

1 **A Late Cretaceous-Eocene Geomagnetic Polarity Time Scale (MQSD20)**
2 **that steadies spreading rates on multiple mid-ocean ridge flanks**
3

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18 **Key Points:**

- 19 • Estimated magnetic polarity block model distances over 13 ridge flank regions (Indian
20 Ocean, S. and N. Pacific, S. Atlantic).
- 21 • Constructed a GPTS for chrons C33-C13 that minimizes global spreading rate variations
22 and fits radioisotopic dates.
- 23 • At ~47 Ma, spreading rates decrease in the Indian Ocean (India-Eurasia collision) and
24 increase in the N. Pacific (Hawaii-Emperor bend).
25

26 **Abstract**

27 Magnetic anomalies over mid-ocean ridge flanks record the history of geomagnetic field
28 reversals, and the width of magnetized crustal blocks can be combined with absolute dates to
29 generate a Geomagnetic Polarity Time Scale (GPTS). We update here the current GPTS for the
30 Late Cretaceous-Eocene (chrons C33-C13, ~84-33 Ma) by extending to several spreading centers
31 the analysis that originally assumed smoothly varying spreading rates in the South Atlantic. We
32 assembled magnetic anomaly tracks from the southern Pacific (23 ship tracks), the northern
33 Pacific (35), the southern Atlantic (33), and the Indian Ocean (55). Tracks were projected onto
34 plate tectonic flow line, and distances to magnetic polarity block boundaries were estimated by
35 fitting measured magnetic anomalies with a Monte Carlo algorithm that iteratively changed
36 block model distances and anomaly skewness angles. Distance data from each track were then
37 assembled in summary sets of block model distances over 13 ridge flank regions. We obtained a
38 final MQSD20 GPTS with another Monte Carlo algorithm that iteratively perturbs ages of
39 polarity chron boundaries to minimize the variability of spreading rates over all ridge flanks and
40 fit an up-to-date set of radioisotopic dates. The MQSD20 GPTS highlights a major plate motion
41 change at ~47 Ma, when spreading rates decreased in the Indian Ocean as India collided with
42 Eurasia while spreading rates increased in the South Atlantic and Northern Pacific and the
43 Hawaii-Emperor seamount chain changed its orientation.

44

45 **Plain Language Summary**

46 As the Earth's magnetic field reversed its polarity during geological time, seafloor spreading
47 created a series of magnetized blocks on mid-ocean ridge flanks that give rise to magnetic
48 anomalies, field highs and lows measured by survey ships. These reversal records are combined
49 with age ties from radioisotopic dating to construct a Geomagnetic Polarity Time Scale (GPTS)
50 that lists the ages of magnetic field reversals. Our study updates the GPTS in the Late
51 Cretaceous-Eocene (~84-33 million years ago) by minimizing the variation of spreading rates in
52 the southern Atlantic, Indian, southern and northern Pacific Oceans using an up-to-date set of
53 154 ship tracks. By providing independent age information, the new GPTS will aid the
54 developing discipline of astrochronology, which is based on the correlation of sediment cycles
55 with astronomical cycles in the Earth's orbit and spin axis orientation. The new GPTS also
56 refines the global history of spreading rates and highlights a major change at about 47 million
57 years ago. At that time, seafloor spreading in the Indian Ocean slowed down as India collided
58 with Eurasia while spreading became faster in the northern Pacific, coinciding with a bend in the
59 orientation of the Hawaii-Emperor seamount chain.

60 **1 Introduction**

61 1.1 Background

62 Accurate time scales are crucial to establish the history of tectonic plate motion and to
63 determine past rates of change documented in the rock record. Magnetic measurements and
64 radioisotopic dating of volcanic rocks led to the discovery of globally synchronous reversals of
65 the Earth's magnetic field (see the historical overview of Glen, 1982). The history of these
66 reversals was recorded by magnetic anomalies created by seafloor spreading on mid-ocean ridge
67 flanks, allowing for the development of a geomagnetic polarity time scale (GPTS; acronyms
68 used in this paper are listed in Table 1).

69
70
71**Table 1.** List of acronyms.

Acronym	Definition
BMD	Magnetic polarity block model distance
CAPANT	Capricorn-Antarctica plate boundary
CAPSOM	Capricorn-Somalia plate boundary
CK95	GPTS of Cande & Kent (1992, 1995)
CV	Coefficient of variation (standard deviation/mean)
GPTS	Geomagnetic polarity time scale
GTS12	GPTS in Geological Time Scale 2012 (Gradstein et al., 2012)
MCMC	Markov chain Monte Carlo
MQSD20	GPTS of this paper
PACANT	Pacific-Antarctica plate boundary
PACBAN	Pacific-Bellingshausen-Antarctica plate boundary
PACFAR	Pacific-Farallon plate boundary
PACFAV	Pacific-Farallon-Vancouver plate boundary
PACVAN	Pacific-Vancouver plate boundary
SAMAFR	South America-Africa (Nubia) plate boundary

72

73 The first GPTS was based on the C-sequence (Late Cretaceous-present) magnetic
74 anomalies in the South Atlantic with the assumption of a constant spreading rate determined by a
75 single age tie at 3.35 Ma (Heirtzler et al., 1968). Cande and Kent (1992, 1995) derived an
76 improved CK95 GPTS for the last 83 Ma that accounted for long-term variations in spreading
77 rate. CK95 was based on a reference South Atlantic plate tectonic flow line defined by a detailed
78 set of finite plate rotations (Cande et al., 1988). The finite rotations provided nine key magnetic
79 polarity block model distances (BMDs); more detail was inserted from the relative widths of
80 polarity blocks representative of uniform seafloor spreading in the South Atlantic and in faster
81 spreading ridges of the North Pacific and Central Indian Oceans. The CK95 GPTS was obtained
82 by interpolating BMDs between nine radioisotopic dates with a cubic spline, thus ensuring a
83 smooth temporal variation in South Atlantic spreading rates. The South Atlantic BMDs of CK95
84 have been the key source of information from marine magnetic anomalies for time scale
85 development over more than two decades, and have been repeatedly used to construct GPTSs
86 with different age constraints (e.g., Ogg & Smith, 2004; Vandenberghe et al., 2012; Wei, 1995).

87 The last few decades also saw the development of astrochronology, based on sediment
88 cycles that record Milankovitch periodicities in the Earth's orbit and the orientation of its spin
89 axis (Hinnov & Hilgen, 2012). In the Neogene portion of the most recent GTS12 GPTS (Hilgen
90 et al., 2012), information from marine magnetic anomalies has been mostly replaced by
91 astronomical dating of sedimentary sections with a reliable magnetostratigraphy.

92 Astronomical dating of older intervals, however, is more challenging, and the marine
93 magnetic anomaly record remains an independent source of information for time scale
94 development. For example, in the Paleogene the GTS12 GPTS uses a combination of
95 astrochronology (66-53 Ma and 37-23 Ma) and a GPTS based on the CK95 BMDs (53-37 Ma),
96 and there are significant discrepancies in the Eocene and Paleocene (Vandenberghe et al., 2012).
97 Many astrochronology studies used the CK95 GPTS to initially match sedimentary cycles with

98 astronomical periods (Herbert et al., 1995; Röhl et al., 2003), to decide between alternative
99 tuning options (Röhl et al., 2003), to estimate the duration of hiatuses (Pälike et al., 2001), to
100 provide age constraints to floating time scales (Jovane et al., 2010), and to compare ages and
101 durations of magnetic polarity chrons (Billups et al., 2004; Herbert et al., 1995; Husson et al.,
102 2011; Westerhold et al., 2007, 2008, 2017).

103 1.2 Updating late Cretaceous-Eocene BMDs and GPTS

104 The two objectives of our work are 1) to generate a global set of BMDs obtained
105 independently over a number of spreading centers and 2) to construct an updated GPTS that
106 minimizes global spreading rate variations. The global record of magnetic anomalies has grown
107 since it was analyzed by Cande and Kent (1992), and detailed finite plate rotations have been
108 determined over a number of spreading centers besides the South Atlantic. We examine here a
109 large data set of 154 marine magnetic anomaly ship tracks projected onto plate tectonic flow
110 lines computed from finite rotations. The resulting up-to-date global BMDs will inform
111 astrochronology interpretations and constrain GPTS construction.

112 A drawback of the CK95 GPTS is that the calculated spreading rates in other ocean
113 basins vary more erratically than in the South Atlantic (e.g., Figure 42 of Cande & Kent, 1992).
114 Huestis and Acton (1997) pointed out that there is no reason to expect that spreading rates
115 change smoothly at one particular location while they are more variable at all other ridges. They
116 argued for a “least favoritism” approach where a GPTS is constructed by minimizing the
117 variation in spreading rates in all the magnetic anomaly profiles examined. Independent
118 astronomical dating supports this suggestion: Wilson (1993) and Krijgsman et al. (1999) found
119 that the spreading rates implied by astrochronology in the last ~10 Ma were less variable than
120 rates computed from the CK95 GPTS. Astronomical age control steadies the spreading rates (see
121 also Baksi, 1994; Gordon, 1993; Langereis et al., 1994), indicating that minimizing spreading
122 rate fluctuations over several spreading centers will provide a more reliable GPTS.

