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# Mean age of oceanic lithosphere drives eustatic sea-level change since Pangea breakup

Jean-Pascal Cogné [a,*], Eric Humler [a,b,1], Vincent Courtillot [a]

[a] Institut de Physique du Globe de Paris et Université de Paris 7, 4 place Jussieu, 75252 Paris cedex 05 — France
[b] Laboratoire de Planétologie et Géodynamique, Université de Nantes, 4 rue de la Houssinière, 44322 Nantes cedex 3 — France

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**Abstract**

The Atlantic and Indian Oceans and the oceanic part of the Antarctic plate have formed at the expense of Panthalassa as a result of Pangea breakup over the last 180 Myr. This major plate reorganization has changed the age vs. surface distribution of oceanic lithosphere and has been a likely driver of sea-level change. Assuming that the age/surface structure of Panthalassa has remained similar to the present-day global distribution from 180 Ma to Present, and using the isochron patterns preserved in the newly formed oceans, we model resulting relative sea-level change. We find a first (slower) phase of sea-level rise (by 90 to 110 m), culminating between 120 and 50 Ma, followed by a (faster) phase of sea-level drop. We show that this result is not strongly sensitive to our hypothesis of constant mean age of Panthalassa, for which much of the information is now erased due to subduction. When the effects of oceanic plateau formation and ice cap development are added, the predicted sea-level curve fits remarkably well the first-order variations of observed sea-level change. We conclude that the changes in mean age of the oceanic lithosphere (varying between 56 and 62 ± 0.2 Myr), which are simply the expression of the Wilson cycle following Pangea breakup, are the main control, accounting for ∼ 70%, of first-order changes in sea-level.


*Keywords:* oceans; sealevel; eustacy; global changes; Pangea breakup

## 1. Introduction — the Pangea breakup

It is well known that over time intervals of hundreds of millions of years, sea-level has fluctuated by several hundred meters. The main evidence is the changing area of marine sediment deposited on continents through time, indicating that at certain periods continents were flooded by seawater far more extensively than they are today. It is often proposed that the most likely cause of large-scale changes in sea-level is the variable volume of ridge material [1], which can produce variations with an amplitude of several tens of meters. If seafloor spreading increases, then the ridge crest volume starts to increase, displacing water and causing additional flooding of continental areas. The critical quantity is the area of seafloor produced per unit of time. This can be changed either by an increase in spreading rate (for a ridge crest of constant length) as proposed by Kominz [2], or by an increase in the length of ridge crest, or by some combination of the two. There are reasons,

* Corresponding author. Equipe de Paléomagnétisme, Institut de Physique du Globe de Paris et Université de Paris 7, 4 place Jussieu, 75252 Paris cedex 05 — France. Tel.: +33 1 44 27 60 93.
*E-mail addresses:* cogne@ipgp.jussieu.fr (J.-P. Cogné), Eric.Humler@univ-nantes.fr (E. Humler).
[1] Tel.: +33 2 51 12 52 64.

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however, to question the foundations upon which this linkage is based, because recent studies fail to show evidence for large variations in either oceanic spreading rate or global ridge length [3–5].

Various processes, other than mid-oceanic ridge dynamics, can affect sea-level over time scales of tens to hundreds of millions of years, such as ice cap growth, ocean sediment volume changes, surface reduction of continental lithosphere, ocean temperature variations, continental breakup, true polar wander events, etc. Some studies (e.g. [6,7]) emphasized that long-term sea-level highstand during the Late Cretaceous was preceded by a major change in plate motions — the breakup of Pangea. In particular, based on the models of Heller and Angevine [8], Heller et al. [7] proposed model curves of sea-level changes in the Mesozoic and Cenozoic. Assuming (1) that the world consists of two oceans, a "rectangular" Atlantic-type ocean and a "triangular" Pacific-type ocean, including the Indian Ocean ("rectangular" and "triangular" refer to the shape of $\{dA/dt\}=f(t)$ curves), (2) that the entire Atlantic rifted simultaneously, (3) that the production rate ($km^2$ $yr^{-1}$) remained constant in the Atlantic, and (4) that subduction consumes as much young crust as old throughout time, these authors demonstrated that this mechanism produces a ~ 100 m sealevel rise and fall between 180 Ma and the Present, with a highstand between 70 and 120 Ma.

We attempt to refine the effects of such a mechanism, using a different approach based on the direct measurement of actual oceanic crust surfaces delineated by ocean floor isochrons. Using the isochron patterns of Royer et al. [9] and Müller et al. [10], we propose a model of evolution of surface/age distribution, as new oceans formed during breakup of Pangea, and the older Panthalassa was being consumed. Our analysis is thus based on (1) a determination of the evolution as a function of time of oceanic lithosphere surfaces in the Atlantic, Indian and circum-Antarctic oceans basins based on the more recent isochron database [9,10], and (2) a model of surface/age balance through time of Panthalassa, excluding Indian and circum-Antarctic oceans, associated to a direct measurement of Panthalassa area at each reconstruction time. Note that in doing so, we avoid strong hypotheses on variations in spreading rates, which are still a matter of debate (e.g. [2–5,11]). Finally, although the basic mechanism is somewhat identical to the one proposed by Heller and Angevine [8], we here propose a detailed analysis of Atlantic, Indian and circum-Antarctic isochrons, rather than relying on models of rectangular Atlantic-type and triangular Pacific-type (including the Indian and Antarctic basins) oceans.

