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1 Earth's rotation and Earth-Moon distance in the Devonian derived from multiple geological records

2

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12

13 Abstract

14 Astronomical insolation forcing plays an important role in pacing Earth's climate history, including
15 paleoclimate dynamics, and its imprint can be seen in various geoarchives. Its signature is often
16 evident through typical rhythmic patterns in sediments. The detailed study of those patterns led to a
17 better understanding of orbital climate forcing, while also providing more precise constraints on the
18 geological time scale. Due to the tidal evolution in the Earth-Moon system, the precession and
19 obliquity periods get shorter when going back in time while the main eccentricity 405 kyr period
20 remains stable. While several astrophysical models describe the evolution of the length of precession-
21 and obliquity cycles, few reliable and quantitative geological information from tidalites and
22 astrochronology are available.

23 To better constrain these key astronomical parameters in the distant past, we calculate precession
24 and obliquity properties for the Devonian (~420-360 million years before present) as reconstructed
25 from a suite of geological datasets. Our results show the period of precession to be 19.4-16.1 kyr, and
26 the dominant p+s3 obliquity period to be 29.50±0.46 long. These findings are compared with and
27 support the presence of oceanic tidal resonances at 300 and 540 Ma, as shown in the recent
28 AstroGeo22 model of the Earth-Moon evolution of (Farhat et al, 2022).

29

30 1. Introduction

31

32 Since the work of George Darwin (1879), it is known that due to the tidal interaction between the
33 Earth and the Moon, the rotation of the Earth slows down and the Moon moves away from Earth. This
34 phenomenon was first measured through ancient eclipses, and since 1969 with laser ranging on
35 reflectors deposited on the Moon by Apollo astronauts. The continuing distance escape rate is recently
36 3.83 cm/year (Williams and Boggs, 2016). The age of the Moon is now also well determined at 4.425
37 Ga, also thanks to the Apollo missions (e.g., Maurice et al., 2020). More than fifty years ago it was
38 realised that with the present tidal recession rate of the Moon, Darwin's tidal model leads to a collision
39 of the Moon with the Earth at about 1.5 Ga (Gerstenkorn, 1967), incompatible with the age of the
40 Moon. Since then, many works have been devoted to resolve this paradox. Until recently, no physical
41 model accounted for both the age of the Moon and the present Lunar recession rate (Daher et al.,
42 2021; Green et al., 2017; Tyler, 2021; Webb, 1980).

43 To overcome this issue, studies have often relied on empirical models fitted to the available geological
44 evidences (Berger and Loutre, 1994; Walker and Zahnle, 1986; Waltham, 2015). With the release of
45 the solution of Farhat et al. (2022) for the evolution of the Earth-Moon system, this situation has
46 changed. Their model is a physical model, following (Webb, 1980), but is improved through taking the
47 continental evolution over the most recent Ga into account, and including the transition to a global
48 ocean in the ancient eons. The Farhat et al. (2022) model has only two parameters, representing the
49 average depth of the ocean and a dissipation factor in the bottom of the ocean. With a proper
50 adjustment of these two parameters, their model (AstroGeo22)¹, gives a match to the present tidal
51 recession and the age of the Moon (Farhat et al., 2022), and also to most cyclostratigraphic data.
52 AstroGeo22 has the potential to become the standard of reference for the Earth-Moon evolution. Yet,
53 it is crucial to continue acquiring reliable geological data in order to confront AstroGeo22, and all
54 models, with geological evidence - especially in the most critical parts that correspond to oceanic tidal
55 resonances (Farhat et al., 2022). Recently, four additional points have been provided to be compared
56 to astronomical solutions, at 259, 455, 655, and 2465 Ma (Zhou et al., 2022), using the TimeOptMCMC
57 method of Meyers and Malinverno (2018). In the present work, we use a different cyclostratigraphic
58 method to derive an additional precession point at 400 Ma, a critical location for the validation of the
59 AstroGeo22 model and an additional data point for comparison with other models.

60 Cyclostratigraphy is an established part of integrated stratigraphy, utilizing the quasi-periodic
61 variations of precession, obliquity and eccentricity and their amplitudes as geochronometer (e.g.
62 Hilgen et al., 2015; Hinnov and Hilgen, 2012). This approach is based on the identification of

¹ <https://www.astrogeo.eu/>

63 Milankovitch cycles in the sedimentary record. Their principal components include long and short
64 eccentricity (405/~100 kyr), and their amplitude modulations (2.4 Myr, very long eccentricity); axial tilt
65 or obliquity (with a present period of about 41 kyr) and its amplitude modulation dominated by a 1.2
66 Myr cycle; as well as climatic precession (recently ~20 kyr, modulated by eccentricity). Orbital and
67 rotational solutions provide insolation properties for Earth's past and future. Geochronology can be
68 correlated to the solutions as 'astronomical tuning', allowing their application as a geochronometer.
69 Also, the parametrization of orbital solutions can be tested through comparison with geological data
70 (Lourens et al., 2001; Zeeden et al., 2013, 2014). Orbital solutions can be computed back back in time
71 (and also for the future) up to about 50 Ma (Laskar et al., 2011a, 2011b). Nevertheless, the 405 kyr
72 eccentricity component is especially stable through Earth history and can be used as a reference
73 chronometer for the determination of the past precession frequency of the Earth through the
74 sedimentary archive (Laskar et al., 2004).