123 We concentrate here on the late Cretaceous-Eocene (chrons C33-C13, ~84-33 Ma), which
124 is the interval where the CK95 GPTS is most uncertain. Cande and Kent (Cande & Kent, 1992 p.
125 13,947-48) recognized that the “largest uncertainties in our new time scale are probably for the
126 anomaly spacings in the late Cretaceous and early Cenozoic. This corresponds to the time
127 interval of the most rapid change in spreading rate [...] in the South Atlantic [...] when there is
128 the most potential for error.” This time interval is also of great interest in paleoenvironmental
129 studies, as it records a long-term warming trend in the Paleocene, a sudden warming event at the
130 Paleocene-Eocene thermal maximum followed by a series of hyperthermals, the greatest
131 Cenozoic warmth in the Early Eocene, and the onset of the cooling trend that resulted in the
132 formation of the Antarctic ice sheets at the Eocene/Oligocene boundary (Vandenbergh et al.,
133 2012; Zachos et al., 2001, 2008). An accurate time scale is critical to advance our understanding
134 of these climatic changes. As noted earlier, astronomical calibration of the Late Cretaceous-
135 Eocene is still in flux, and an updated GPTS would be most useful to constrain time scale
136 development in this critical interval.

137 The GPTS we generate uses only an up-to-date set of radioisotopic dates and includes no
138 astrochronological constraints. Our goal is to provide independent information to
139 astrochronology that can help resolve time scale inconsistencies, for example around chrons C23
140 (Vandenbergh et al., 2012; Westerhold et al., 2017) and C28 (Hilgen et al., 2010; Westerhold et

141 al., 2008). A GPTS that fully integrates information from the global marine magnetic anomaly
 142 record, radioisotopic dates, and astrochronology will be a future development.

143 In this paper, we first introduce the Monte Carlo procedure applied to obtain BMDs that
 144 match measured magnetic anomalies and a GPTS that fits radioisotopic dates and minimizes
 145 global spreading rate variations. We then describe the fundamental data used here for GPTS
 146 construction: BMDs obtained over 13 mid-ocean ridge flank regions and radioisotopic dates tied
 147 to magnetostratigraphy. A new MQSD20 GPTS is constructed following the approach previously
 148 applied by Malinverno et al. (2012) to the M-sequence magnetic anomalies (Late Jurassic-Early
 149 Cretaceous). We conclude by comparing the ages and chron durations in MQSD20 with those in
 150 existing GPTSs, exploring the impact of the newly obtained BMDs on testing astrochronology
 151 interpretations, and describing a global change in spreading rates at ~47 Ma, when India collided
 152 with Eurasia and the Hawaii-Emperor seamount chain changed its orientation.

153 1.3 Nomenclature

154 We use here the CK95 sequence of chrons to define a series of magnetic polarity crustal
 155 blocks that recorded field reversals, and do not consider magnetic field excursions such as tiny
 156 wiggles (Cande & Kent, 1992). Following general nomenclature (Gee & Kent, 2007; Opdyke &
 157 Channell, 1996), C-sequence magnetic anomalies are named 13n, 13r, etc., and the
 158 corresponding polarity chrons are C13n, C13r, etc. Magnetic polarity is denoted by “n” for
 159 normal and “r” for reversed. Boundaries of magnetic polarity blocks and chrons are denoted by
 160 appending “y” for the young boundary and “o” for the old (e.g., C13ny is the young end of chron
 161 C13n). We denote years of age as “a” and years of duration as “yr,” with the usual prefixes (e.g.,
 162 1 Ma = 1 million years ago). We report uncertainties as one or two standard deviations (1σ or
 163 2σ , respectively).

164 2 Markov chain Monte Carlo sampling

165 To determine best values and uncertainties of BMDs estimated from ship track magnetic
 166 anomalies and of a GPTS that minimizes the global variation of spreading rates, we use here a
 167 Markov chain Monte Carlo (MCMC) algorithm (Brooks et al., 2011; Gilks et al., 1996). The
 168 algorithm asymptotically generates a sample of model parameter vectors \mathbf{m} (e.g., distances to
 169 polarity block boundaries) that are distributed as in a target probability density function (PDF).
 170 We follow a Bayesian formulation, where the target distribution is a posterior PDF proportional
 171 to the product of a prior PDF $p(\mathbf{m})$ that quantifies prior information on the parameters and a
 172 likelihood function $p(\mathbf{d}|\mathbf{m})$ that quantifies how closely the measured data in a vector \mathbf{d} (e.g.,
 173 magnetic anomalies) are fitted by data predicted by the parameters in \mathbf{m} . The posterior PDF is
 174 given by Bayes’ rule as

$$175 \quad p(\mathbf{m}|\mathbf{d}) = k p(\mathbf{m}) p(\mathbf{d}|\mathbf{m}), \quad (1)$$

176 where k is a normalizing constant. In our application, the parameter vector \mathbf{m} also contains
 177 “hyperparameters,” which are additional variables that affect the solution and are not closely
 178 constrained a priori (Gelman et al., 2004; Malinverno & Briggs, 2004). An example is the
 179 variance of the misfit between predicted and measured data, which is needed to define the
 180 likelihood function but is not known beforehand.

181 We apply here the Metropolis-Hastings MCMC algorithm (Chib & Greenberg, 1995;
 182 Metropolis et al., 1953), which performs a random walk in the space of the parameter vector \mathbf{m} .
 183 The algorithm first proposes a candidate parameter vector \mathbf{m}^* that is a small perturbation on the

184 current value of the parameters. The construction of candidate parameter vectors needs to
 185 perform a random walk that can go from any point to any other point in the space of the
 186 parameters. At each step of the random walk, the proposed candidate is accepted or rejected with
 187 a probability that depends on the ratio of the posterior PDF for the current and the candidate
 188 parameter vector (so that the normalizing constant k in Equation 1 is irrelevant). By applying
 189 this simple accept/reject rule, it can be shown that the resulting Markov chain will asymptotically
 190 sample the posterior PDF. This MCMC procedure has been widely used in geophysical inverse
 191 problems (e.g., Malinverno, 2002; Malinverno & Leaney, 2005; Piana Agostinetti & Malinverno,
 192 2010; Sambridge & Mosegaard, 2002; Sen & Stoffa, 2013).

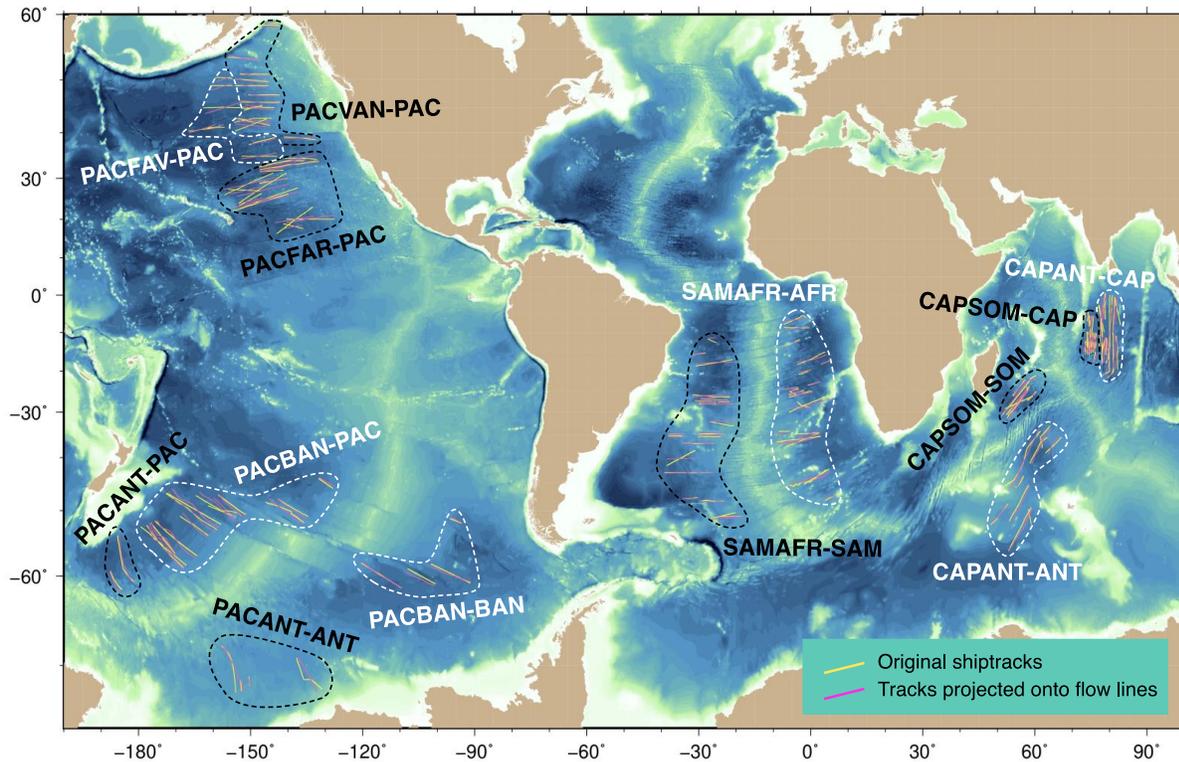
193 We implement here the simple MCMC scheme proposed by Mosegaard and Tarantola
 194 (1995). If the random walk that samples candidate model vectors is designed to sample the prior
 195 PDF of the parameters, then the probability of accepting the candidate simply depends on the
 196 ratio of the likelihoods. The sampling algorithm starts by defining an initial model parameter
 197 vector \mathbf{m} and calculating its likelihood $p(\mathbf{d}|\mathbf{m})$. Each sampling iteration is as follows:

- 198 • Sample a candidate \mathbf{m}^* following a random walk that samples the prior PDF of the model
 199 parameter vector;
- 200 • Compute the candidate likelihood $p(\mathbf{d}|\mathbf{m}^*)$;
- 201 • Accept the candidate with probability

$$202 \quad P_{\text{acc}} = \min [1, p(\mathbf{d}|\mathbf{m}^*) / p(\mathbf{d}|\mathbf{m})]; \quad (2)$$

- 203 • If the candidate is accepted, set $\mathbf{m} = \mathbf{m}^*$ and $p(\mathbf{d}|\mathbf{m}) = p(\mathbf{d}|\mathbf{m}^*)$; if not, \mathbf{m} and the
 204 likelihood stay the same.

