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Convergence of tectonic reconstructions and mantle convection models for significant fluctuations in seafloor spreading

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Abstract

For 50 years of data collection and kinematic reconstruction efforts plate models have provided alternative scenarios for plate motions and seafloor spreading for the past 200 My. However, these efforts are naturally limited by the incomplete preservation of very old seafloor, and therefore the time-dependence of the production of new seafloor is controversial. There is no consensus on how much it has varied in the past 200 My, and how it could have fluctuated over longer timescales. We explore how seafloor spreading and continental drift evolve over long geological periods using independently derived models: a recently developed geodynamic modelling approach and state-of-the-art plate reconstructions. Both kinematic reconstructions and geodynamic models converge on variations by a factor of 2 in the rate of production of new seafloor over a Wilson cycle, with concomitant changes

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of the shape of the area-age distribution of the seafloor between end members of rectangular, triangular and skewed distributions. Convection models show that significant fluctuations over longer periods (~ 1 Gy) should exist, involving changes in ridge length and global tectonic reorganisations. Although independent, both convection models and kinematic reconstructions suggest that changes in ridge length are at least as significant as spreading rate fluctuations in driving changes in the seafloor area-age distribution through time.

Keywords: Mantle convection, Plate tectonics, Reconstruction, Seafloor spreading

1. Introduction

The theory of plate tectonics has provided the necessary framework for reconstructing ocean basins, including now subducted seafloor, and paleogeography (Kominz, 1984). Over 50 years of data collection and kinematic reconstruction efforts have led to significant improvements in plate tectonic modelling (Pilger, 1982; Rowley and Lottes, 1988; Scotese et al., 1988; Lithgow-Bertelloni and Richards, 1998; Müller et al., 1997; Seton et al., 2012). Plate tectonic models describing seafloor area-age distributions with relatively small uncertainties exist only for times where geological and geophysical data coverage is sufficient. Challenges remain for reconstructing ancient ocean basins and associated plate boundaries for times earlier than 200 Ma, as they are naturally limited by the preservation of very old seafloor. In addition, only 5% of the history of the planet can be reconstructed using

15 evidence from geological and geophysical data.

16 However, geodynamic models can now help to evaluate how seafloor
17 spreading evolves over longer time periods. Recent numerical models of man-
18 tle convection with pseudo-plasticity can generate long-term solutions pro-
19 ducing a form of seafloor spreading (Moresi and Solomatov, 1998; Trompert
20 and Hansen, 1998; Tackley, 2000), although developing a more complete
21 and consistent physical model for the rheology will eventually be required
22 (Bercovici, 2003; Bercovici and Ricard, 2012). These models have a mechan-
23 ically strong boundary layer at the surface, which becomes weak in regions
24 of higher stresses. Hence, strain localises in relatively narrow regions while
25 rigid body motion dominates elsewhere (van Heck and Tackley, 2008). These
26 models also generate a significant toroidal component in the surface velocity
27 field, as observed on Earth. The introduction of models of continental litho-
28 sphere (Yoshida, 2010; Rolf and Tackley, 2011) further improve the quality of
29 such predictions: the computed distribution of seafloor ages reproduces the
30 consumption of young seafloor as observed on the present-day Earth (Coltice
31 et al., 2012).

32 The time-dependence of the production of new seafloor has long been
33 debated and there is no consensus on how much it has varied in the past
34 150 My, and how it could have fluctuated over longer timescales. Using
35 plate reconstructions, Parsons (1982) and Rowley (2002) proposed that the
36 area-age distribution of the seafloor has experienced limited fluctuations in
37 the past 200 My, while others have suggested that larger variations would
38 fit the observations equally well (Demicco, 2004; Seton et al., 2009). In
39 addition, relatively fast seafloor spreading was proposed for the mid-Cenozoic

40 (Conrad and Lithgow-Bertelloni, 2007). A careful analysis by Becker et al.
41 (2009) concluded that the present-day area vs. age distribution of the seafloor
42 accounts for significant fluctuations of the rate of seafloor production in the
43 past 200 My, an interpretation opposite to that reached by Parsons (1982)
44 and Rowley (2002).

45 Here we investigate the global dynamics of seafloor spreading using two
46 independent modelling approaches: state-of-the-art plate reconstructions and
47 geodynamic models. Both kinematic reconstructions and geodynamic models
48 converge to suggest that the rate of production of new seafloor can vary by
49 a factor of 2 over a Wilson cycle, with concomitant changes of the shape of
50 the area-age distribution of the seafloor.

51 **2. The area-age distribution of the seafloor**

52 The evolution of the area-age distribution of the seafloor through time is
53 of fundamental importance since it impacts on global variations in heat flow,
54 tectonic forces and sea-level. The area-age distribution provides a statistical
55 representation of the state of the seafloor. It can be used to quantitatively
56 compare seafloor spreading states with different continental configurations
57 and plate distributions.

58 The evolution of the area-age distribution has been the subject of in-
59 tense debate in the past 30 years. The present-day distribution displays a
60 linear decrease of the area for increasing age. Young seafloor dominates, but
61 areas with ages as old as 180 Ma exist. The shape of this distribution is
62 called triangular. The physics behind this distribution has been questioned
63 by Labrosse and Jaupart (2007), particularly because it suggests that litho-

64 sphere of young age (hot) is subducted with the same probability as that of
65 older ages (cold). Indeed, a principle of convection is that when a material
66 at the surface of a thermal boundary layer of convecting fluid has cooled suf-
67 ficiently its buoyancy becomes large enough to start sinking into the viscous
68 interior. The onset of the downwellings corresponds to a critical value of the
69 local Rayleigh number, which in dimensional values can be converted to a
70 critical age. As a consequence, convection appears to favour the sinking of
71 lithosphere only when a critical age is attained, implying that a rectangular
72 distribution is expected.