75 For the reconstruction of astronomical properties, one may investigate the best suitable datasets
76 which are available. This is commonly done in Neogene reconstructions (Lourens et al., 2001; Meyers
77 and Malinverno, 2018; Zeeden et al., 2014, 2013), where relatively noise-free high-resolution data
78 featuring a visually clear expression of precession, obliquity and precession are available. Also for the
79 Paleoproterozoic, clearly expressed Milankovitch cycles have been reported (Lantink et al., 2022).
80 However, generally, deep marine records are sparse for times older than the recent ocean floor
81 (Middle Jurassic) (Ruddiman, 2001). When going back in time, such datasets with clear and visually
82 identifiable expression of Milankovitch cycles in outcrops become sparse or unavailable, and the need
83 to use also noisier datasets becomes apparent for times where no other datasets are available. For
84 this reason, we developed a new approach that enables the integration of relatively noisy geological
85 proxy records with a demonstrated orbital imprint for the calculation of the precession and obliquity
86 cycle periods, and the underlying precession constant k . We name this approach 'CTest', short for
87 consistency test between geological observations and astronomical constraints. Conceptually, this
88 approach requires confidence that neither noise nor distortions of frequency spectra through
89 sedimentary processes (e.g., Fischer et al., 1991) change the frequency ratio of astronomical climate
90 forcing. In our approach, we test the orbital imprint of multiple individual datasets for consistency,
91 and in this way we provide more confidence in unideal datasets, and aim to reduce uncertainty of k .
92 While in theory also assessment of the g_2 to g_5 and s_3 components is possible, the here analysed
93 datasets did not allow confined statements on their frequency. The g_2 - g_5 terms represent precession
94 of the perihelions for planets, and the s_3 term is related to precession of the orbital plane of Earth.
95 We determine the frequency of dominant precession and obliquity components, and also the
96 underlying precession constant p , with their respective uncertainty for the Devonian ca. 420-360

97 million years before present. Through analyses of eight (sub)datasets of similar age (Figs. 1, 2) we can
98 increase confidence through consistency of these datasets. Further, we increase precision through
99 calculating a combined probability.

100

101 **2. Datasets**

102 In this study, we use four published magnetic susceptibility records and divide these into eight sub-
103 datasets covering most of the Devonian (Da Silva et al., 2016, 2013; De Vleeschouwer et al., 2015; Pas
104 et al., 2018; Tab. 1; Figs 1, 2) and the interpretations of these in terms of Milankovitch insolation
105 forcing in the Devonian. The Lower Devonian records from the Prague Basin sedimentologically
106 represents the carbonate distal offshore facies, and are composed of hemipelagic clayey limestones
107 intercalated by submarine landslide deposits (synthesis in Da Silva et al., 2016, and references
108 therein). The Middle Devonian records from the Rhenish Basin (Baileux and La Thure) are mainly
109 composed of shallow-water carbonates deposited either within the ramp, the fore-reef or the
110 rimmed-shelf (Da Silva et al., 2013; Mabilie and Boulvain, 2008; Pas et al., 2017). The Upper Devonian
111 record from the Sullivan core (Illinois Basin, USA) is mainly composed of shales, siltstone and
112 calcareous shale deposited in deep-shelf environments (Pas et al., 2018, and references therein). All
113 these records were tested for diagenetic alteration, pointing to a good preservation of the primary
114 information versus secondary imprint (Da Silva et al., 2013, 2016, 2019; Pas et al., 2017).

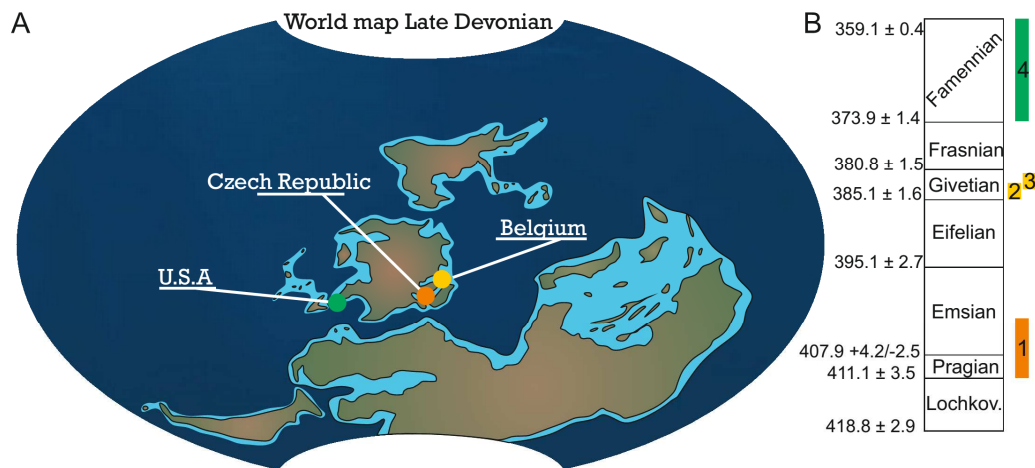
115 While all used datasets show a clear orbital imprint, and quasi-cyclic behavior at different frequencies
116 related to orbital climate forcing, it is possible that not all individual cycles are present in the datasets,
117 as intervals of low deposition/preservation may occur. Datasets and derived sedimentation rates are
118 consistent with biostratigraphical constraints. We regard our statistical assessment robust for
119 assessing the periodograms of the datasets, and do not see an issue with utilizing the shallow marine
120 possibly incomplete datasets. In this relatively shallow marine setting, not all outcrops/datasets
121 visually show obvious cyclicity. In such cases, one would not put heavy weight on individual datasets.
122 However, datasets are from different localities (Fig.1), making common systematic error unlikely. .
123 Although datasets are not from the exact same time interval, but from different stages within the
124 Devonian, we treat these as time-equivalent. This is to allow uncertainty propagation to establish a
125 reconstruction of Milankovitch forcing for the whole Devonian. This is motivated by the considerable
126 uncertainty of k reconstructions derived from individual datasets (Tab. 1, Fig., 4).