205 Finally, to ensure that the parameter values output by the MCMC algorithm converge to
 206 sampling the posterior PDF, we compare the results of multiple independent sampling chains as
 207 suggested by Gelman et al. (2004). The detailed implementation of the MCMC sampling
 208 algorithm is described in the Supporting Information.



209

210 **Figure 1.** Location map of 153 ship tracks with measured magnetic anomalies over 13 ridge flank
 211 regions. Original tracks and tracks projected onto nearby plate tectonic flow lines are both shown.
 212 Detailed maps are in the Supporting Information.

213 3 Marine magnetic anomaly data

214 This section describes how magnetic anomaly ship tracks were processed to obtain
 215 distances along plate tectonic flow lines to the boundaries of modeled magnetic polarity blocks.
 216 These block model distances (BMDs) are the input to construct a GPTS that minimizes the
 217 global variability of spreading rates.

218 Ship tracks were selected over thirteen mid-ocean ridge flank regions that recorded
 219 anomalies between 13my and 34my at intermediate and fast spreading rates and that had
 220 previously determined sequences of finite rotation poles (Figure 1 and Table 2). The main source
 221 of magnetic anomaly data was the NOAA-NCEI archive of trackline geophysical measurements
 222 (NOAA National Geophysical Data Center, 1977), supplemented by additional surveys in the
 223 Indian Ocean (Yatheesh et al., 2019). We chose tracks that approximately followed the direction
 224 of plate motion, did not go over seamounts, and did not cross the fracture zones and ridge axis
 225 discontinuities listed in the Global Seafloor Fabric and Magnetic Lineation Data Base (Matthews
 226 et al., 2011). Each track was projected on a nearby plate tectonic flow line defined by the finite
 227 rotation poles. This projection ensured that the BMDs determined on each projected track were
 228 measured along the direction of plate motion.

229 Initial BMDs in each projected track were determined from the position of key anomaly
 230 picks taken from the Global Seafloor Fabric and Magnetic Lineation Data Base (Seton et al.,
 231 2014). These key anomaly picks were then interpolated assuming piecewise constant spreading

232 rates to obtain a set of BMDs for all the polarity blocks defined by the CK95 GPTS. Anomalies
 233 predicted in each track by initial BMDs and an initial anomaly skewness angle (Schouten &
 234 McCamy, 1972) were compared to the measured anomalies. The initial BMDs and skewness
 235 were manually adjusted to improve the overall fit to the measured data. Tracks or track
 236 segments that did not display an unambiguous correlation to the overall predicted anomaly
 237 pattern were discarded, resulting in a data set of 154 original and projected tracks (location maps
 238 are in the Supporting Information).

239

240 **Table 2.** Ridge flank regions with distances to polarity block boundaries and sources for finite plate
 241 rotations used to define flow lines.

242

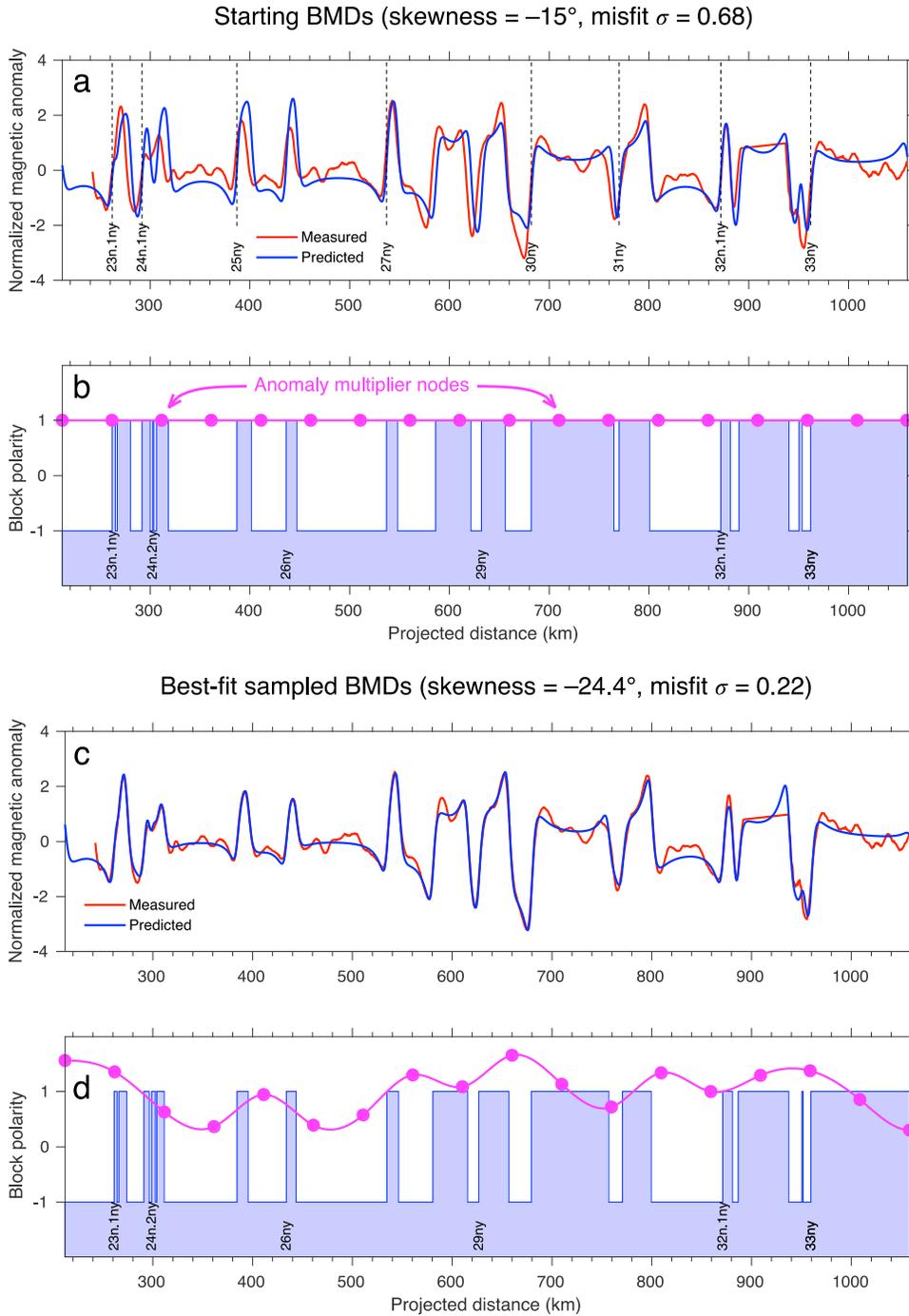
Ocean basin	Ridge flank region	Tracks	Chron boundaries	Sources for finite rotations
S. Atlantic	SAMAFR-AFR	23	C13ny--C34ny	(Müller et al., 1999)
	SAMAFR-SAM	22	C13ny--C34ny	
Indian Ocean	CAPSOM-CAP	18	C18n.1ny--C30ny	(Cande et al., 2010; Cande & Patriat, 2015)
	CAPSOM-SOM	7	C13ny--C29ry	
	CAPANT-CAP	17	C13ny--C34ny	
	CAPANT-ANT	9	C13ny--C34ny	
S. Pacific	PACANT-PAC	2	C20ny--C33ry	(Croon et al., 2008; Wright et al., 2016)
	PACANT-ANT	4	C13ny--C30ny	
	PACBAN-PAC ^a	13	C13ny--C33ry	
	PACBAN-BAN ^a	4	C13ny--C28ny	
N. Pacific	PACFAR-PAC	14	C18n.2ry--C33ny	(Wright et al., 2015, 2016)
	PACFAV-PAC ^b	7	C24n.1ny--C33ny	
	PACVAN-PAC	14	C13ny--C24n.1ny	
Total		154		

243

244 ^aFinite rotations for Pacific-Bellingshausen plate pair (anomalies 33-28) followed by Pacific-Antarctica
 245 (26-13). ^bFinite rotations for Pacific-Farallon plate pair (anomalies 34-25) followed by Pacific-
 246 Vancouver (24-13).