73 Two effects can be proposed to force a convective system to adopt a
74 distribution that is skewed (or triangular): continent configuration and time-
75 dependence of the flow. Continents are relatively unsinkable and conductive,
76 therefore the entire continental area cannot participate in seafloor spreading
77 and subduction. As observed on Earth today, subduction zones tend to
78 locate themselves at the continent-ocean boundary. As shown in Figure 1,
79 the orientation and shape of the subduction zone along a continent, relative
80 to the opening ridge governs the shape of the area-age distribution.

81 The time-dependence of seafloor spreading also implies modifications of
82 the area-age distribution, as proposed earlier by Demicco (2004). Indeed,
83 since the integral of the distribution is the total seafloor area, a conserved
84 quantity in recent geological time, increasing the rate of production of new
85 seafloor necessarily involves the sinking of older seafloor. As shown in Fig-
86 ure 2, fluctuations of seafloor production can lead to triangular-like shape.
87 The more time-dependent the system is, the more variable the area-age dis-
88 tribution can be. However, the time-dependence of the rate of production

89 of new seafloor has been challenged by Parsons (1982) and Rowley (2002),
90 who propose that the fluctuations in the past 150 My do not exceed 30%
91 of the present-day value. In the following we will address the extent of the
92 time-dependence with the most recent plate reconstructions and mantle con-
93 vection models.

94 **3. Reconstructed seafloor history since 200 Ma**

95 We reconstruct the seafloor spreading history for the past 200 million
96 years based on a merged absolute reference frame (O'Neill et al. (2005) and
97 Steinberger and Torsvik (2009)) with relative plate motions based on Seton
98 et al. (2012). The plate reconstructions are underpinned by over 70,000 mag-
99 netic anomaly and fracture zone identifications for currently preserved crust.
100 For crust that has been subducted, we use simple assumptions of spreading
101 symmetry, adherence to the rules of plate tectonics and onshore geological
102 data to constrain our plate reconstructions (Müller et al., 2008; Seton et al.,
103 2012). We extend the model back to the Triassic (250 Ma) by incorporating
104 a longer history of seafloor spreading between the three major plates that
105 form Panthalassa (Izanagi, Farallon, Phoenix plates) similar to its Jurassic-
106 Cretaceous opening history, the closure of the Mongol-Okhotsk Ocean based
107 on Van der Voo et al. (1999) and a more extensive paleo-Tethys ocean largely
108 consistent with Stampfli and Borel (2002) and Golonka (2007). Our plate re-
109 constructions also include an accompanying set of continuously closed plate
110 polygons (CPP) and plate boundaries (Gurnis et al., 2012) allowing us to
111 track the properties of the plates themselves through time.

112 In the Triassic, the vast Panthalassic and the smaller Tethys Ocean sur-

113 rounded the supercontinent, Pangaea. Panthalassa, modeled as a simple
114 three plate spreading system between the Izanagi, Farallon and Phoenix
115 plates dominated the planet, accounting for over half of its surface area. The
116 expansion of the Tethys Ocean at the expense of the palaeo-Tethys (which
117 was being consumed along the Tethyan subduction zone) was accommodated
118 by the Meso-Tethys spreading ridge system. The predominant plate bound-
119 ary regime operating in the Triassic/Jurassic was subduction, particularly
120 around the rim of Panthalassa and along the northern Tethyan margin.

121 By 200 Ma, Pangaea was undergoing slow continental break-up centered
122 along a rift zone extending along the north and central Atlantic, through
123 eastern Africa and southern South America (Figure 3) leading to the onset
124 of a progressive increase in ridge lengths and increasing crustal production
125 (Figure 4). The initial break-up separated Pangaea into Laurentia, Laurasia
126 and the China/Amuria block in the northern hemisphere and Gondwanaland
127 in the southern hemisphere. The birth of the Pacific plate within Panthalassa
128 at 190 Ma and the change from rift to drift along the central Atlantic initi-
129 ated a period of younging of the ocean floor and increase in the global ridge
130 length. The final break-up of Pangaea was established by 160 Ma, dividing
131 Gondwanaland into its eastern and western portions via rifting and seafloor
132 spreading between Africa, India, Antarctica, Madagascar and east Gond-
133 wana. The closure of the palaeo-Tethys, composed of mature oceanic crust
134 was completed by around 170 Ma and the Mongol-Okhotsk Ocean by 150 Ma.
135 The continual growth of the Pacific plate at the expense of the Izanagi, Far-
136 allon and Phoenix plates led to an increasing length of mid ocean ridges and
137 production of young ocean crust in the Pacific domain (Figure 3). The higher

138 proportion of new crust produced at the mid ocean ridges compared to old
139 crust being destroyed along the subduction zones of the northern Tethys and
140 circum-Panthalassa is reflected in the change from a rectangular-like area-age
141 distribution during Pangaea amalgamation towards a triangular distribution,
142 reflecting a scenario consistent with a near constant production of oceanic
143 lithosphere compared to what is destroyed, similar to the present-day state
144 of the planet (Figure 3).

145 The early-mid Cretaceous marks a significant increase in seafloor spread-
146 ing rates in Panthalassa, as documented by magnetic lineations in the Pacific
147 Ocean (Larson and Chase, 1972; Nakanishi and Winterer, 1992; Seton et al.,
148 2009). Seafloor spreading occurred in a complex arrangement between the
149 Pacific, Farallon, Izanagi and Phoenix plates. At 120 Ma, spreading was
150 further complicated by the break-up of the Ontong-Java-Manihiki-Hikurangi
151 plateaus (Taylor, 2006; Chandler et al., 2012), leading to a marked increase
152 in the length of the mid ocean ridge system until its termination at ~ 85 Ma.
153 During this time period, the majority of old ocean floor on the edges of Pan-
154 thalassa was subducted, leaving behind a significantly younger Panthalassic
155 ocean per unit area and the highest rates of crustal production observed
156 from Mesozoic to the present day (Figure 4). The mid Cretaceous also cor-
157 responds to the peak time for African intra-continental rifts, associated with
158 the opening of the South and Equatorial Atlantic. While the mid ocean ridges
159 of the Meso-Tethys were progressively being subducted along the southern
160 Eurasian margin, the spreading systems of the proto-Indian Ocean such as
161 the west Australian margins, the Enderby Basin and along east Africa were
162 producing new crust. The mid Cretaceous (120-80 Ma) is characterized by

163 a minimum of the average age of oceanic lithosphere (~ 38 My old), mid
164 ocean ridge lengths ($> 60,000$ km), crustal production rates (> 5.5 km y^{-1})
165 (Figure 4) and a substantial decrease in the proportion of older ocean floor
166 being subducted. This is shown in the skewness of the area-age distribution
167 reflecting a high proportion of young ocean floor at this time compared to
168 older ocean floor.