127 The aforementioned studies interpret frequency ranges as eccentricity, obliquity and most studies
128 also interpret climatic precession (Fig. 2). Here, we interpret the 405 kyr eccentricity cycle as identified

129 in the studied Devonian records as g2-g5, the interpreted short eccentricity frequency range related
 130 to the ~95-130 kyr as including the astronomical components g3-g2, g4-g2 (lower frequencies) and g4-
 131 g5, g3-g5 (higher frequencies). In cases where double peaks were found in the frequency range related
 132 to ~100 kyr eccentricity, interpretations regarding the lower vs. higher frequency eccentricity
 133 components in this interval (g3-g2, g4-g2/ g4-g5, g3-g5) were made in addition. The obliquity related
 134 peaks in the Devonian records are here interpreted as k+s3 component, because it is the dominant
 135 obliquity component (Laskar et al., 2004). The frequency ranges of climatic precession frequency were
 136 used from original studies, but in some cases more specific interpretations were made. These concern
 137 specifically which peaks in periodograms correspond to the low frequency component k+g5 (recently
 138 23.69 kyr duration), the medium frequency component k+g2 (recently 22.39 kyr duration) and short
 139 frequency components (combined k+g4, k+g5; recently 18.96 and 19.10 kyr duration) were made.
 140 Details of the Milankovitch interpretations of the Devonian dataset's periodograms are listed in
 141 Supplements.

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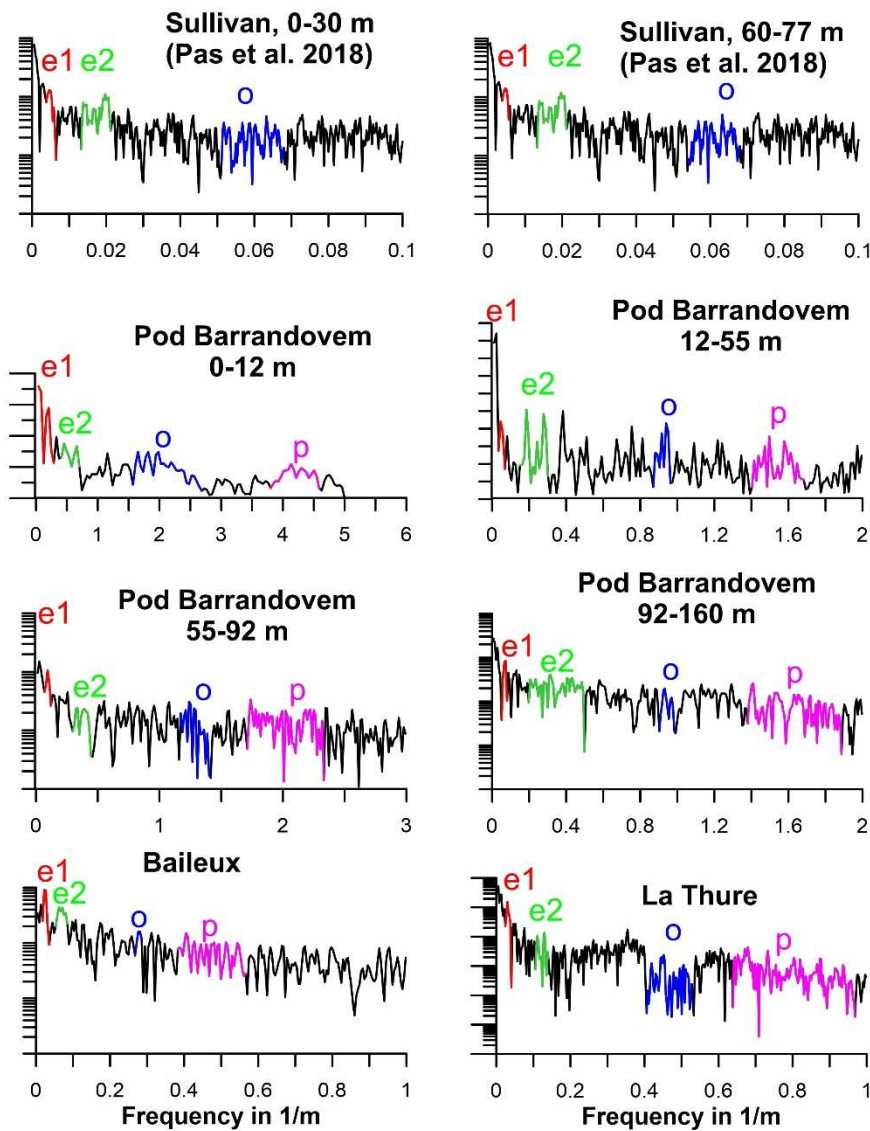


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145 Figure 1: A) Paleogeographic locations of magnetic susceptibility data used in this study (modified
 146 after De Vleeschouwer et al., 2017), and their respective intervals within the Devonian time scale (B,
 147 after De Vleeschouwer and Parnell, 2014). 1: dataset from Pod Barrandovem in the Czech Republic
 148 (Da Silva et al., 2016), 2 and 3 data from Baileux (Da Silva et al., 2013) and La Thure (De Vleeschouwer
 149 et al., 2015) in Belgium respectively, and 4 data from the Sullivan core in the US (Pas et al., 2018).

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153 Figure 2: Periodograms showing the frequency components of Devonian magnetic susceptibility
 154 datasets (abscissa) versus their power (ordinate) and their cyclostratigraphic interpretation based on
 155 original studies (Da Silva et al., 2016, 2013; De Vleeschouwer et al., 2015; Pas et al., 2018). The
 156 interpretation regarding the 405 kyr (e1, red) and the ~ 100 kyr eccentricity (94-131 kyr; e2, green)
 157 components, obliquity (o, blue) and precession components (p, magenta) is included as colour
 158 scheme. Note that the precession components were not interpreted in the Sullivan core (Pas et al.,
 159 2018).