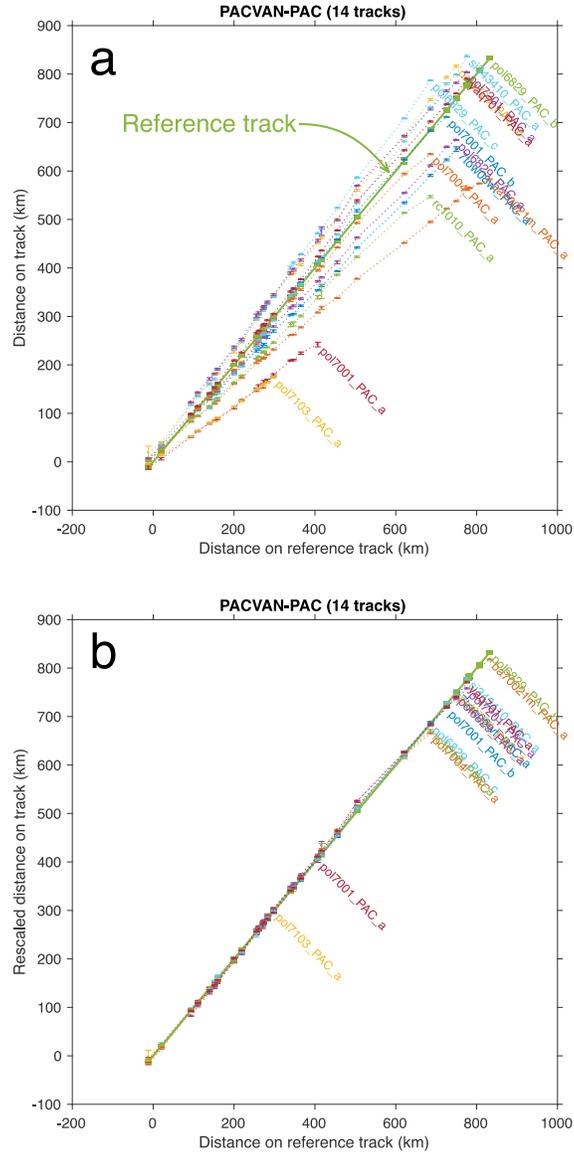
247

248 The manually adjusted skewness angle and BMDs for each track were then iteratively
 249 modified by a Markov chain Monte Carlo (MCMC) algorithm to obtain a sample of BMDs that
 250 fit the magnetic anomaly data. The MCMC algorithm also adjusted a set of nodes that define an
 251 interpolated multiplier for the magnetic anomaly amplitudes (Figure 2). Accounting for the
 252 variation of anomaly amplitudes along tracks proved necessary to prevent the Monte Carlo
 253 algorithm from occasionally sampling unrealistically narrow polarity blocks. If the amplitudes of
 254 the predicted anomalies were not adjusted, a narrow, low-amplitude anomaly could only be fitted
 255 by making the corresponding polarity block narrower than it should be. The final product of
 256 Monte Carlo sampling is a best value (the sample average) and uncertainty (the sample standard
 257 deviation) of the BMDs in each projected track. Details on the MCMC procedure and figures
 258 with the geographic locations of block model boundaries in the original tracks are in the
 259 Supporting Information.



260

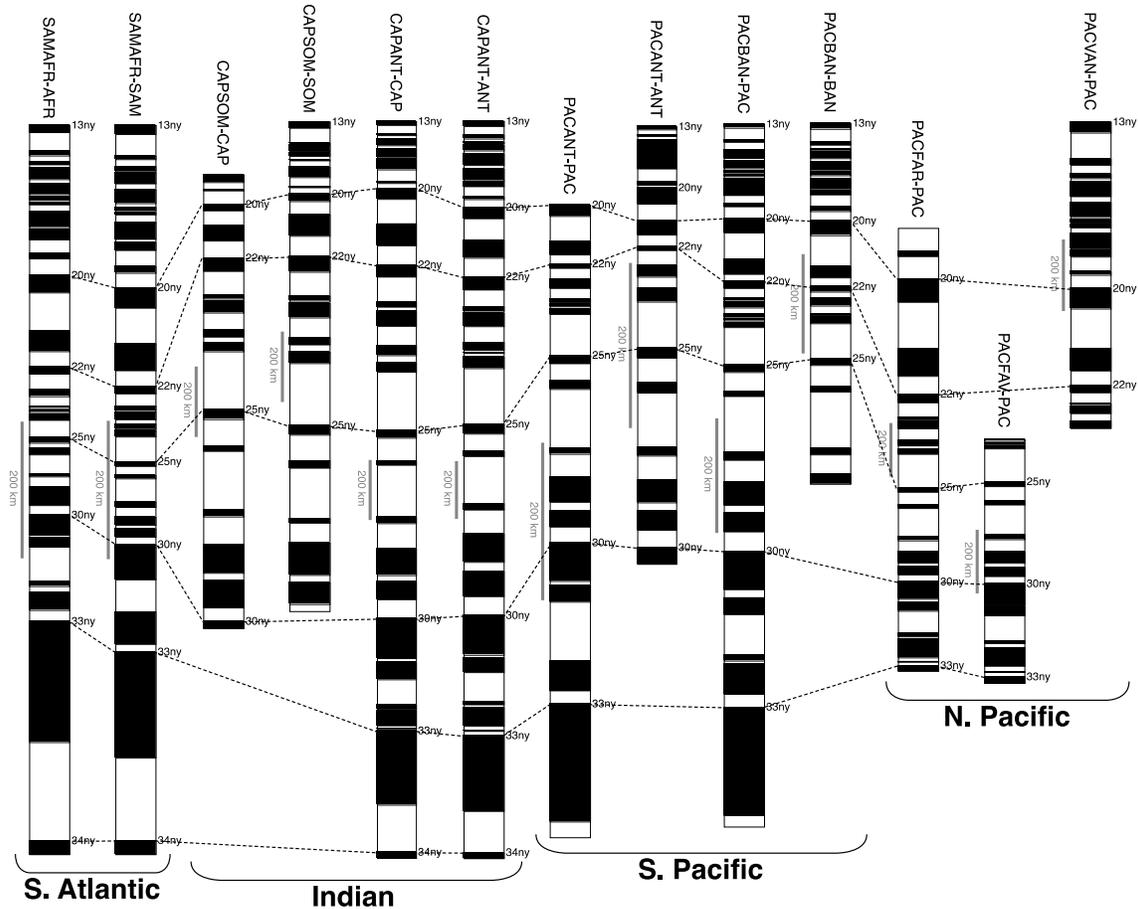
261 **Figure 2.** Comparison measured-predicted magnetic anomalies for starting BMDs (a, b) and best-fit
 262 BMDs sampled by a MCMC algorithm (c, d). The projected ship track is nbp9604_PAC_a in the
 263 PACVAN-PAC ridge flank region. The vertical dashed lines in (a) show the starting BMDs manually
 264 adjusted to approximately fit measured anomalies. The MCMC algorithm modifies iteratively the starting
 265 BMDs, the anomaly multiplier nodes, and the skewness angle to maximize the fit between measured and
 266 predicted anomalies.



267
 268 **Figure 3.** BMDs in projected ship tracks over a ridge flank region (PACVAN-PAC in the figure) plotted
 269 versus BMDs in a reference track show a systematic variation due to the change in spreading rate at
 270 different distances from the plate rotation pole (a). When rescaled to fit the spreading rate in the reference
 271 track, BMDs are consistent and can be averaged to obtain a summary BMD for the whole ridge flank
 272 region (b).

273
 274 We then obtained summary BMDs over each of the 13 ridge flank regions listed in Table
 275 2 by rescaling and averaging the BMDs estimated in each projected track. Rescaling the BMDs
 276 accounts for the systematic variation of local spreading rates as a function of the distance
 277 between the track and the plate rotation poles (Figure 3). The rescaling was based on a reference
 278 projected track in each ridge flank region. This reference track was either a single long track or
 279 multiple tracks that spanned the full range of anomalies recorded over the ridge flank region.
 280 The BMDs estimated in each of the other projected tracks were rescaled with a least-squares fit

281 so that the average spreading rate in the interval covered by the track was the same as in the
 282 matching interval in the reference track. This simple rescaling resulted in a consistent set of
 283 BMDs in each ridge flank region (see Figure 3 for an example). The best value for the ridge
 284 flank region BMDs was set to the median of the rescaled BMDs on each track. We used the
 285 median because it is a central value estimator that is not affected by occasional outliers. The
 286 uncertainty of the ridge flank region BMDs was quantified from the standard deviation of the
 287 rescaled BMDs for each track. The standard deviation will be increased by outliers, but this is a
 288 useful characteristic as it will decrease the influence on GPTS construction of BMDs that contain
 289 outliers and are poorly determined.



290
 291 **Figure 4.** Summary block model distances in the 13 ridge flank regions used for GPTS construction.

292
 293 Finally, we deleted from the summary BMDs polarity blocks narrower than 2 km.
 294 Narrow polarity blocks are poorly recorded by magnetic anomalies generated by a source layer
 295 whose top is at ~4.5 km water depth in 33 Ma crust (Parsons & Sclater, 1977). The width of
 296 these narrow blocks is mostly constrained by the distances to adjacent polarity block boundaries
 297 and does not provide independent information. The summary BMDs for 13 ridge flank regions
 298 are illustrated in Figure 4. Files listing the 154 tracks used here, the final positions and BMDs in
 299 each of the original and projected tracks, and the summary BMDs for each of the 13 ridge flank
 300 regions are available in two open access data publications (Malinverno et al., 2019a, 2019b).