169 Since the peak of crustal production and seafloor spreading rates in the
170 mid Cretaceous, there has been a progressive decline in seafloor spreading
171 rates (Seton et al., 2009), crustal production (Figure 4) and a steady increase
172 in the area-age distribution of the oceanic lithosphere. Although the decline
173 in crustal production initiated at around 80 Ma, there is a major inflection
174 point in mid ocean ridge lengths and age of the oceanic lithosphere at 60-
175 50 Ma, related to the destruction of the margin-wide Pacific-Izanagi ridge
176 system and consumption of remnants of the Izanagi plate. This major event
177 marked the change over from a skewed distribution towards a triangular
178 distribution indicating the more constant crustal production that we observe
179 today.

180 Over the last 250 My, our reconstructions predict that the seafloor pro-
181 duction rate changes quite significantly, by a factor of 2 to 3, contrary to
182 previous studies based on present day preserved ocean crust (Parsons, 1982;
183 Rowley, 2002). We find that the rates of crustal production and the area-
184 age distributions can be related to cycles of supercontinent amalgamation
185 and break-up. Supercontinent amalgamation is related to a rectangular-like
186 distribution and low/moderate crustal production rates whereas break-up
187 is associated with a triangular distribution, which eventually develops into

188 a skewed distribution towards the young end as progressively new crust is
189 created at the expense of older crust.

190 **4. Convection models with seafloor spreading and continental drift**

191 -Mantle convection with self-consistent plate generation is an indepen-
192 dent and complementary approach to plate tectonic reconstructions for the
193 investigation of the fluctuations of seafloor spreading. Convection models
194 with self-consistent plate generation provide an analog of Earth's mantle
195 convection which, contrary to the plate reconstructions of tectonic history
196 that are limited in time, allows for the investigation of how seafloor spread-
197 ing may have functioned over longer geological time. However, convection
198 models themselves cannot compute a solution directly comparable to the
199 Earth because, for instance, initial conditions are unknown. The numeri-
200 cal models employed in this study are the first generation of 3D spherical
201 mantle convection models that self-consistently generate a form a seafloor
202 spreading and continental drift. They are built on successive generations
203 of software that started with the cartesian models of Tackley (2000) incor-
204 porating pseudo-plasticity, were extended to spherical geometry (van Heck
205 and Tackley, 2008) and now include a basic model of continental lithosphere
206 (Yoshida, 2010; Rolf and Tackley, 2011), represented as thick, buoyant and
207 100 times more viscous rafts. The numerical models used here are described
208 in more detail in Rolf and Tackley (2011) and Rolf et al. (2012). The resolu-
209 tion here is improved relative to our previous publications, reaching as little
210 as 30 km vertically in the top boundary layer. This resolution appears rel-
211 atively crude, but is sufficient to resolve the physical processes studied here

212 (when made possible, observed differences with regards to results of Coltice
213 et al. (2012) using lower resolution are small) and is limited by the fact that
214 computing a 3D time-dependent spherical mantle convection solution with 7
215 orders of magnitude variation in viscosity is already very demanding.

216 Tackley (2000) developed diagnostics to evaluate how the computed so-
217 lutions reproduce characteristics of Earth’s plate dynamics: the plateness,
218 which evaluates how close surface motion is to that of rigid plates deforming
219 only at their boundaries, mobility, which evaluates whether surface plates are
220 moving with a similar velocity to underlying mantle flow, and the toroidal
221 to poloidal ratio, which evaluates the role of transform motion. The com-
222 puted solutions presented here display a high degree of plateness, mobility
223 and toroidal to poloidal ratio, similar to those presented in van Heck and
224 Tackley (2008). They generate area-age distributions which are often trian-
225 gular, as that of the present-day Earth (Coltice et al., 2012), suggesting a
226 form of seafloor spreading comparable to observations. The continental rafts
227 drift apart in the presented models but breakup is slower than observed on
228 Earth (supercontinents can persist for 500-1000 My). The description of the
229 continental lithosphere (which on Earth has weaker and thinner parts) and
230 of the rheology, which could include a memory component, would potentially
231 improve this aspect, especially for more effective dispersal. Such models are
232 currently in development.

233 The models presented here are at statistical steady-state. Heating is
234 internal except in one case with 14% basal heating. Three values of the
235 non-dimensional yield stress (the maximum stress material can sustain, be-
236 fore deforming plastically) are used here: 5×10^3 (low), 10^4 (intermedi-

237 ate) and 1.5×10^4 (high), ensuring a plate-like regime for surface motions
238 with and without continental rafts (Rolf and Tackley, 2011). Higher yield
239 stresses would lead to surface tectonics that is absent (stagnant lid regime) or
240 episodic, i.e. displaying times without any production or consumption of new
241 seafloor interrupted by short events of very high production and consump-
242 tion. Such a regime is not investigated here since it does not represent
243 the modern Earth. Cases without continents, with a supercontinent, and
244 with 6 identical continents are considered. The total continental area is kept
245 at 30% of the surface area of the spherical domain. The Rayleigh number
246 (based on the temperature drop over the surface boundary layer) is, 10^6 , 10
247 to 100 times lower than expected on Earth, for computational reasons. As
248 a consequence, timescales are computed with respect to a transit time of
249 85 My as described in Gurnis and Davies (1986). The calculations are run
250 for at least 3 Gy such that statistics of seafloor production rate and average
251 root-mean square (rms) surface velocity can be made. The seafloor area-age
252 distribution in the models is computed by converting heat flow into an age
253 assuming a half-space cooling model, following the approach of Labrosse and
254 Jaupart (2007) used in Coltice et al. (2012).