160

161 3. Methods

162 We developed a method to extract orbital properties from geological datasets in the depth domain
 163 using five steps. Generally, the CTest approach relies on the identification of frequency ranges of
 164 eccentricity, obliquity and precession. Sedimentation rate is assessed based on the interpretation of

165 eccentricity peaks in periodograms. The CTest method samples orbital components: p, g- and s-
166 frequencies from Laskar et al., (2004), within specified bounds as outlined on the next paragraph.
167 CTest then tests if these orbital frequencies are consistent with frequency components from the
168 geological data and the interpretation of periodograms (Fig. 2). Geological data are interpreted in the
169 depth domain (and not on a tuned time scale) to avoid imposing orbital signals upon records through
170 frequency modulation (Huybers and Aharonson, 2010; Zeeden et al., 2019).

171 Initially, we (a) assess sedimentation rate based on eccentricity components only. In practice, this is
172 done through calculating maximum and minimum sedimentation rates consistent with the
173 interpretation of 405- and ~100 kyr eccentricity-related components. This sedimentation rate range is
174 resampled as an uniform distribution between minimum- and maximum possible values. Next, we (b)
175 resample the deposition time (age of the deposit in Ma) from a uniform distribution between
176 conservative estimates for minimum and maximum age. Following, we (c) resample the precession
177 constant (Laskar et al., 2004) with high uncertainty from a uniform distribution, for the Devonian we
178 used very large boundaries of 10,000 to 26,000 years. For the data from the Walvis Ridge (~55 Ma)
179 and Xiamaling formation (~1400 Ma) ranges of k are set to 5,000 – 26,000 years and 18,000 – 30,000
180 years, respectively. These were set in a range which is clearly wider than a realistic range for k, to
181 avoid imposing result through choice of the initial k to be tested. In the next step, we (d) sample g2-
182 g5 and s3 frequencies. The uncertainty is sampled as normal distribution with standard deviation as a
183 linear extrapolation of the uncertainty given in Laskar et al., (2011a) (their Tab. 6). Next, we (e) test
184 the consistency of the sampled astronomical parameters and sedimentation rate with observed cycles
185 and their interpreted frequency range. If consistent, parameters are saved, otherwise discarded. This
186 procedure was repeated until 1000 consistent results were generated for every data(sub)set. A
187 combined Devonian probability is calculated as multiplication of the probability density distributions
188 from all datasets. The method thus provides zero probability for values inconsistent with any given
189 dataset. An R function, R scripts and an extended documentation for reproducing all experiments are
190 available as supplementary information.

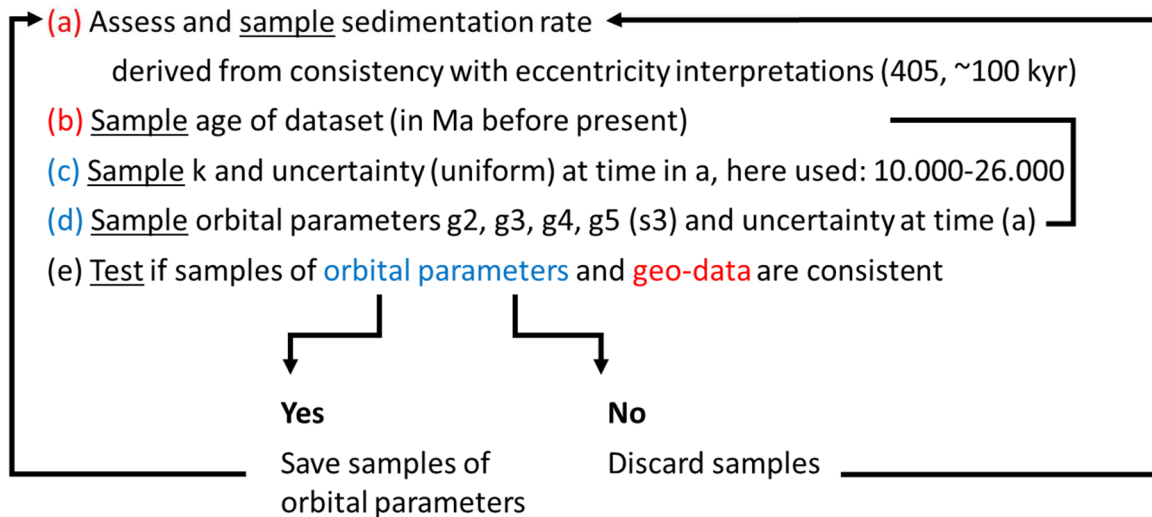
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Geological data

Dataset of stratigraphy, age
 Periodogram thereof
 Interpretation of peaks as relating to astronomical cycles

Astronomical parameters

k, g2, g3, g4, g5, s3
 Uncertainty: estimated (k) and extrapolated from models (g2, g3, g4, g5, s3)



Repeat sampling, until e.g., 1000 successful samples have been drawn
 Combine probabilities – here by multiplication of individual probabilities

194 Figure 3: Schematic summary of the CTest approach deriving orbital components k, g2, g3, g4, g5, and
 195 s3, where s3 is only derived if an obliquity component is analysed. Note that the uncertainty for k is
 196 sampled as a uniform distribution, whereas uncertainty for k, g2, g3, g4, g5, and s3 is taken and
 197 extrapolated from (Laskar et al., 2011a). Red text highlights steps using geological data, blue text
 198 represents steps done using astronomical theoretical parameters.

