailed lithofacies log that he also converted into a discretized numerical log, with its two end-
98 members being shaly siltstones (low values) and dark, often biohermal, limestones (high values)
99 (**Fig. 2B**). He also recognized several orders of bundled cyclicity with: a basic ~5-m ‘rhythm’;
100 ~25-m ‘cyclothem’ consisting of several rhythms; ~100-m ‘supercycles’; and a ‘long term trend’
101 (**Fig. 1B**). Spectral analysis of the digitized lithofacies confirms the presence of the ‘rhythms’ (4.5–
102 6.0 m) and ‘cyclothem’ (20–30 m) (**Fig. 2C**). The evolutive power spectral analysis suggests that
103 these cycles are relatively constant in thickness and are especially clearly developed in the middle
104 and upper Lie de Vin Formation (Fm.) (**Fig. 2C**). An eccentricity–precession origin of the
105 cyclothem and rhythms is suggested by the ratio between the thicknesses of the different cycles
106 and the clear amplitude modulation pattern expressed as the bundled alternations of intervals with
107 clearer and darker limestones beds with lighter marlstones alternating with intervals with less
108 distinguishable limestone-marlstone couplets (**Fig. 1**). The rhythm/cyclothem thickness ~1:5 to
109 1:6 ratio is also close to the early Cambrian short to long obliquity duration ratio (Laskar, 2020;
110 Farhat et al., 2022).

111 These hypotheses can be independently tested using the exceptional availability of multiple
112 volcanic zircon CA-ID-TIMS U-Pb ages. These ages occur throughout the studied interval, and
113 bracket it stratigraphically (**Fig. 2A**). When dividing the time difference between the bentonite

114 ages by the number of cyclothem *sensu* [Monninger \(1979\)](#) in between the bentonites, each
115 cyclothem has an average duration of ~100 k.y. (84–116 k.y. considering both minimal and
116 maximal U-Pb duration and cycle number estimates), consistent with a SE interpretation (**Fig. 2A**).
117 This is also an argument for the relative stratigraphic completeness of the section on at least the
118 ~100 k.y. time scale. Moreover, the long-term U-Pb derived average accumulation rates are in the
119 order of ~260 m m.y.⁻¹ (**Fig. 3**). This is close to the optimal solution obtained by eTimeOpt analysis
120 (~250 m m.y.⁻¹; **see the Supplemental Material**), and suggests that the ~5 m ‘rhythms’, ~25 m
121 ‘cyclothem’ and ~100 m ‘supercycles’ correspond with the expected Cambrian periodicities of
122 ~19 k.y. climatic precession, ~100 k.y. SE and 405 k.y. long eccentricity ([Laskar, 2020](#); [Farhat et al., 2022](#)).
123 The long eccentricity periodicity is less prominent, both statistically and visually. This
124 might be explained by non-astronomically driven changes in the sedimentary environment (e.g.
125 tectonic evolution or sea-level changes) that occurred on similar timescales.

126 We have provided the first demonstration of an astronomical origin for the lithological
127 cycles in the Lie de Vin and Igoudine formations, in contrast to previous suggestions of an
128 autocyclic origin ([Monninger, 1979](#); [Maloof et al., 2005](#)). We suggest that changes in detrital
129 terrigenous input ([Monninger, 1979](#)) reflect astronomically forced changes in climate by precession
130 forcing of the monsoonal circulation, in turn controlling precipitation patterns, and thus the
131 transport of siliciclastic sediment ([Wang et al., 2014](#); [Sinnesael et al., 2021](#)). Because strong
132 precession signals are most evident in low-latitude monsoon-dominated climatic regimes, the
133 prominent expression of such cyclicity in Morocco hints that Gondwana occupied a low rather
134 than high paleolatitude, potentially informing the contested configuration of Cambrian
135 paleocontinents ([Wong Hearing et al., 2021](#); [Keppie et al., 2023](#)).