255 **5. Synthetic seafloor histories**

256 *5.1. An example of seafloor spreading history*

257 Figure 5 shows 746 My of evolution of seafloor spreading and continental
258 drift in a model with 6 continents, intermediate yield stress (10^4) and 14%
259 of core heating. The first 4 model snapshots have been chosen to encompass
260 200 My and be similar in duration to the reconstruction sequence shown

261 in Figure 3. This sequence is characterised by relatively little continental
262 motion, and thus highlights the effect of seafloor spreading dynamics. The
263 bottom snapshot, taken 549 My later, shows a situation in which the conti-
264 nents have significantly drifted, reflecting a major tectonic reorganisation.

265 The tectonic evolution in the 200 My sequence displays a situation for
266 which subduction is located mostly around the continents, with 3 main
267 oceanic domains: a western domain with an elongated NE-SW ridge sys-
268 tem with a clear triple junction in the North; a median domain with a long
269 N-S ridge system, and an eastern domain with a E-W ridge system. At
270 746 Ma, the median and eastern domains encircle a continent, ultimately
271 aggregating on the West side to close a section of the N-S ridge system. At
272 664 Ma, after this closure, the N-S ridge system starts to divide into 2 parts
273 at the equator. The eastern domain starts to be more active, as younger
274 seafloor ages dominate. At 603 Ma, new ridge systems have appeared in
275 the median and eastern domains, the western domain being stable in terms
276 of plate boundaries but production of young seafloor accelerates. A triple
277 junction in the South of the median domain has progressed towards the sub-
278 duction zone at the edge of a continent. At 549 Ma, the seafloor production
279 rate in the eastern domain decreases and the 2 ridge systems of the median
280 domain have differentiated. Given the area-age distribution, the average age
281 of the seafloor is slightly older than in the previous state. The situation at
282 0Ma contains continents that have drifted with 3 aggregated continents in
283 the North and 3 aggregated continents in the South. The eastern domain is
284 closing and has almost disappeared. The group of continents that are almost
285 connected at 40°S are here dispersed with a ridge system connecting the me-

286 dian and western domain. An ocean-ocean subduction in the North-West is
287 generated, highlighted by older ages.

288 This example of a seafloor spreading history computed from a convection
289 model shows significant variations in of the area-age distribution, compara-
290 ble to those in the plate reconstructions. This is a representative example
291 for the computed models here. At 746 Ma, seafloor spreading is the slowest
292 within Figure 5 and the ridge system is the shortest. The area-age distri-
293 bution is rectangular-like, with a production rate of new seafloor lower than
294 $3 \text{ km}^2 \text{ y}^{-1}$. At 603 Ma, where elongation of the ridge system is important,
295 the distribution is skewed and the production rate of new seafloor reaches
296 $5.2 \text{ km}^2 \text{ y}^{-1}$. Hence, the production rate of new seafloor has doubled over
297 143 My and the area-age distribution has changed accordingly. The other
298 snapshots show intermediate states, which differ from each other, but display
299 triangular-like area-age distributions like that observed on Earth today.

300 *5.2. Seafloor production evolution*

301 The rate of production of new seafloor is calculated by computing the
302 area that has ages between 0 and 8 My. The maximum seafloor age barely
303 changes in our calculations, being between 200 and 250 My. Because the total
304 area of the seafloor is constant, a change in the rate of production of new
305 seafloor implies a change in the shape of the global distribution, as discussed
306 earlier: older ages have to disappear if new seafloor is generated, and the
307 distribution becomes more skewed. If the rate of production of new seafloor
308 decreases, the distribution becomes more rectangular-like (see Figure 5 at
309 746 Ma or 549 Ma). Hence the evolution of the rate of production of new
310 seafloor depicted in Figure 6 also expresses the variability of the shape of the

311 distribution.

312 The average production rate of new seafloor is slightly higher in our nu-
313 merical solutions than on the present-day Earth. The lowest average produc-
314 tion rate is for the case with a supercontinent, at $3.7 \text{ km}^2 \text{ y}^{-1}$. The highest
315 production rate is for the case with the lower yield stress, i.e. the weaker
316 lithosphere, at $6.3 \text{ km}^2 \text{ y}^{-1}$. The yield stress is anti-correlated with the av-
317 erage production rate. The stronger the lithosphere, the lower the average
318 production rate of new seafloor.

319 The fluctuations in the production rate occur in short and intense events
320 in cases with continents and low to intermediate yield stress. The production
321 rate can vary by a factor of 2-3 over 100 My. Such events happen at most
322 once every 1Gy. Without continents and in particular with a higher yield
323 stress, such events barely exist. The case with the strongest lithosphere is
324 least time-dependent, since peak-to-peak fluctuations do not exceed a factor
325 of 2 of the average value. This is reflected by the standard deviation, which is
326 the smallest (15%) for the present calculations; for other cases it is around
327 20-23%, and and 30% for the supercontinent case. The effects of a small
328 amount of core heating (here: 14%) are small, but higher core heating rates
329 should be explored in the future since recent estimates point to higher values
330 (Pozzo et al., 2012).

331 The fluctuations in the production rate correlate with the surface velocity.
332 However, peaks in the production rate do not correspond in all cases to peaks
333 in the surface velocity, or at least peaks of the same relative increase. This
334 result confirms the observations made on Figure 5: peaks of production also
335 correspond to increase of ridge length. Hence, the length of ridges varies

336 significantly with time. Methods to quantify precisely the ridge length in
337 such models are under development.