301 **4 Radioisotopic dates**

302 The radioisotopic dates used here (Table 3) are from Table 28.1 of GTS12
 303 (Vandenberghe et al., 2012) with a few modifications. GTS12 reports both a radioisotopic
 304 dating uncertainty and a stratigraphic position uncertainty expressed as a fraction of the
 305 stratigraphic thickness of the polarity chron (assumed here to represent two standard deviations).
 306 For GPTS construction, we then assigned to each radioisotopic date a total uncertainty from the
 307 sum of the variances due to radioisotopic dating uncertainty and stratigraphic uncertainty. The
 308 temporal uncertainty due to stratigraphic uncertainty was calculated as the product of the
 309 dimensionless stratigraphic uncertainty times the duration of the respective chron in CK95.
 310

311 **Table 3.** Radioisotopic dates used to constrain the MQSD20 GPTS, modified after Table 28.1 of Vandenberghe et
 312 al. (2012).
 313

Chron	Radioisotopic date		Stratigraphic position		Chron duration in CK95 (Ma)	Date uncert. due to stratigr. uncertainty (2 σ , Ma)	Total date uncertainty (2 σ , Ma)
	Date (Ma)	Uncert. (2 σ , Ma)	Up from base	Uncert. (2 σ)			
C13r ^a	34.8	0.2	0.19	0.1	1.11	0.11	0.23
C20n	43.35	0.5	0.1	0.1	1.253	0.13	0.52
C21n	46.24	0.5	0.75	0.1	1.642	0.16	0.53
C21r	48.41	0.21	0.1	0.1	1.131	0.11	0.24
C22n	48.96	0.33	0.45	0.1	0.677	0.07	0.34
C24n.1n	52.93	0.23	0	0.05	0.299	0.01	0.23
C24n.3r ^b	55.48	0.12	0.5	0.1	2.557	0.26	0.28
C24n.3r ^b	55.785	0.075	0.375	0.05	2.557	0.13	0.15
C26r	59.39	0.3	0.9	0.05	3.009	0.15	0.34
C28r	64.73	0.12	0.9	0.1	0.342	0.03	0.12
C29n	64.94	0.12	0.9	0.05	0.769	0.04	0.13
C29r	65.611	0.15	0.8	0.05	0.833	0.04	0.16
C29r ^c	65.84	0.12	0.57	0.05	0.833	0.04	0.13
C29r	65.99	0.12	0.5	0.05	0.833	0.04	0.13
C33n ^d	79.84	0.5	0	0.1	5.456	0.55	0.74
C33r ^d	83.6	0.5	0	0.1	3.925	0.39	0.64

314

315 ^aAverage of two dates in C13r with updated stratigraphic positions (see Supplementary Information for details).

316 ^bChron was listed as C24r in Table 28.1 of Vandenberghe et al. (2012); it corresponds to C24n.3r in CK95 and in the
 317 nomenclature used in this paper. ^cA date of 66.28 Ma reported in Table 28.1 of Vandenberghe et al. (2012) for the
 318 same stratigraphic position does not correspond to a date in the original reference (Swisher et al., 1993) and was
 319 omitted. ^dStratigraphic uncertainty was not reported in Table 28.1 of Vandenberghe et al. (2012), and was set
 320 conservatively as the maximum given elsewhere (0.1).
 321

322 The two radioisotopic dates in chron C13r listed in Table 28.1 of GTS12 have been
 323 averaged to a single date (first row of Table 3). These dates were obtained in the Massignano
 324 quarry stratotype section from biotite-rich clayey layers of possible volcanic origin (Odin et al.,
 325 1991). GTS12 used a Fish Canyon sanidine age of 28.201 Ma to recalculate the original Ar/Ar
 326 radioisotopic dates as 34.4 ± 0.2 Ma (14.7 m stratigraphic height in Massignano quarry section,
 327 0.4 up from base of C13r, 2 σ uncertainty) and 35.2 ± 0.2 Ma. (12.7 m stratigraphic height, 0.14

328 up from base). We referred these dates to the stratigraphic framework of a drill core located
 329 about 110 m south of the Massignano stratotype section (Lanci et al., 1996). The drill core
 330 samples were taken every 12-15 cm, a much more detailed sampling interval than that possible in
 331 the Massignano outcrop, where strong weathering makes it difficult to obtain closely spaced,
 332 pristine samples. The C13r interval in the drill core was clearly established between
 333 stratigraphic depths of 14.2 m and 24.8 m (Figure 6 of Lanci et al., 1996). Using the conversion
 334 in Figure 3 of Lanci et al. (1996), the predicted stratigraphic height of C13r in the quarry section
 335 is 11.7 to 22.3 m. This estimate is in close agreement with the location of reversely magnetized
 336 samples in the outcrop (Figure 9 of Lowrie & Lanci, 1994). Based on the high-resolution
 337 magnetostratigraphy in the drill core, the stratigraphic positions of the two dates in C13r become
 338 0.28 and 0.09 up from base.

339 If taken at face value, the two dates indicate a duration of C13r that is $(35.2 - 34.4)/(0.28$
 340 $- 0.09) = 4.21$ Ma, which is almost four times the duration of C13r in CK95 (1.11 Ma). A
 341 >4 Ma duration of C13r also conflicts with the average sedimentation rate of 10.6 m/Ma
 342 estimated from astrochronology in the Massignano section (Brown et al., 2009, p. 123). As the
 343 C13r interval in Massignano is 9 to 10.6 m thick (Lanci et al., 1996; Montanari et al., 1993), the
 344 estimated sedimentation rate implies a duration of ~ 1 Ma.

345 Using directly the two C13r dates listed in GTS12 with the stated small uncertainties of
 346 0.2 Ma will unduly bias the duration of C13r in the GPTS. To avoid this, we simply averaged
 347 the two dates (34.8 Ma) and located the average age midway between the two stratigraphic
 348 positions (0.19 up from the base of C13r). We did not change the radioisotopic date uncertainty,
 349 but increased the 2σ stratigraphic position uncertainty (0.05 in GTS12) to half the range of the
 350 two original dates, which is $(0.28 - 0.09) / 2 \approx 0.1$.

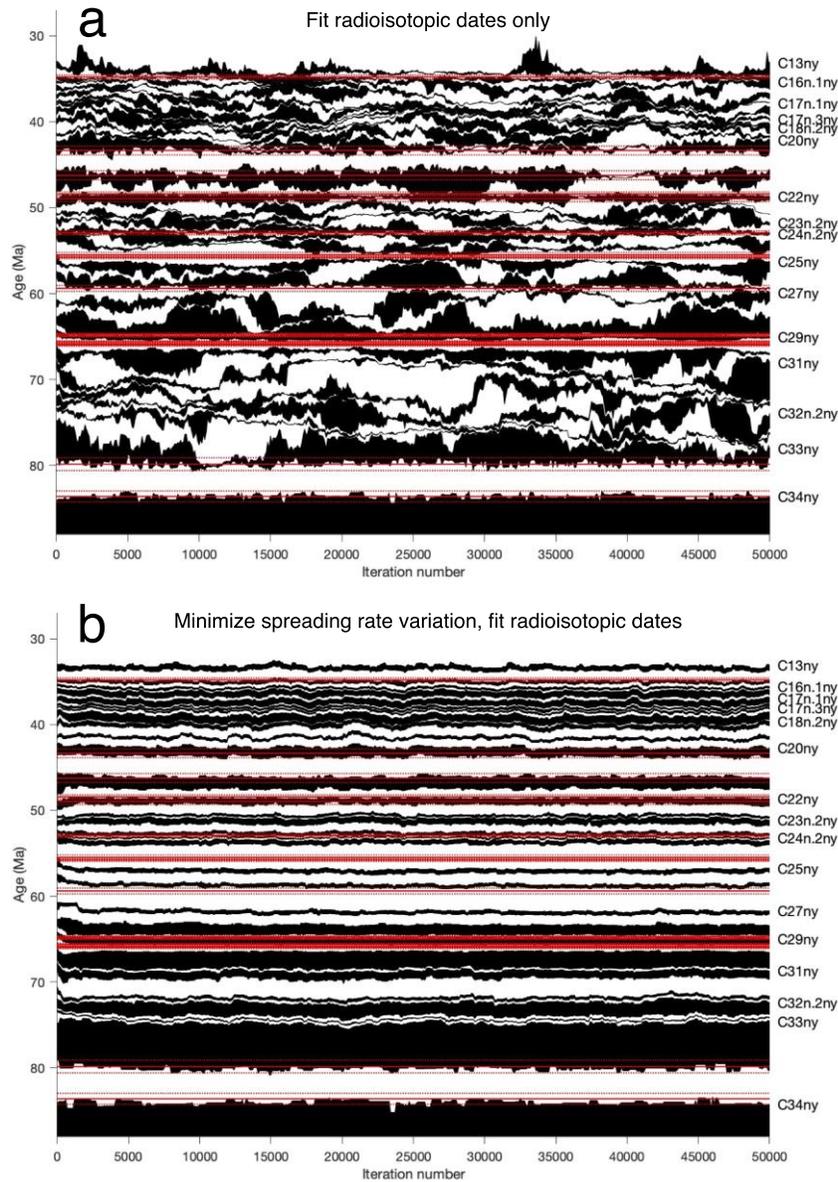
351 **5 The MQSD20 GPTS**

352 We obtain a new MQSD20 GPTS with a MCMC algorithm that generates a large
 353 ensemble of GPTSs. This ensemble will be asymptotically distributed as in the posterior PDF of
 354 Equation 1, and is used to calculate a reference GPTS and quantify its posterior uncertainty. Full
 355 details of the MCMC procedure are in the Supporting Information, and here we illustrate how the
 356 sampling proceeds when the GPTS is constrained by different types of information (Figure 5).

357 Figure 5a shows the progress of MCMC sampling if spreading rate variations are ignored
 358 and the data vector \mathbf{d} in the likelihood function of Equation 1 only contains a set of radioisotopic
 359 dates (Table 3). The sampling starts from a perturbed version of the CK95 GPTS and proceeds
 360 by iteratively changing chron boundary ages, accepting or rejecting such changes as in the
 361 Metropolis acceptance probability of Equation 2. The sampled GPTSs fit the radioisotopic dates
 362 within their uncertainty, but the chron boundary ages and durations in intervals between
 363 radioisotopic age ties are unconstrained and extremely variable (e.g., between about 66 Ma and 80
 364 Ma).