136

137 **A Bayesian Astrochronology**

138 Having established that the section is complete on the 100 k.y. scale, and that the
139 ‘cyclothem’ correspond to SE cycles, we included the cyclothem as additional constraints in a
140 Bayesian age-depth model for the Tiout section, resulting in a median age estimate for the FO of
141 trilobites of 519.62 Ma (519.70–519.54 Ma 95% highest posterior distribution, or HPD, model A)
142 (**Fig. 3**). The posterior distribution for the cyclothem duration in model A resulted in a median
143 duration of 96.3 k.y. (92.5-99.9 k.y. 95% HPD), further supporting our SE interpretation. The
144 median age estimates of both our radio-isotopic only models, with (519.75 Ma, 519.98-519.47 Ma
145 95% HPD, model C) and without (519.76 Ma, 520.10-519.41 Ma 95% HPD, model B) detrital
146 zircon constraints, are close to each other, with a slightly broader HPD interval for model B. In
147 our model the detrital age constraint serves as a simple maximum age for that depth. [Landing et](#)
148 [al. \(2021\)](#) created a probability density function applying a uniform probability between the detrital
149 age constraint and that of the next overlying volcanic zircon age – reasoning that the depositional
150 age cannot be younger than the age of the overlying volcanic ash. Their approach resulted in an
151 older trilobite FO age estimate of 519.95 Ma (520.38-519.55 Ma 95% highest density interval)
152 overlapping with our preferred estimate of 519.62 Ma (519.70–519.54 Ma 95% HPD), but being
153 about 320 k.y. older and ~5 times less precise. Our new younger astrochronological age estimate
154 is the result of the additional cycle information incorporated, showing that accumulation rates were
155 lower in the Lie De Vin Fm. and increased towards the Igoudine Formation (**Fig. 3**).

156 Precise and accurate age determinations within deep-time biological transitions like the
157 Cambrian Explosion are needed worldwide to resolve their detailed evolutionary dynamics. [Zhang](#)
158 [et al. \(2022\)](#) constrained the FO of trilobite fossils in South China using a floating astrochronology
159 based on the 405 k.y. eccentricity cycle that was anchored on a correlated SHRIMP U-Pb age

160 (Compston et al., 2008) whose low precision of 1.90 m.y. dominates the final uncertainty estimate
161 of 1.91 m.y.. The FO of trilobite fossils in Avalonia is best constrained by a dated ash bed around
162 the local level of trilobite FO in Wales (UK) with an age of 519.30 ± 0.77 Ma (including tracer
163 calibration and ^{238}U decay constant errors; Harvey et al., 2011). Other sections worldwide lack any
164 form of direct age control and their stratigraphic position of the local FO of trilobite fossils is
165 usually based on $\delta^{13}\text{C}$ correlations. For example, the oldest trilobite fossil remains are thought to
166 be documented in Siberia, occurring below the peak of the IV $\delta^{13}\text{C}$ excursion (Varlamov et al.,
167 2008; Bowyer et al., 2023), while they occurred above the IV $\delta^{13}\text{C}$ excursion in the Moroccan
168 sections (Tucker, 1986). Unfortunately, the $\delta^{13}\text{C}$ profile of the Tiout section only features low-
169 resolution $\delta^{13}\text{C}$ data, in contrast to other Cambrian sections in southern Morocco (Maloof et al.,
170 2005), and we therefore only present a conservative age estimate for the IV $\delta^{13}\text{C}$ peak as discussed
171 in the **Supplemental Material**. While improving age estimates for biostratigraphic horizons it
172 stays crucial to keep in mind geographic, environmental, and taphonomic controls on fossil
173 occurrences too (Cramer et al., 2015; Landing et al., 2021).