338 *5.3. Timescales of seafloor production fluctuations*

339 To investigate the significance of different periods in the time-series of
340 the rate of production of new seafloor, we have computed periodograms per-
341 forming Fourier transform, which provide an estimate of the spectral density
342 of the time series of the production of new seafloor. Figure 7 shows that
343 all models display dominant timescales. No convection model presented here
344 features significant periods smaller than 100 My. Most models have major
345 periods around 200 My and 800 My. The supercontinent case and the higher
346 yield stress case both have fluctuations at >1 Gy periods. The case with
347 the strongest lithosphere shows a very long-term period, comparable to the
348 duration of the run. However, because of the truncation of the run length
349 there is certainly a bias for such a long period. Therefore, very long periods
350 with significant power should not be over-interpreted since they suggest pe-
351 riods that >1 Gy are present. Moreover, convection solutions in this study
352 are at statistical steady-state with constant heat sources. Hence, they do not
353 represent seafloor spreading changes caused by the slow cooling of the planet,
354 which becomes significant over a 1 Gy time scale. Interactions between the
355 cooling timescale and the long timescales found here with a constant heat
356 budget are expected. As a consequence, stronger fluctuations over >1 Gy
357 should exist.

358 Because convection is a self-organising system, it is difficult to interpret
359 timescales. However, the timescale of 200 My could correspond to the insta-
360 bility onset (Howard, 1964), since it corresponds to the maximum age of the

361 seafloor. The longer peak period between 600 and 900 My, could be the time
362 of global reorganisation of the system: it corresponds to the overturn time,
363 and to the time it takes for a continent to move around the sphere (assuming
364 a velocity of 3 cm y^{-1}). The cases with the longer periods are characterized
365 by longer-wavelength flows. Indeed, increasing the yield stress (van Heck and
366 Tackley, 2008) or the individual size of a continent (Rolf et al., 2012) results
367 in longer wavelength of convection. This suggests that the longer periods in
368 the supercontinent and stiff lithosphere cases could emphasise the fact that
369 very large-scale plate boundary topologies could be stable over a very long
370 time. However, additional calculations would need to be performed to inves-
371 tigate the origin of the long period evolution of the production rate of new
372 seafloor.

373 **6. Discussion**

374 *6.1. Limitations*

375 Tectonic reconstructions and convection models presented here have limi-
376 tations that must be acknowledged when making interpretations. As already
377 explained, uncertainties in the reconstructions depend on the quantity and
378 quality of available data, which generally decrease going further back in time.
379 Another source of uncertainty comes from the limitations of plate tectonics
380 theory, since deformation in continents and in some specific areas in ocean
381 basins is diffuse. However, the reconstructions presented here do take some
382 large-scale deformation of continents into account. Convection models are
383 themselves limited in resolution and in the physics for which they solve. In-
384 deed, the targeted 1km resolution suggested by static studies, is out of reach

385 (Alisic et al., 2012). As a consequence, the convective vigour is here lower
386 than that of the Earth’s mantle and the impact of the evolution of convec-
387 tive vigour because of decaying radioactive heat sources is not studied here.
388 The material properties are much more complex on Earth, and the rheol-
389 ogy employed is simplified compared to what is expected for mantle rocks
390 (Bercovici and Ricard, 2012). These limitations arise because of compu-
391 tational resources and experimental/theoretical gaps. The most important
392 symptoms of these limitations in the present models are the difficulty in ob-
393 taining continents that break up as efficiently as on Earth, and existence of
394 symmetric subduction in oceanic regions (plates on both sides of the suture
395 sink). Solving these issues is work in progress (Crameri et al., 2012). Current
396 computational limitations forced us to be limited to 6 convection calculations;
397 however, due to the rapidly expanding power of high performance computers
398 it will be possible to explore this parameter space better in the near future.

399 *6.2. Convergence of tectonic reconstructions and convection models*

400 Both tectonic reconstructions and convection models show that the dis-
401 tribution of seafloor ages varies significantly over 200 My. Indeed, periods
402 of tectonic quietness display area-age distributions that are rectangular-like
403 with small production rates of new seafloor, while periods of generation of
404 new plate boundaries feature area-age distributions that are skewed with the
405 maximal production rate of new seafloor. Intermediate periods have more
406 triangular-like distributions as the Earth has today.

407 The production rate of new seafloor varies by a factor of 2 in both tec-
408 tonic reconstructions and convection models, and fluctuates over various
409 timescales, including a 200 My timescale that corresponds to the maximum

410 age of the seafloor. Such variations corroborate the hypothesis that the
411 present-day area-age distribution results from strongly time-dependent pro-
412 duction of new seafloor (Demicco, 2004; Becker et al., 2009; Seton et al.,
413 2009). The rms surface velocity varies significantly in both reconstructions
414 (Conrad and Lithgow-Bertelloni, 2007; Seton et al., 2009) and models, corre-
415 lating with production of new seafloor. However, reconstructions and convec-
416 tion models suggest that changes in ridge length are as important as changes
417 in rms surface velocity regarding fluctuation of seafloor production. The re-
418 constructions in Figure 3 and the convection sequence in Figure 5 display
419 significant ridge length changes. For example, the development of the ridge
420 systems in the Tethys and Atlantic Oceans in the Early Cretaceous (Fig-
421 ure 3) corresponds to increases in ridge length and spreading rate by 20%
422 and 40% respectively, concomitantly with an 30% increase in crustal produc-
423 tion (Seton et al., 2009). In the convection sequence, direct measurements
424 on the 664 Ma and 603 Ma synthetic maps lead to a ridge length increase
425 by $20\% \pm 5\%$ in 61 My caused by the development of a new ridge system
426 (Figure 5).

427 This convergence holds with the different yield stresses (producing plate-
428 like behavior) and with a limited amount of core heating. Tectonic recon-
429 structions and convection models suggest that both time-dependence and the
430 geometry of the flow/continental boundaries play an important role in the
431 consumption of young seafloor.