365 Figure 5b shows the MCMC sampling progress when the data vector \mathbf{d} in the likelihood
 366 function of Equation 1 includes both radioisotopic dates and the BMDs estimated in each of the
 367 13 ridge flank regions (Figure 4). In this case, the likelihood function is greater if the GPTS
 368 implies a smaller variation of spreading rates on each ridge flank (which depend on the BMDs).
 369 The variability of the sampled chron ages between radioisotopic age ties is much less than in
 370 Figure 5a, as it is constrained by the need to minimize spreading rate fluctuations. The final

371 sample of GPTSs used to derive MQSD20 is constructed by combining the results of ten
 372 independent sampling chains such as that in Figure 5b (see the Supporting Information).



373
 374 **Figure 5.** Progress of MCMC sampling of a GPTS. Each column in the images displays the GPTS
 375 sampled at the respective iteration number (black indicates normal and white reversed chrons). Solid red
 376 lines show radioisotopic dates and dotted red lines bracket their 2σ uncertainty (Table 3). Sampling is
 377 constrained to fit only the radioisotopic dates (a) or to fit radioisotopic dates while minimizing spreading
 378 rate variability over 13 ridge flank regions (b).

379
 380 The MQSD20 chron boundary ages, chron durations, and respective uncertainties are in
 381 Table 4 and Figure 6. The reference GPTS chron boundary ages and chron durations are the
 382 average values of the ensemble obtained by MCMC sampling. GPTS uncertainties are
 383 quantified from the standard deviations of chron ages and durations in the ensemble. Near age

384 ties, the uncertainties in the GPTS chron boundary ages are smaller than the uncertainties of the
 385 radioisotopic dates themselves (Figure 6), reflecting the additional constraints given by spreading
 386 rate information.

387

388 **Table 4.** MQSD20 GPTS ages, chron durations, and respective uncertainties.

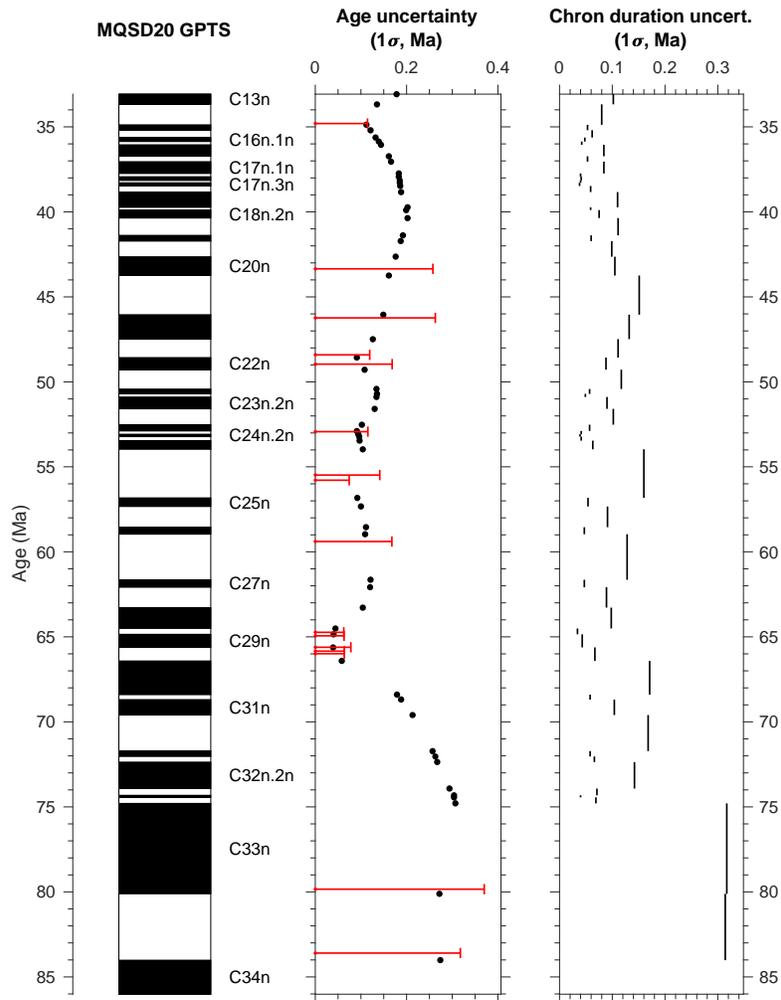
389

Chron	End age (Ma)		Duration (Ma)		Chron	End age (Ma)		Duration (Ma)	
	Age	Uncert. (1 σ)	Duration	Uncert. (1 σ)		Age	Uncert. (1 σ)	Duration	Uncert. (1 σ)
C13n	33.076	0.178	0.599	0.102	C24n.1n	52.520	0.102	0.372	0.057
C13r	33.675	0.135	1.200	0.080	C24n.1r	52.892	0.091	0.187	0.041
C15n	34.875	0.112	0.324	0.053	C24n.2n	53.079	0.094	0.143	0.039
C15r	35.199	0.121	0.428	0.062	C24n.2r	53.222	0.096	0.232	0.041
C16n.1n	35.627	0.132	0.236	0.048	C24n.3n	53.455	0.097	0.514	0.063
C16n.1r	35.863	0.139	0.191	0.042	C24n.3r	53.969	0.104	2.855	0.160
C16n.2n	36.054	0.144	0.674	0.084	C25n	56.824	0.092	0.503	0.054
C16n.2r	36.728	0.161	0.322	0.053	C25r	57.327	0.100	1.220	0.091
C17n.1n	37.049	0.166	0.692	0.084	C26n	58.547	0.111	0.417	0.047
C17n.1r	37.741	0.183	0.193	0.040	C26r	58.963	0.109	2.677	0.128
C17n.2n	37.934	0.183	0.216	0.041	C27n	61.640	0.121	0.440	0.047
C17n.2r	38.150	0.185	0.137	0.040	C27r	62.080	0.120	1.201	0.089
C17n.3n	38.287	0.185	0.189	0.038	C28n	63.280	0.104	1.226	0.098
C17n.3r	38.477	0.186	0.359	0.059	C28r	64.506	0.044	0.343	0.034
C18n.1n	38.835	0.188	0.898	0.110	C29n	64.849	0.040	0.775	0.043
C18n.1r	39.734	0.202	0.164	0.059	C29r	65.623	0.039	0.789	0.067
C18n.2n	39.897	0.199	0.469	0.075	C30n	66.412	0.058	1.985	0.171
C18n.2r	40.366	0.202	1.014	0.111	C30r	68.397	0.179	0.288	0.058
C19n	41.380	0.192	0.338	0.060	C31n	68.685	0.188	0.913	0.104
C19r	41.718	0.187	0.917	0.099	C31r	69.598	0.213	2.124	0.168
C20n	42.634	0.176	1.109	0.105	C32n.1n	71.722	0.257	0.316	0.058
C20r	43.744	0.161	2.307	0.151	C32n.1r	72.038	0.263	0.325	0.066
C21n	46.050	0.149	1.438	0.132	C32n.2n	72.363	0.267	1.558	0.142
C21r	47.488	0.126	1.081	0.111	C32n.2r	73.921	0.294	0.399	0.071
C22n	48.569	0.091	0.717	0.088	C32r.1n	74.319	0.304	0.123	0.040
C22r	49.286	0.108	1.132	0.117	C32r.1r	74.442	0.304	0.353	0.069
C23n.1n	50.418	0.134	0.288	0.057	C33n	74.795	0.307	5.320	0.317
C23n.1r	50.705	0.135	0.183	0.049	C33r	80.115	0.272	3.902	0.314
C23n.2n	50.888	0.134	0.699	0.090	C34n	84.017	0.274		
C23n.2r	51.587	0.130	0.933	0.102					

390

391 The chron boundary ages and chron durations of MQSD20 are compared to those of
 392 CK95 (Cande & Kent, 1992, 1995) and of GTS12 (Ogg, 2012) in Figure 7. The differences in
 393 chron boundary ages with CK95 reach ~1 Ma for chrons C24 and earlier (ages \geq 53 Ma), and are
 394 partly due to radioisotopic age recalibration. As MQSD20 used the same radioisotopic age ties
 395 as GTS12, the age differences are smaller (0.5 Ma or less), though they exceed the 2σ age
 396 uncertainty of MQSD20 for chrons C25-C29 (ages ~56-65 Ma). Chron duration differences are
 397 at most 0.3 Ma with respect to both CK95 and GTS12, and are generally within the the 2σ
 398 uncertainty of the chron durations in MQSD20.