174

175 CONCLUSIONS

176 We demonstrated an astronomical origin for the enigmatic lithological alternations of the
177 lower Cambrian section of Tiout, Morocco and showed how explicitly using individual
178 astronomical cycles in a Bayesian age-depth model can improve both the precision and accuracy
179 of the FO of trilobite fossils in West Gondwana (519.62 Ma, 519.70–519.54 Ma 95% HPD). Our
180 work further demonstrates the potential for the use of astrochronology, preferably with multiple
181 high-quality radio-isotopic constraints from the same section, to better constrain time scales and
182 major changes in the evolution of life – especially in deep-time intervals where many other

183 classical stratigraphic tools like biostratigraphy or magnetostratigraphy have limited utility.
184 Similar work in time-equivalent sections worldwide may yield the equally high-quality age
185 estimates of chemostratigraphic events, FO of trilobite fossils, and other Fortunian taxa that
186 currently continue to suffer from exceedingly poor age control required to resolve their precise
187 evolutionary dynamics.

188

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197

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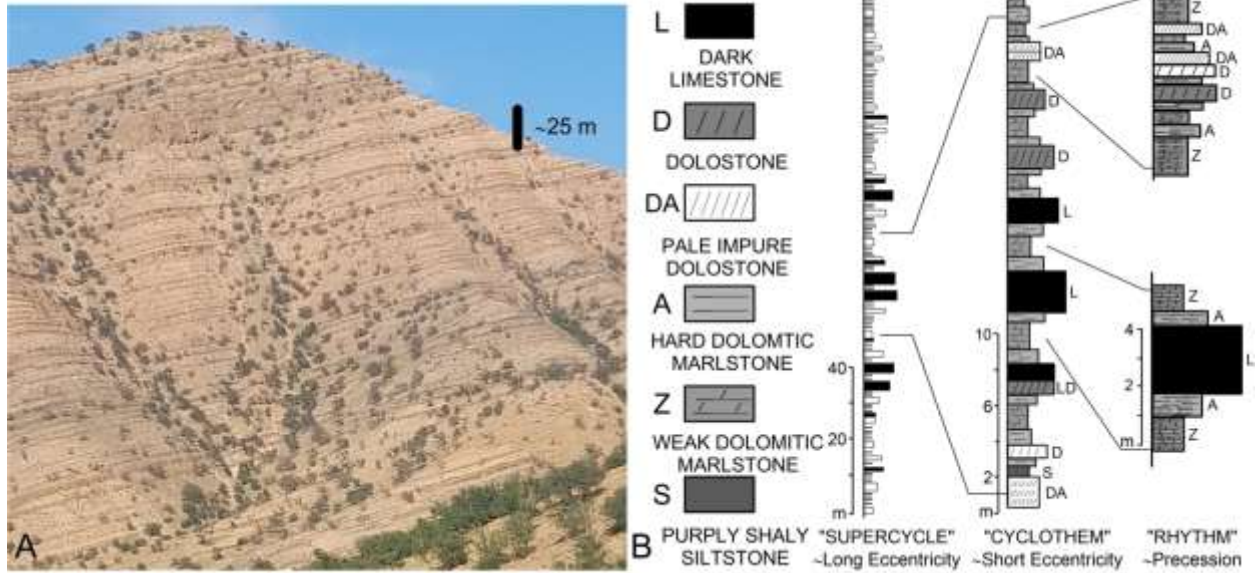
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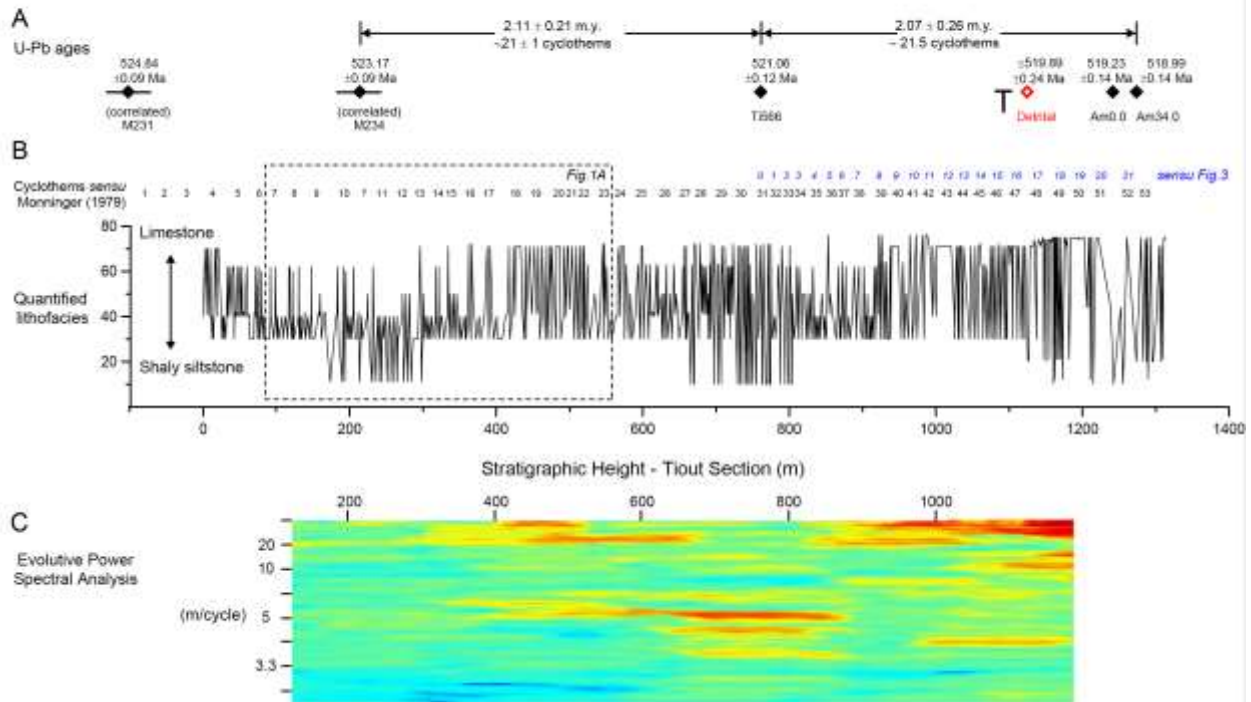
314 **FIGURE CAPTIONS**