432 *6.3. Predictions of convection models over longer timescales*

433 The convection models provide the long timescale perspective. Our cal-
434 culations show that variability of seafloor spreading over timescales longer

435 than 200 My is significant. However, no other end-member distributions
436 than rectangular-like, triangular-like and skewed are observed. The produc-
437 tion rate of new seafloor evolves also over 600-900 My, which may correspond
438 to the time needed to reorganise the convective flow on a global scale. Long
439 periods suggest that some oceanic domains could persist for almost 1 Gy. The
440 Pacific domain, being a remnant of Panthalassa, could represent a potential
441 example.

442 Convection models question the existence of sudden peaks of production
443 of new seafloor reaching 2.5 times the average value. Such events, displaying
444 very intense generation of new ridges and subduction zones, and disruption
445 of the plate organisation, happen over a 600-900 My period. They are not
446 necessarily correlated with peaks of plate velocity. However, these peaks do
447 not exist if the lithospheric strength is higher while still obtaining smoothly-
448 evolving plate tectonics (i.e. avoiding the episodic tectonics regime). As a
449 consequence, additional observations are needed to evaluate if such dynamics
450 is relevant to the Earth. Sea-level reconstruction in deep time, for instance,
451 could help to qualify the relevant behaviour for the lithosphere to be used in
452 convection models.

453 **7. Conclusions**

454 Although they are independent modelling approaches, both tectonic re-
455 constructions and convection models with plate-like behaviour and conti-
456 nental lithosphere converge to support that seafloor spreading fluctuates
457 significantly over 200 My. Indeed, the shape of the area-age distribution
458 is time-dependent and changes from rectangular-like in periods of tectonic

459 quietness, to skewed in periods of generation of new plate boundaries. The
460 triangular-like distribution of the present-day Earth corresponds to an inter-
461 mediate state. In the past 200 My, aggregation of Pangaea led to a quiet
462 period and dispersal phases involved subsequent skewed distributions. The
463 convection models show that seafloor spreading dynamics itself, without sig-
464 nificant continental drift, can lead to such time-dependence. Therefore, both
465 kinematic reconstructions and convection models converge to show that the
466 area-age distribution of the seafloor does not remain triangular. Over a pe-
467 riod of 200 My, the production rate of new seafloor varies by a factor of 2 in
468 both tectonic reconstructions and convection models. Both reconstructions
469 and convection models suggest that changes in ridge length are as impor-
470 tant as changes in spreading rates. Time-dependence over longer timescales
471 (600-900 My and eventually >1 Gy) is suggested by convection models. As a
472 consequence, some oceanic domains could persist for periods as long as Wil-
473 son cycles and eventually longer. Sudden and extreme peaks of production
474 of new seafloor may exist sparsely over time, occurring at most once every
475 billion years. However, observations are needed to constrain the strength of
476 the lithosphere in convection models to confirm the existence of such events
477 on Earth.

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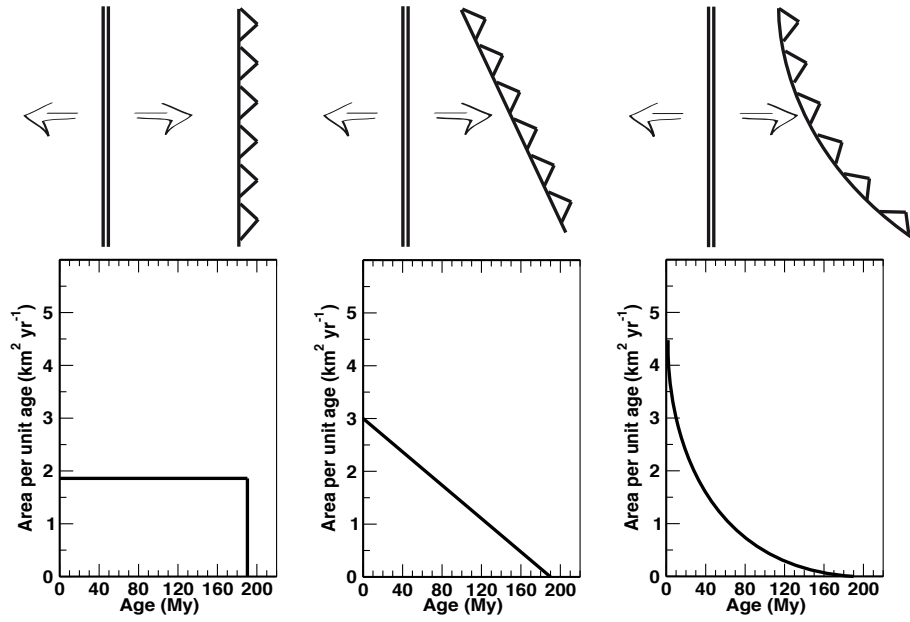


Figure 1: The shape of the area-age distribution depends on the geometry of plate boundaries.

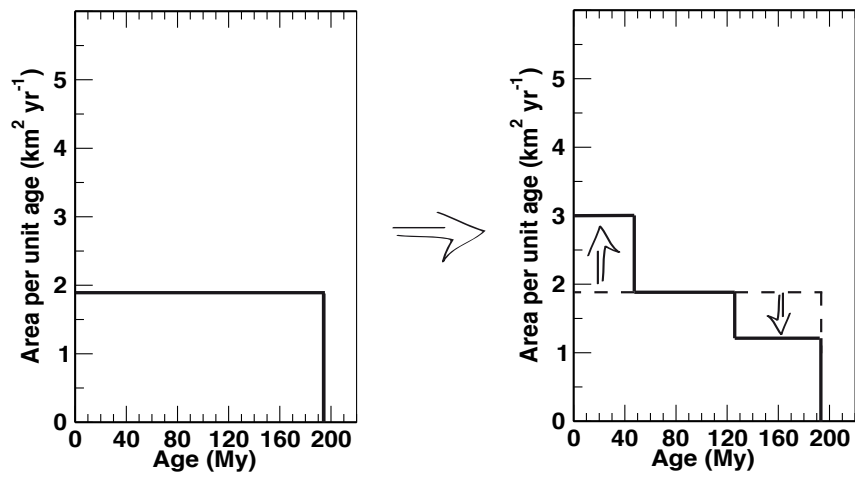


Figure 2: The time dependence of the production of new seafloor implies changes of shape of the area-age distribution.