399

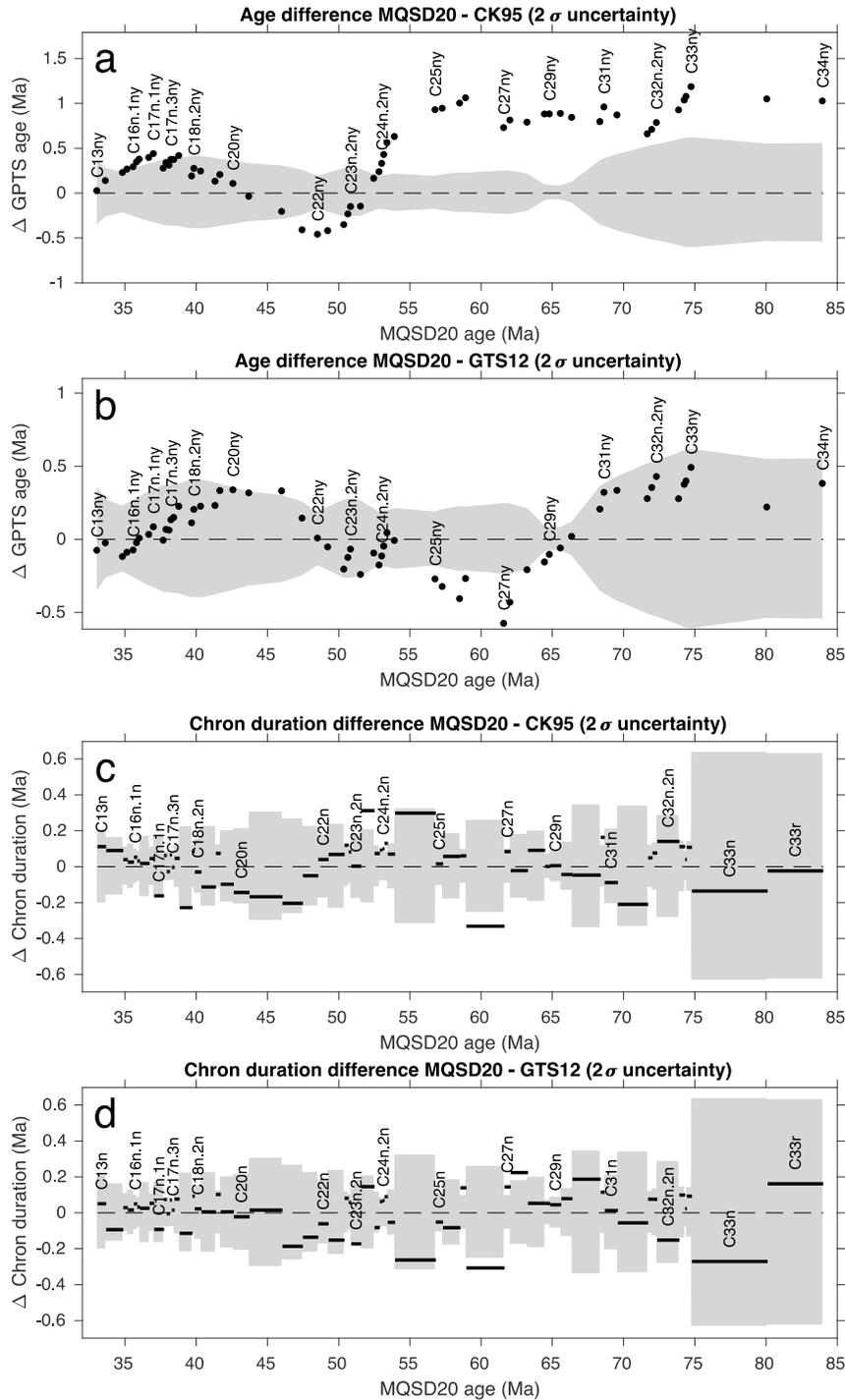


400

401 **Figure 6.** MQSD20 GPTS and its 1σ uncertainties in chron boundary ages and chron duration. Red error
 402 bars show the 1σ uncertainties of radiometric dates (Table 3).

403

404 The half-spreading rates implied by MQSD20, CK95, and GTS12 for the summary
 405 BMDs in the 13 ridge flank regions considered here are compared in Supporting Information
 406 Figures S17-S29. The overall variability of spreading rate in each ridge flank region can be
 407 quantified by a coefficient of variation (CV) that equals the standard deviation of spreading rate
 408 divided by its mean value. Table 5 lists the CVs of spreading rate computed using different
 409 GPTSs and the summary BMDs in the 13 ridge flank regions. As MQSD20 minimizes spreading
 410 rate variability, the CVs of spreading rate are less than those implied by CK95 and GTS12. The
 411 exception is PACVAN-PAC in the North Pacific (Figure 1), where MQSD20 has more variable
 412 spreading rates around chrons C17-C18 than CK95 and GTS12 (see Supporting Information
 413 Figure S29). The likely reason is that the duration of chrons C17-C18 in CK95 and GTS12 is
 414 mostly controlled by magnetic anomaly records in this area of the North Pacific, whereas
 415 MQSD20 includes information from other mid-ocean ridge flanks.



416

417 **Figure 7.** GPTS comparison between MQSD20, CK95, and GTS12. Differences in chron boundary ages
 418 are in (a) and (b); differences in chron durations are in (c) and (d). The shaded areas encompass the 2σ
 419 uncertainty of the MQSD20 GPTS.

420

421 **Table 5.** Coefficient of variation (CV) of spreading rate in each of the 13 ridge flank regions for different
 422 GPTSs.

423

Ridge flank region	MQSD20	CK95	GTS12
SAMAFR-AFR	0.31	0.46	0.47
SAMAFR-SAM	0.31	0.47	0.53
CAPSOM-CAP	0.28	0.33	0.31
CAPSOM-SOM	0.45	0.63	0.52
CAPANT-CAP	0.43	0.56	0.47
CAPANT-ANT	0.44	0.58	0.49
PACANT-PAC	0.24	0.38	0.30
PACANT-ANT	0.32	0.32	0.38
PACBAN-PAC	0.37	0.55	0.50
PACBAN-BAN	0.26	0.30	0.44
PACFAR-PAC	0.32	0.40	0.36
PACFAV-PAC	0.16	0.33	0.25
PACVAN-PAC	0.23	0.19	0.20

424

425 **6 Discussion**

426 6.1 Addressing the 50 Ma discrepancy

427 As it has been obtained independently from astronomical dating, the MQSD20 GPTS can
 428 be used to address conflicting results in astrochronology interpretations. We discuss here as an
 429 example the “50 Ma discrepancy” noted by Vanderberghe et al. (2012), which centers on the
 430 duration of chron C23n.2n. Whereas this chron lasts 696 kyr in the CK95 GPTS, it has been
 431 estimated to be less than 400 kyr in several astrochronology studies. From an analysis of the
 432 sedimentary record at ODP Site 1258, Westerhold and Röhl (2009) obtained a C23n.2n duration
 433 of 379 to 399 kyr, depending on the astronomical cycle chosen (long eccentricity or precession,
 434 respectively). Westerhold et al. (2015) confirmed this interpretation in a study that included other
 435 drill sites and listed a duration of 377 kyr for C23n.2n. From the ODP Site 1263 record,
 436 Laurentano et al. (2016) reported an even shorter C23n.2n duration of 295 kyr in their preferred
 437 age model (with an alternative estimate of 395 kyr). When spreading rates are calculated from
 438 the South Atlantic BMDs of CK95, these astronomically determined durations result in
 439 spreading rates that are more than twice as fast during chron C23n.2n than in adjacent chrons
 440 (Figure 6a of Westerhold et al., 2017). A possible explanation offered for this discrepancy is that
 441 the CK95 BMDs may be poorly determined around chron C23 (Westerhold et al., 2015;
 442 Westerhold & Röhl, 2009), as the width of the chron C23 block has the largest uncertainties
 443 reported in CK95 (17.3% of its width; see Table 4 of Cande & Kent, 1992).

444 Distances to both the young and old end of C23n.2n were estimated in 85 of the 154 ship
 445 tracks examined here. All the ridge flank region BMDs record the young and old end of C23n.2n
 446 except for PACFAV-PAC, which only spans chrons C24n and older. When spreading rate
 447 variations over all ridge flank regions are considered, the duration of C23n.2n in MQSD20 is 699
 448 \pm 180 ka (2σ ; Table 4). Although we examined a larger magnetic anomaly data set and used a
 449 different set of radiometric dates, the duration of C23n.2n we obtain is effectively the same as

450 that in CK95 (696 kyr). This supports the reliability of the CK95 BMDs and implies that a 300-
451 400 kyr duration requires a doubling of spreading rates during C23n.2n in multiple mid-ocean
452 ridges, which is implausible. The duration of C23n.2n in MQSD20 supports the solution of the
453 50 Ma discrepancy put forward by Westerhold et al. (2017), who concluded that chron C23n is
454 too short in the magnetostratigraphic interpretation of Site 1258. Their revised astronomical time
455 scale gives a C23n.2n duration of 712 ± 123 kyr, which is consistent with the MQSD20 results.