## 2. Mechanism and surface balance

Let us first briefly recall Earth evolution since the Late Carboniferous (~ 250 Ma). At that time, continents were assembled in a single unit called Pangea, surrounded by a global ocean named Panthalassa, including 3 main units: Mongol–Okhotsk, Tethys, and paleo-Pacific oceans (Fig. 1a). This configuration remained quite stable for about 70 million years. At 190–180 Ma, the super-continent Pangea began to rift apart to form the central Atlantic ocean, with North America rotating away from Africa. Concurrently, the Mongol–Okhotsk ocean began to vanish, and closure was achieved by ~ 135 Ma [12–14]. At about 160 Ma, the Somalia and Southwest Indian basins opened, when a plate composed of Madagascar, India, Antarctica and Australia (East Gondwana) rotated away from East Africa (partly west of Gondwana). East Gondwana broke up between ~ 120 and ~ 90 Ma, opening the rest of the Indian ocean. The main episode of Tethys ocean closure began at ~ 100 Ma (e.g. [15]), during the fast northward drift of India, which collided with Eurasia at 50 Ma [16]. Prior to this time, at about 130 Ma, the South Atlantic ocean opened, and the whole Atlantic (central and southern parts) continued opening up to the Present, mainly at the expense of the paleo-Pacific, propagating in the north Atlantic area and separating North America, Greenland and Europe. The distribution of magnetic lineations on the seafloor [9,10] can be used to reconstruct the positions of the continents for the past 150 Myr. Because there is little seafloor older than this, reconstructions prior to about 180 Ma are primarily based on paleomagnetic measurements in continental rocks [17,18] together with geological studies of orogenic belts.

The basic idea underlying the way in which such a history could have led to sea-level changes is the following (e.g. [7]): when Pangea existed, say between ~ 250 and 180 Ma, the global ocean, Panthalassa (Fig. 1a), with its three main units, Tethys, Mongol–Okhotsk, and paleo-Pacific oceans (including now vanished or partially subducted parts such as Izanagi, Kula, Farallon, Cocos and Nazca plates), was an old, or "average" ocean. The meaning of "old" or "average" is discussed below. Importantly, this ocean started being consumed due to the expansion of new oceans, such as the Atlantic and Indian oceans, and to the expansion of the Antarctic plate as well. Note that, in the present analysis, all the now subducted Tethyan parts of the Indian ocean, north of the northern margin of India, and between Africa and Eurasia, are included in Panthalassa, not in Indian ocean history. Therefore, this older ocean (Fig. 1d) started