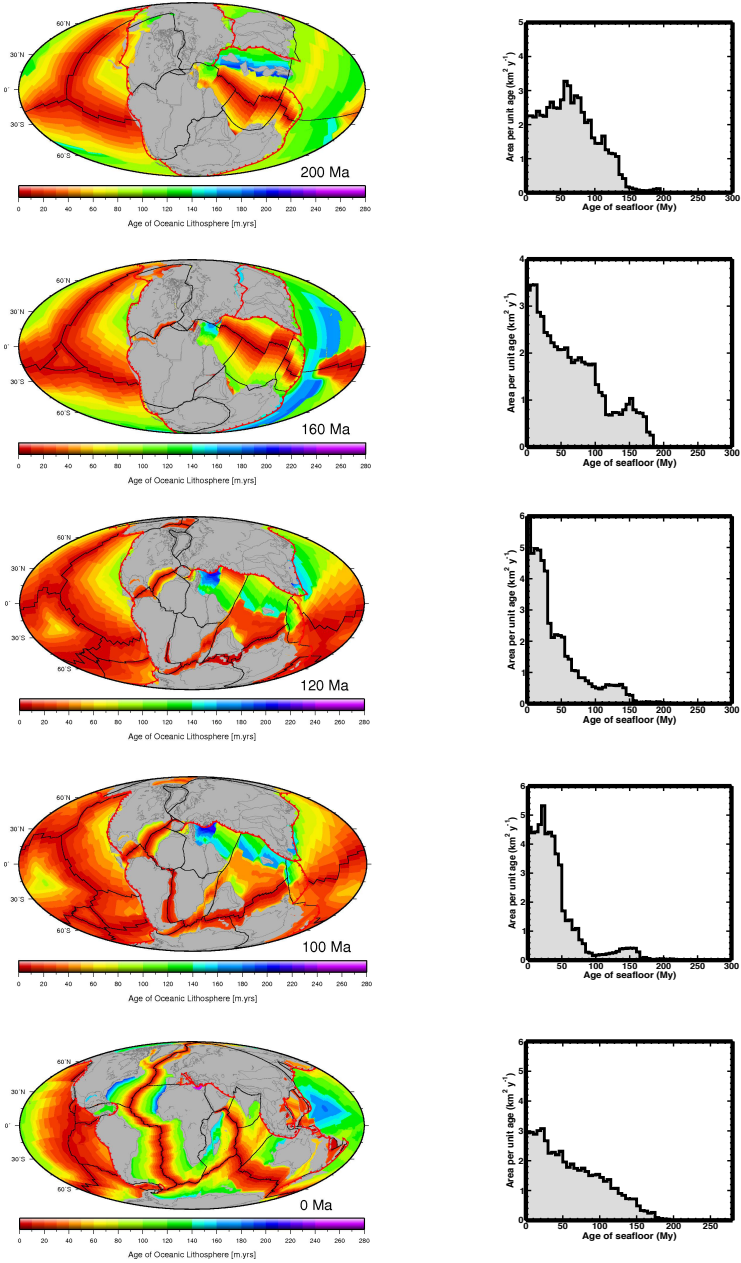


Figure 3: Maps of reconstructed distribution of seafloor ages and associated area-age distributions in the past 200 My (Seton et al., 2012).

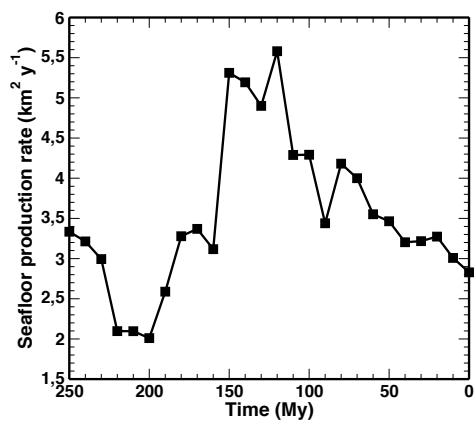


Figure 4: Reconstructed evolution of the rate of production of new seafloor derived from the plate tectonic reconstructions of Seton et al. (2012).