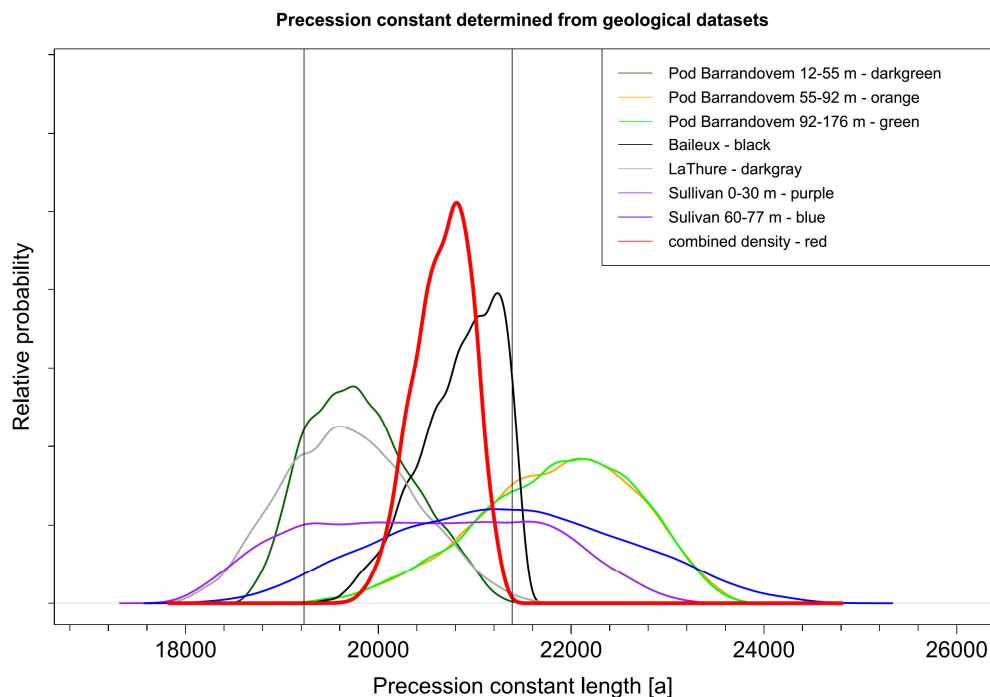
200 **4. Results: Devonian Milankovitch cycle durations**

201 To independently test our approach, we applied the CTest method to the Eocene deep sea a* record
 202 of the Walvis Ridge (Zachos, 2004), and the ca. 1.4 Ga Xiamaling Formation (Zhang et al., 2015). These
 203 datasets were previously analysed in Meyers and Malinverno (2018) using a Bayesian optimisation
 204 approach. Results obtained with our CTest method are consistent with the results obtained in Meyers
 205 and Malinverno (2018), but CTest retains higher uncertainty in sedimentation rate (vs. optimisation;
 206 see Tab. 1).

207 Testing of a clear precession amplitude relationship with eccentricity led to significant (at >80%
 208 confidence using the (Baddouh et al., 2016; Ebisuzaki, 1997) approach for testing significance as
 209 implemented in the 'surrogateCor' {astrochron} function (Meyers, 2014)) results for most Devonian
 210 datasets showing precession in the depth domain. The lowermost part of the Pod Barrandovem (0-12
 211 m) dataset failed such a test. Therefore, the CTest results of this dataset are reported, but not
 212 considered in a combined Devonian estimate (Fig. 4).

213 The CTest results from all individually Devonian datasets analysed here give consistent durations for
 214 precession, obliquity and the underlying precession constant. Figure 4 shows the probability density
 215 distributions from all investigated datasets; Tab. 1 summarizes the results. When combining the
 216 results from multiple datasets through consideration of shared probability, uncertainty can be
 217 reduced, as demonstrated in this study through the more confined combined uncertainty of k (Fig. 4,
 218 Tab.1). Here we calculate the obliquity length in the Devonian (~400 Ma) to be 28.79 ± 0.49 kyr (recent:
 219 40.98 kyr). The long (p+g5), intermediate (p+g2) and short precession components (here: combined
 220 p+g3, p+g4) are estimated to have been 19.00 ± 0.45 kyr (recent: 23.67 kyr), 18.16 ± 0.41 kyr (recent:
 221 22.36 kyr), and 15.91 ± 0.38 (recent: 19.10, 18.94) kyr in duration, respectively. The precession constant
 222 is determined at 20.3 ± 0.25 kyr (recently 25.68 kyr). If considering the mean of all k reconstructions
 223 (also inconsistent with other datasets), k is calculated to 21.01 ± 1.19 kyr.

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226 Fig. 4: Reconstructed precession constant (p) from seven Devonian datasets where relative probability
 227 (ordinate) is plotted versus the duration of the precession constant in years (abscissa). The bottom
 228 part of the Pod Barrandovem dataset (0-12 m) was not considered because it does not show
 229 statistically significant precession- or short eccentric amplitude variations. The combined probability
 230 is plotted in red, vertical lines indicate the boundaries of shared values for the precession length of all
 231 datasets. The resulting precession constant k is calculated to 20.70 ± 0.22 kyr using the
 232 abovementioned uncertainty assessment.

233

234 Table 1: Reconstructed precession constant (p), precession- and obliquity periods for eight Devonian
 235 (sub)datasets (first 8 rows), a Devonian synthesis, and several reference data. Note that data from the
 236 0-12m interval from Pod Barrandovem are not included in the Devonian synthesis, and that data from
 237 the Sullivan core (Pas et al., 2018) do not reliably record precession but allow reconstruction of
 238 obliquity. Uncertainty is given as 1-sigma here. Data from models and literature are marked bold, the
 239 remaining data were derived using the CTest method.