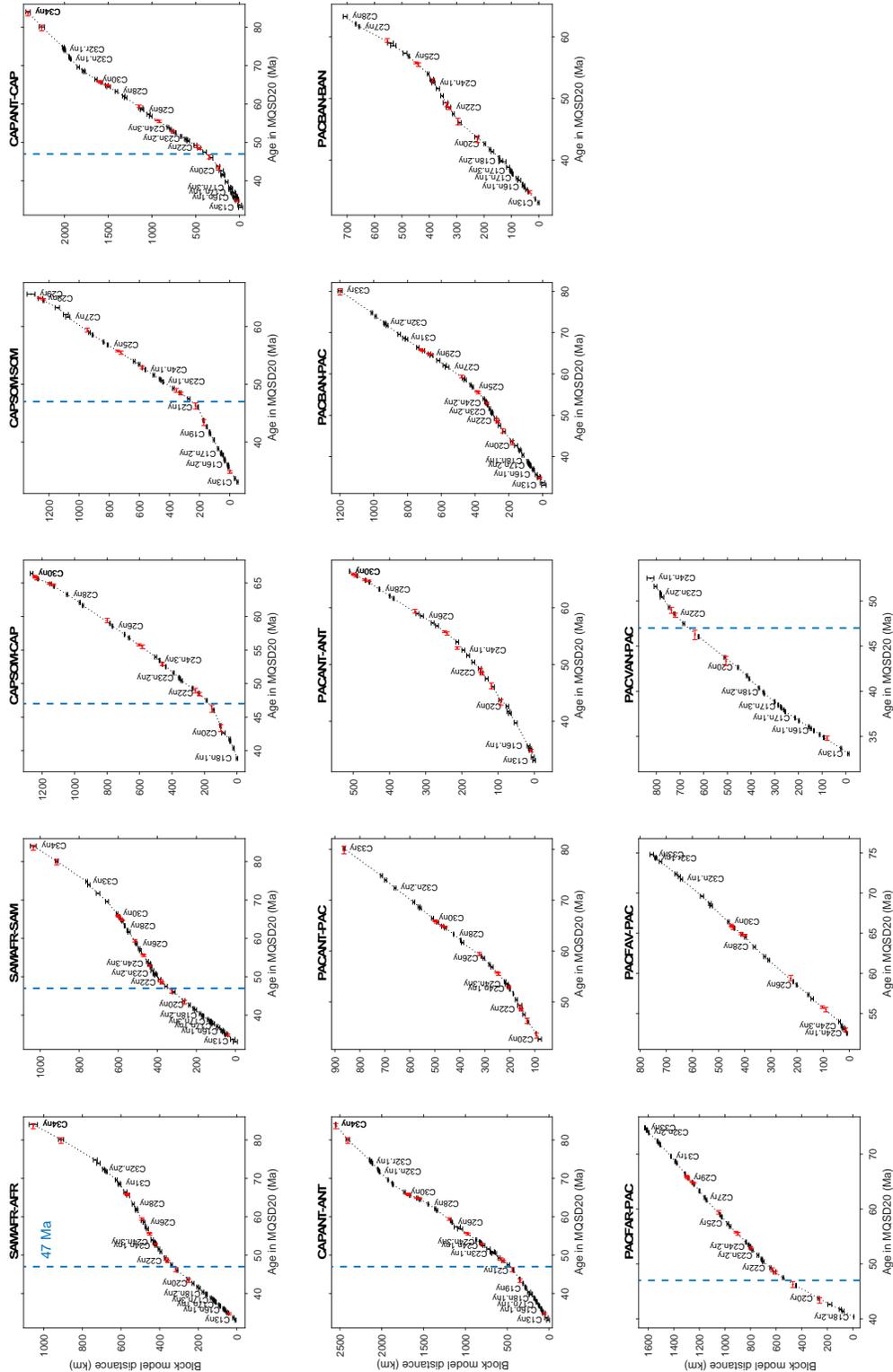
456 6.2 Spreading rate changes and global tectonic events at ~47 Ma (chron C21)

457 Figure 8 plots the summary BMDs in each of the 13 ridge flank regions as a function of
458 age in MQSD20. The minimization of global spreading rate fluctuations highlights a major
459 spreading rate change centered at about 47 Ma (chron C21n). Around this time, spreading rates
460 decreased by a factor of 2-3 in the Indian Ocean (Supporting Information Figures S19-S22)
461 while they approximately doubled in the South Atlantic (Figures S17 and S18) and in the North
462 Pacific (Figures S27 and S29). These spreading rate changes coincide with a previously noted set
463 of plate reorganizations (Wessel et al., 2006; Whittaker et al., 2007) that we summarize below.

464 The prominent decrease in Indian Ocean spreading rates around C21 is related to the
465 onset of the collision between the India subcontinent and Eurasia (Copley et al., 2010; Molnar &
466 Stock, 2009; Patriat & Achache, 1984). To the west, the contemporaneous spreading rate
467 increase in the South Atlantic confirms a general pattern of spreading rate anticorrelation
468 between the Indian and South Atlantic Ocean observed throughout the period 80-30 Ma (Figure
469 14 of Cande & Patriat, 2015). Moving eastward in the Indian Ocean, in the interval C22-C20
470 spreading rates decreased substantially in the Wharton Ridge separating the Indian and
471 Australian plates (Jacob et al., 2014). At the same time, a major Australia-Antarctic plate
472 reorganization took place (Whittaker et al., 2007), with Southeast Indian Ridge spreading rates
473 markedly increasing immediately after C21 (Figure 2h of Cogné & Humler, 2006).

474 In the southeast Pacific Ocean, a major plate boundary reorganization took place around
475 C21, when the Pacific-Antarctic ridge propagated northward breaking off a large fragment of the
476 Pacific plate that became attached to the Antarctic plate (Cande et al., 1982). In the western
477 Pacific, the onset of subduction in the Izu-Bonin-Mariana and Tonga Kermadec arcs has been
478 dated to 45-50 Ma (Bloomer et al., 2013; Cosca et al., 1998; Ishizuka et al., 2011).

479 In the northern Pacific, an about twofold increase in spreading rate at C21 time has been
480 noted by others (Barckhausen et al., 2013; Wright et al., 2015). This spreading rate increase
481 coincides with the prominent change in orientation in the Hawaiian-Emperor seamount chain
482 (Hawaiian-Emperor Bend or HEB), whose date has been recently updated to ~47 Ma (O'Connor
483 et al., 2013; Torsvik et al., 2017; Wessel et al., 2006). The HEB was originally explained by a
484 change in absolute motion of the Pacific plate over a fixed hotspot, but later on several authors
485 argued that it resulted from a slowing southward motion of the Hawaiian hotspot (Norton, 1995;
486 Tarduno et al., 2003; Wright et al., 2015). Torsvik et al. (2017), however, recently concluded that
487 both a southward shift of the Hawaiian hotspot and a change in Pacific plate motion direction are
488 necessary to explain the HEB. The substantial increase in northern Pacific spreading rates at the
489 same time of the HEB strongly suggests a connection. We conjecture that even if the direction of
490 absolute Pacific plate motion did not change, a substantial acceleration in Pacific spreading rate
491 at the time of the HEB over a southward drifting Hawaiian hotspot may have turned the
492 orientation of the Hawaiian-Emperor seamount chain closer to an E-W direction.



493

494 **Figure 8.** Summary block model distances in 13 ridge flank regions versus MQSD20 GPTS ages. The
 495 slope of these distance-age plots is the half-spreading rate. Red symbols are radioisotopic ages (Table 3).
 496 Dashed lines highlight a change in spreading rate around 47 Ma in the South Atlantic (SAMAFR-AFR
 497 and SAMAFR-SAM), Indian (CAPSOM-CAP, CAPSOM-SOM, CAPANT-CAP, and CAPANT-ANT),
 498 and North Pacific Oceans (PACFAR-PAC and PACVAN-PAC).

499 Contemporaneous worldwide spreading rate changes and plate boundary reorganizations
500 suggest a global connection. As plate motion changes are likely controlled by changes in plate
501 boundary forces (e.g., Gordon et al., 1978), we speculate that the effects of the India-Eurasia
502 collision may have propagated throughout the global plate tectonic system. A comprehensive
503 explanation of the connection between the 47 Ma events is beyond the scope of this paper;
504 however, we stress the importance of a time scale constrained by the global magnetic anomaly
505 record to time and correlate major plate tectonic events.

506 **7 Conclusions**

507 We estimated here a new set of magnetic polarity block model distances (BMDs)
508 spanning the chron C33-C13 interval in 154 ship tracks projected onto plate tectonic flow lines.
509 The ship track data were assembled in summary BMDs over 13 ridge flank regions in the
510 southern and northern Pacific, the southern Atlantic, and the Indian Ocean. This new set of
511 BMDs extends substantially the South Atlantic-based distances originally compiled by Cande &
512 Kent (1992). We used these BMDs to construct a Late Cretaceous-Eocene MQSD20 GPTS that
513 minimizes the variability of spreading rates over all ridge flank regions and fits an up-to-date set
514 of radioisotopic dates. At ~47 Ma, MQSD20 shows a marked spreading rate decrease in the
515 Indian Ocean and a contemporaneous increase in the South Atlantic and Northern Pacific. This
516 spreading rate change coincides with the India-Eurasia collision and with the bend in the Hawaii-
517 Emperor seamount chain.

518 The MQSD20 GPTS deliberately did not include astrochronology constraints in order to
519 provide an independent source of information to check sediment cycle interpretations. The next
520 step forward in GPTS construction will be to directly incorporate in the time scale information
521 from astrochronology. Such an integration procedure will improve the usual approach, which is
522 to build the time scale on a best data set that is typically taken to supersede other sources of
523 information that are deemed less accurate. For example, future time scale development is often
524 viewed as astronomical dating replacing GPTSs based on marine magnetic anomalies (e.g.,
525 Gradstein, 2012 p. 13; Hilgen et al., 2012 p. 947). A GPTS constructed on the basis of magnetic
526 anomalies from multiple spreading centers, rather than from a single mid-ocean ridge, points to a
527 better approach where diverse data sources are combined rather than selectively discarded. In
528 this view, the GPTS is the result of an integration of astrochronology, radioisotopic dates, and
529 magnetic anomaly data, where each piece of information is weighted by a measure of its
530 uncertainty (e.g., Malinverno et al., 2012). The global set of BMDs and the Monte Carlo
531 methods presented here provide the basis for this advance in time scale construction.

532 **Acknowledgments, Samples, and Data**

533 This study was supported by award OCE-1535937 of the U.S. National Science
534 Foundation. Data supporting the conclusions of this study are in two open access data
535 publications that list the 154 ship tracks used here, the geographic positions and distances to
536 polarity block model boundaries (BMDs) in each of the original and projected ship tracks, and
537 the summary BMDs for each of the 13 ridge flank regions (Malinverno et al., 2019a, 2019b). The
538 authors declare no conflict of interest.

539

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