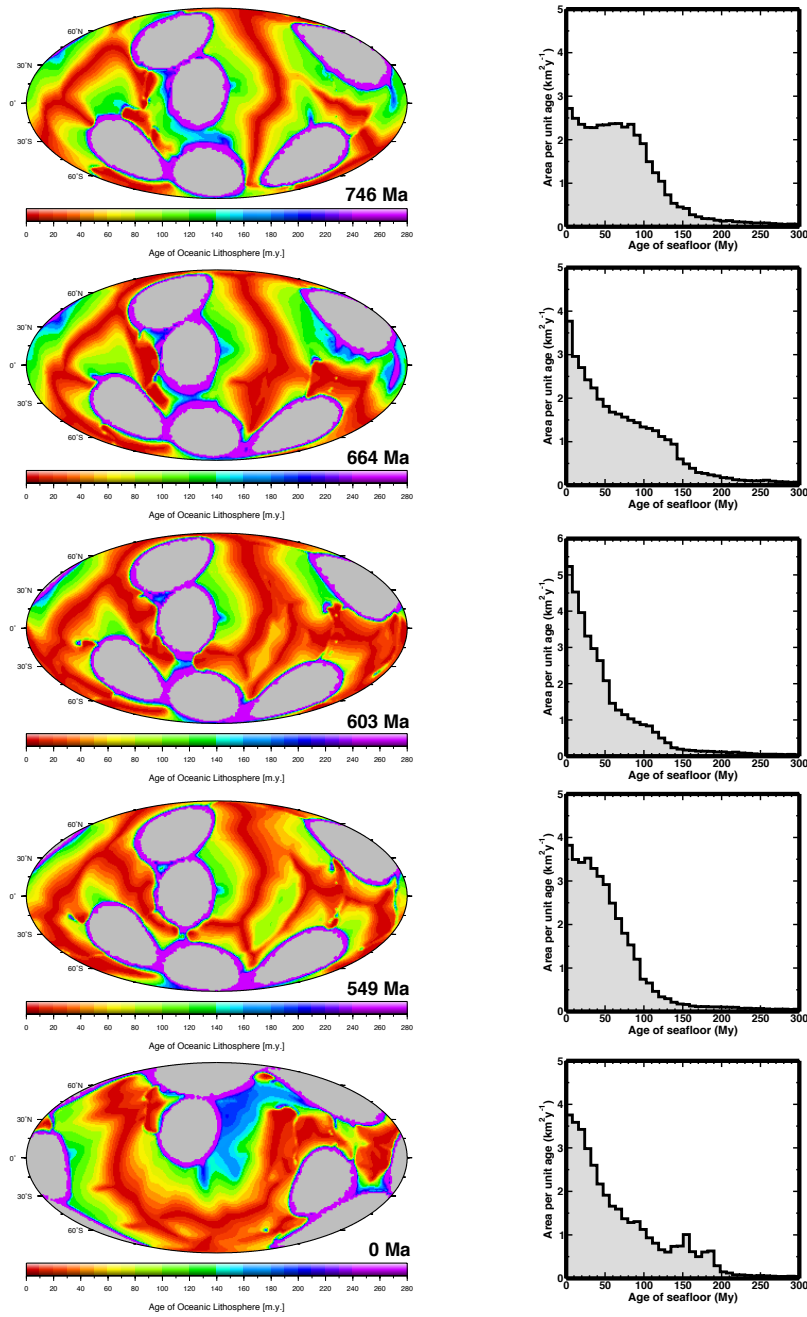


Figure 5: Synthetic maps of seafloor ages and associated area-age distributions in the mantle convection model with 6 continental rafts and 14% of core heating. The gray area represents the continental area. The selected results present 200My of evolution in the first four rows and the situation 549My after that 200My evolution.

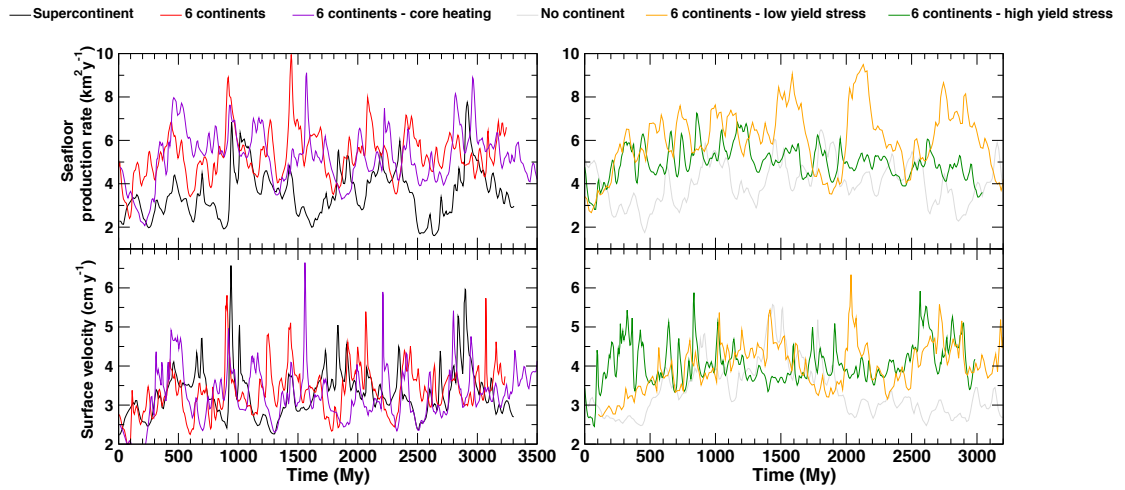


Figure 6: Computed evolution of the rate of production of new seafloor and RMS surface velocity in convection models. The solutions are for an intermediate yield stress value of 10^4 , except for the low (5000) and high yield stress solutions ($2 \cdot 10^4$). Core heating corresponds to 14% of the whole heat budget.

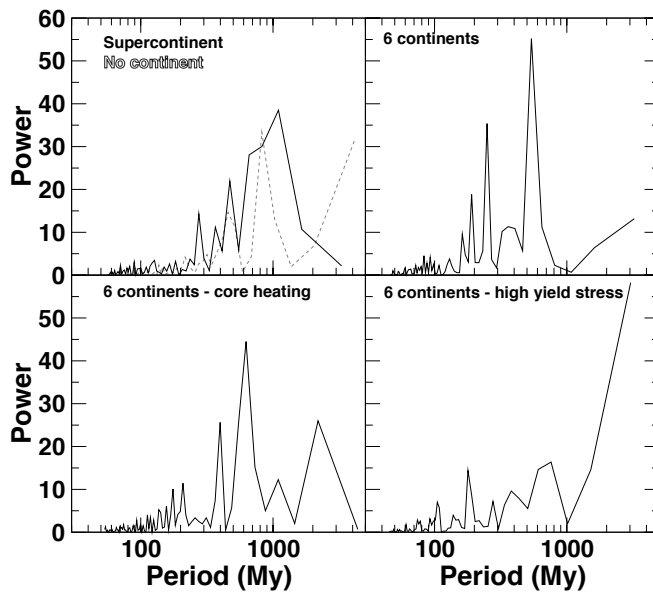


Figure 7: Periodograms of the production rate of new seafloor in the mantle convection models obtained by Fourier transform of the time-series. Periods with large power dominate the spectral content of the time-series and can be interpreted as the characteristic timescales of the system.