Data	Age in Ma	p [kyr]	p+g5 [kyr]	p+g2 [kyr]	p+g4 [kyr]	p+g3 [kyr]	p+s3 [kyr]
Pod Barrandovem, 0-12m	~408-411	18.53±0.67	17.47±0.60	16.74±0.55	14.87±0.46	14.85±0.45	25.39±1.27
Pod Barrandovem, 12-55m	~407-409	19.82±0.54	18.60±0.48	17.79±0.43	15.63±0.37	15.64±0.39	27.85±1.07
Pod Barrandovem, 55-92m	~405-407	21.85±0.83	20.39±0.72	19.41±0.65	16.77±0.53	16.83±0.53	32.07±1.77
Pod Barrandovem, 92-160m	~403-406	21.85±0.83	20.39±0.72	19.41±0.65	16.77±0.53	16.83±0.54	32.06±1.77
Baileux	~386-390	20.85±0.42	19.52±0.37	18.62±0.33	16.16±0.27	16.19±0.27	29.94±0.86
La Thure	~370-400	19.69±0.68	18.50±0.60	17.69±0.55	15.50±0.47	15.51±0.46	27.62±1.33
Sullivan core, 0-30 m	~365-373	21.54±1.48	-	-	-	-	31.48±3.16
Sullivan core, 60m-top	~359-368	21.33±1.21	-	-	-	-	30.98±2.56
combined Devonian	~359-411	20.70±0.22	19.35±0.20	18.47±0.18	16.13±0.23	16.18±0.16	29.50±0.46
La2004 model, Devonian	385	20.29	19.02	18.17	15.95	15.85	27.78
Farhat et al., 2022 model	385	21.2	19.82	18.89	16.39	16.51	30.64
Berger & Loutre 1994	385	21.98	20.5	19.51	16.86	16.98	32.31
Eocene WR	~55	25.88±1.01	23.85±0.86	22.52±0.76	19.06±0.56	19.20±0.56	-

Xiamaling formation	~1400	15.76±1.32	14.98±1.20	14.44±1.11	12.95±0.94	12.99±0.94	-
La2004 model, used as test	0	25.37	23.42	22.14	18.79	18.92	40.25
La2004 model, recent	0	25.68	23.68	22.37	18.95	19.10	40.98

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5. Discussion

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The CTest approach combines cyclostratigraphic data, statistics and astronomical theory to improve our understanding of Earth's rotation history. This method is especially powerful when information from several datasets is combined. Several previous studies have provided reconstructions (e.g., Bond et al., 1991; Fang et al., 2016; Hinnov, 2013; Lantink et al., 2022; Lourens et al., 2001; Meyers and Malinverno, 2018; Williams, 1991; Wu et al., 2018, 2013; Zeeden et al., 2014; Zhou et al., 2022) (e.g. Bond et al., 1991; Fang et al., 2016; Hinnov, 2013; Williams, 1991; Wu et al., 2018, 2013) of the precession constant from geological archives influenced by Milankovitch forcing, and also using the interpretation of tidal rhythmites (tidalites). It should be noted that the analysis of tidalites and bioarchives is undoubtedly valuable. Yet (as for astrochronology) it is depending on the correct interpretation of tidal cycles as such, leaving space for re-interpretation and bias (de Winter et al., 2020; Heubeck et al., 2016; Meyers and Malinverno, 2018; Williams, 1989). The completeness of the deposits is difficult to prove, and relatively little experience exists with such datasets. Further, usually only one or few tidal cycles are preserved consecutively, making statistical analyses challenging. .

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The CTest approach does not the use of datasets with a clear, and possibly even visually present, astronomical forcing. Instead, it requires datasets showing spectral properties related to eccentricity, obliquity and possibly precession. CTest can use either the expression of obliquity, precession, or both, to determine p. One may argue that unideal datasets are likely noisy in both proxy data and sedimentation rate, as can be seen in evolutive harmonic analyses of datasets in (Da Silva et al., 2016; Pas et al., 2018). Sedimentary noise has the potential to change (frequency) properties of insolation, and can be expected in shallow marine strata due to changing base level, complex sedimentation processes, and possible reworking by wave action in some environments. Therefore, we interpreted the frequency range especially of precession rather wide. In our opinion, noise makes the detailed interpretation of individual datasets especially from the shallow marine realm challenging, but consistent findings in multiple datasets provides confidence allowing interpretations. The clearer and certain the orbital origin of quasi-regular cycles in a dataset, the more robust results will be. In

269 addition, the more independent constraints on sedimentation rate and on completeness exist, the
270 better. These may come from detailed sedimentological analyses, and dating from e.g., magneto- or
271 bio-stratigraphy. One may argue that deriving information from one such dataset may lead to
272 misinterpretation. Yet, in absence of more suitable datasets with clearly visible cycles and cycle
273 amplitudes of precession/eccentricity and/or short eccentricity/long eccentricity origin, and the
274 analyses of multiple datasets, we regard our approach useful. At the same time we advocate for
275 preferentially utilizing highest quality datasets, and analysing these using both visual (Lantink et al.,
276 2022) and quantitative methods (as CTest and timeOptMCMC; Meyers and Malinverno, 2018).
277 Generally, we argue that a dataset should have such an amplitude relationship to be used for
278 reconstructing astronomical properties, because these are strong arguments for a real imprint of
279 Milankovitch cycles (Meyers, 2015; Meyers and Malinverno, 2018; Shackleton et al., 1995; Zeeden et
280 al., 2019, 2015). Using amplitude relationships as argument for a forcing by Milankovitch cycles also
281 avoids challenges related to frequency spectra and their significance tests.