315

316 Figure 1: (A) Illustrative photograph of characteristic bundles of alternations between dark
 317 limestones and lighter marlstones in the Lie De Vin Formation ©Kilian Eichenseer. (B) Schematic
 318 representation of the different lithologies and various orders of lithological cyclicity (from
 319 [Monninger, 1979](#)). The thickness ratios and bundling patterns suggest an eccentricity-precession
 320 signature of the cyclothems and rhythms, respectively.

TERRENEUVIAN				SERIES 2	
Adoudou Fm.	Lie-de-vin Formation			Igoudine Fm.	Amouslek Fm.
Tiout Mb.	lower sequence	middle sequence	upper sequence	Informal lower Mb.	Tiout Mb.



321

322 Figure 2: Stratigraphic overview of radio-isotopic age constraints and lithofacies of the Tiout

323 section. (A) U-Pb radio-isotopic age constraints, following Maloof et al. (2010) for

324 stratigraphically correlated bentonite samples M231 and M234, and Landing et al. (2021) for

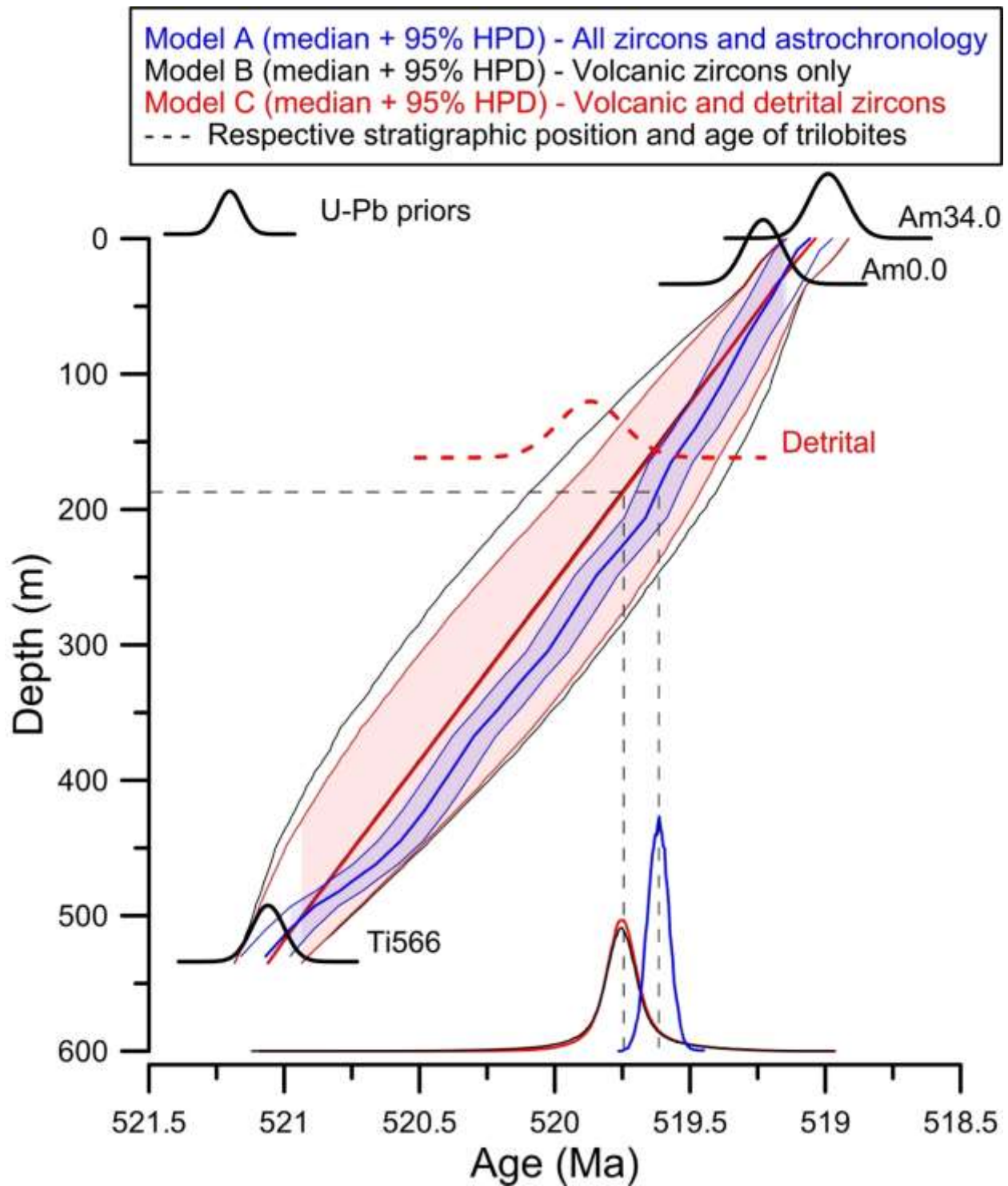
325 bentonites Ti566, Detrital, Am0.0 and Am34.0. ‘T’ indicates the position of the first trilobite fossil

326 remains. (B) Quantified lithofacies and positions of cyclothem units according to Monninger (1979).

327 (C) Evolutive power spectral analysis of the lithofacies shown in Fig. 2B., with no results for the

328 lowest and highest parts of the log because of the moving window approach (i.e. half the window

329 size of 250 m).



330

331 Figure 3: Our three OxCal Bayesian age-depth models for the Tiout section. The integration of
 332 astrochronological information with the available U-Pb constraints (model A) makes the age
 333 estimate for the first occurrence of trilobites in southern Morocco more precise and a few hundred

334 thousand years younger compared to estimates solely based on U-Pb constraints coming from
335 volcanic zircons only (model B) and both volcanic and detrital zircons (model C). The depth scale
336 for model A is calculated in function of number of cycles and rescaled to the depth-m-scale for
337 plotting.

338

339 ¹Supplemental Material. [*Lithofacies log from Monniger 1979, time-series analyses script in R*
340 *and Oxcal age-depth model files*] Please visit <https://doi.org/10.1130/XXXX> to access the
341 supplemental material, and contact editing@geosociety.org with any questions.

342



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