282 To evaluate CTest, we have reconstructed the results provided by Meyers and Malinverno, (2018; see
283 Tab. 1) using CTest. CTest results in a higher degree of uncertainty, due to the inclusion of higher
284 uncertainty in the sedimentation rate and the retention of wider spread of sedimentation rates in the
285 results, e.g., for the Xiamaling Formation a range of 0.25 to 0.44 cm/kyr (vs. ~ 0.33 to ~ 0.38 from the
286 TimeOptMCMC approach). Although within uncertainty, our approach leads to longer climatic
287 precession cycles in the Proterozoic than Meyers and Malinverno, (2018). This is due to the strict
288 interpretation of the precession components in our case (Supplementary Fig. 2), and vanishes if the
289 same upper/lower limits for all precession components are used.

290 While the TimeOptMCMC uses a combination of spectral properties and amplitude relationships of
291 precession and eccentricity, our method also utilizes and provides results for the obliquity component.
292 Obliquity is longer than precession (obliquity is recently ~ 41 kyr, while precession has several
293 components around 20 kyr; Tab.1) which may be regarded as potentially less impacted by high-
294 frequency noise and/or too low sedimentation rate to detect precession-scale cycles throughout a
295 record. A further difference between the two approaches is that the TimeOpt MCMC method
296 represents a search for a combined optimisation of sedimentation rate as well as the g1-g5 and k
297 components to fit geological and astronomical data, while our approach only searches for consistency
298 between astronomical and geological data. As one may expect, the search for consistency allows for
299 a larger spread in results than an optimisation of the fit.

300 In our opinion, the application of CTest here is not prone to bias of an individual record, because
301 several datasets from different settings and continents provide consistent results, even though

302 individual datasets may be difficult to interpret alone. The considered data in this study are from
303 rather shallow marine strata on the shelf. In such settings, one may argue that high-frequency
304 oscillations may not be recorded and preserved as good as lower frequency components, and that
305 longer cycles – or cycles deposited as rather thick – have higher preservation potential. It was shown
306 in a modelling study (Fischer et al., 1991) that this may lead to a bias towards the lower frequency
307 components especially of precession, which may result in rather long precession estimates from our
308 study.. This seems not an issue in our case, because the contrary is found: our estimate is on the short
309 end of precession cycle length reported for the time interval (Fig. 5), and high-frequency cycles are in
310 average not longer than expected by theory and orbital forcing. Further, we include both obliquity-
311 and precession components in our interpretation. Misinterpretations of either obliquity or precession
312 components within a dataset would lead to inconsistent k determinations and no possible k
313 reconstruction. Different interpretations of the frequency components related to precession and
314 obliquity would result in inconsistency between individual datasets.

315 Our measures for Devonian Milankovitch periods are in average shorter than predicted by the
316 empirical model of Berger & Loutre, (1994) (Fig. 5, black dashed curve), and closer to an extrapolation
317 of the astronomical solution of Laskar et al., (2004) (Fig. 5, dotted red curve). Nevertheless, it is
318 acknowledged that the La2004 tidal model cannot be used for extended time. Indeed, as it is based
319 on a body tide model that is adjusted to the present tidal recession of the Moon, it would lead to a
320 collision of the Moon and the Earth in less than 2 Ga ago, as other models including the (Walker and
321 Zahnle, 1986) model. Interestingly, our present estimate of the precession frequency in the Devonian
322 is in agreement with the recent physical model AstroGeo22 of (Farhat et al., 2022; Fig. 5). This model
323 takes the possible oceanic resonances that enhance the tidal dissipative torque (Farhat et al., 2022)
324 into account, which occur when the tidal frequency related to the spin of the Earth is close to the
325 internal oceanic proper frequencies. In AstroGeo22, such resonances occur around 300 and 540 Ma
326 (Farhat et al., 2022; their Fig. 4). The resulting effects are high slopes in the precession frequency
327 variations, and a staircase shape at ~ 0.5 - 0.3 Ga (Fig. 5). Our Devonian geological data point is thus
328 critical to validate or challenge this staircase shape of the precession variation, related to the
329 amplitude of the oceanic tidal resonances. The cyclostratigraphic determination of the precession
330 frequency in Zhong et al., (2020) at 445 Ma is not compatible with AstroGeo22, while the recent
331 determination in Zhou et al., (2022) at 455 Ma is in agreement with AstroGeo22. The present
332 determination of the precession frequency for the Devonian represents crucial evidence of the
333 occurrence of the oceanic resonances in geological data – here at 300 and 540 Ma (Fig. 5). The
334 available data - including ours - implies that few data points (and missing ones for times of oceanic
335 resonances) reconstructing the Earth-Moon history, and an interpolation of these, may lead to a

336 simplified, and for some time intervals incorrect, planetary history because interpolation over longer
337 times can miss resonances. Specifically, our study implies that for cyclostratigraphical and
338 paleoclimatic studies the Farhat et al., (2022) tidal Earth-Moon evolution is capturing details of
339 precession evolution, and their history of the Earth-moon distance should be preferred over earlier
340 simple models. Our results further underline that the tidal dissipation was unexpectedly low during
341 the Devonian, and the Farhat et al. (2022) model implies that this was followed by a period of large
342 tidal dissipation during the Carboniferous, corresponding to the crossing of an oceanic tidal resonance.
343 When comparing Farhat et al.'s (2022) model with the available geological data, the correspondence
344 with the past rotation state provided by geological evidence is striking, also for our data point which
345 would be considered challenging to explain in the context of the available geological data, which
346 points to a longer precession period (Fig. 5). The Farhat et al., (2022) model is also consistent with
347 the recent determinations of the past precession period of the Earth based on cyclostratigraphy
348 (Huang et al., 2020; Lantink et al., 2022; Meyers and Malinverno, 2018; Sørensen et al., 2020).
349 Consequently, we consider that the (Zhong et al., 2020) determination of the precession period at 455
350 Ma is challenging and worth testing. We suggest to establish multiple determinations of k for any
351 Geological time from different (paleo)localities. Reliable and precise cyclostratigraphic determinations
352 of precession and obliquity length in the Paleozoic Era, and specifically in the Devonian and
353 Carboniferous Periods, are of crucial importance to fully validate – or challenge – the results of this
354 study and the new tidal model of Farhat et al., (2022), and are expected to help better understand
355 the amplitude effect of tidal resonances.

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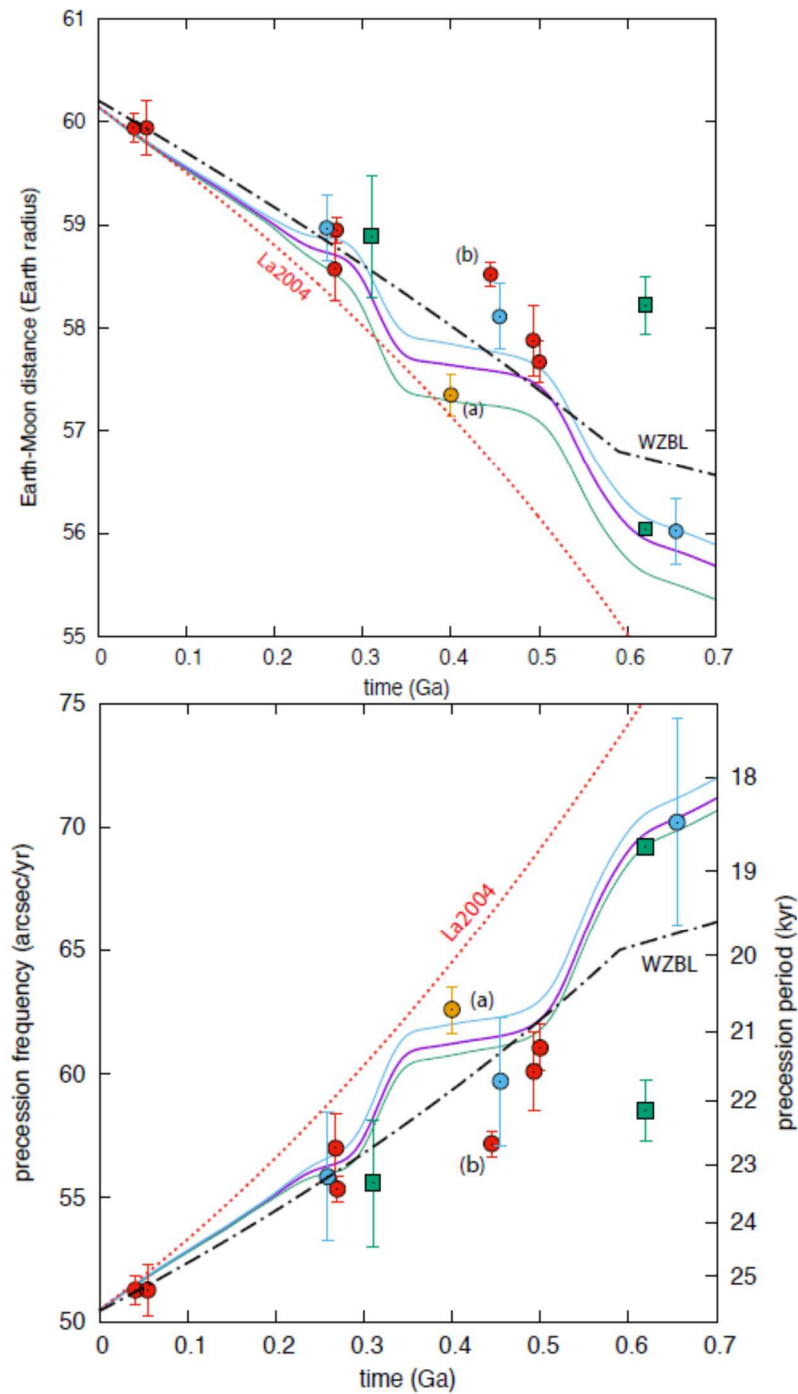


Fig. 5: Precession frequency (in

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arcsec/yr and as precession period; bottom) and Earth-Moon distance (in Earth radius; top) over the last 700 Ma. The yellow data point comes from this study. The solutions for Earth-Moon distance and precession of La2004 are taken both from Laskar et al, (2004). As they do not correspond to the tidal model of Farhat et al., (2022) the transfer of the precession curve of La2004 through the tidal model of Farhat et al, 2022 do not correspond to the precession curve of La2004., with uncertainty given by the blue and green side curves. The dotted red curve is extrapolated from the La2004 solution (Laskar et al., 2004; their eqs 39 and 40). The dashed black curve (WZBL) is the empirical model of (Berger and Loutre, 1994; Walker and Zahnle, 1986). The green square markers are obtained from tidal rhythmites

366 (Sonett and Chan, 1998; Williams, 1997, 2000). The red dots are obtained from cyclostratigraphic
367 analysis (De Vleeschouwer et al., 2023; Fang et al., 2020; Huang et al., 2020; Meyers and Malinverno,
368 2018; Sørensen et al., 2020; Zhong et al., 2020). The blue dots represent cyclostratigraphic data from
369 (Zhou et al., 2022). The red data point (b) in this figure by Zhong et al., (2020) is off the AstroGeo22
370 curve, but it should be noted that both the (Zhou et al., 2022; blue) and the data resulting from the
371 present study (a) are in good agreement with AstroGeo22. The passage from precession frequency to
372 Earth-Moon distance has been realized by interpolation using the nominal AstroGeo22 solution for all
373 data points except for the blue points of (Zhou et al., 2022), who provide Earth-Moon distance values
374 and associated uncertainties in their paper.

375

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