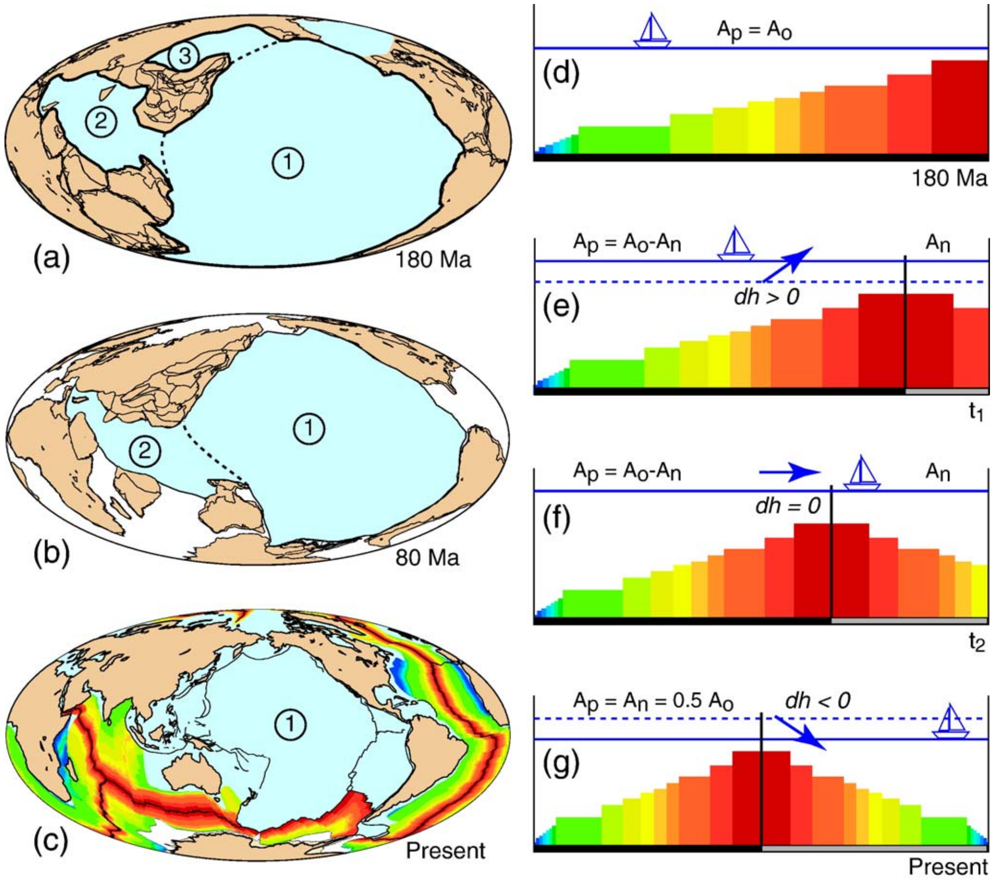


Fig. 1. *Left column:* Hammer–Aitoff projections centered on 180° Longitude illustrating the reduction of Panthalassa from 180 Ma (a) to the Present (c) through 80 Ma (b); circled 1, 2 and 3: paleo-Pacific, Tethys and Mongol–Okhotsk oceans respectively; limits between these units (black dotted lines) are arbitrary; (c) Present-day configuration with isochrons in Atlantic and Indian oceans, and oceanic part of the Antarctic plate, following Royer et al. [9] and Müller et al. [10]; the Pacific area is intentionally left blank (see text). *Right column:* Schematic sketch of the proposed mechanism for sea-level change between 180 Ma (d) and the Present (g), shown as seafloor topography and water depth (vertical) vs. crust age, as percentages of the global ocean area A (horizontal); although schematic, the distributions in (d) and (g) reflect the present-day distribution of global oceanic surfaces; in each box (d) to (g) the colored bars represent the percentage of oceanic crust of a given age range (width), vs. depth under sea-level (blue lines); the color scale follows the isochron color scale of Müller et al. [10] (see Fig. 2b) modified for Gradstein et al. [36] magnetostratigraphic scale, with hot (cold) colors for young (older) lithosphere; A: area of the oceans; subscripts $o$, $p$ and $n$ stand for Total, Panthalassa and New oceans respectively; black and grey bars at the bottom of each box underline the relative amount of Panthalassa (black) and new oceans (grey) respectively; blue arrows and d$h$ indicate the sense of expected sea-level change between each step; $t_1$ and $t_2$ are intermediate ages between 180 Ma and the Present.

to be progressively replaced by a younger, hence shallower, ocean, thus leaving less place for water than was available above the older, deeper and disappeared, subducted crust (Fig. 1e). Then, because new oceans subsequently grow older and deeper, more space became available again (Fig. 1f). Finally, the present-day situation (Fig. 1g), in which the Pacific (including Nazca and Cocos) represents approximately half of the global ocean, and the others, the other half, was attained. At this stage, both parts have a similar surface/age structure (Fig. 1g), and globally, this structure is identical (in terms of space available for seawater) to the one we model at the starting age of 180 Ma (Fig. 1d). Thus, sea-level has come back to its initial value at 180 Ma.

Because of constant Earth radius and continental lithospheric surfaces, it can be confidently assumed that the total oceanic lithospheric area has remained constant in the last 200 Myr. On the other hand, based on the isochron maps of Royer et al. [9] and Müller et al. [10], one can assume that the new oceans which formed following Pangea breakup, the Atlantic and Indian oceans (excluding their Tethyan parts), together with the oceanic part of the Antarctic plate, have not been significantly subducted in any part. Indeed, there are exceptions to this simplifying first-order scheme, in the northeastern Indian ocean (Sumatra subduction) and in the western Central Atlantic (Caribbean arc), but they are thought to be of secondary importance for the present model. Therefore, the measurement of oceanic crust segment areas delineated by isochron patterns in these oceans (Fig. 1c) can be used as a proxy for the history of disappeared old Panthalassa surfaces during geological times since 180 Ma.

This measurement has been made by several authors, since global isochrons became available (e.g. [3,4,19]), demonstrating growth of these oceans by ~ 150 million $km^2$ (M $km^2$) since the beginning of breakup. Using the global paleogeographic reconstructions of Besse and Courtillot [17,18], including Müller et al. [10] for major continental plates, and Yang and Besse [20] for Asian microplates (e.g. Fig. 1a and b), we have checked that the area of Panthalassa was indeed reduced from ~ 300 to ~ 150 M $km^2$ between 180 Ma and the Present. This surface decrease was achieved first by closure of the Mongol–Okhotsk ocean at 135 Ma, then by closure of the Tethys ocean, accompanied by reduction of the paleo-Pacific ocean.

## 3. Model and results

The birth of new oceans decreases the average age of the seafloor and should, therefore, decrease the global volume of ocean basins. In order to quantify this effect, we first need to know the surface/age structure of Panthalassa, from at least 180 Ma to the Present. This appears to be impossible for older and totally subducted oceans such as Mongol–Okhotsk, rather speculative for Tethys [21] which is completely subducted as well, and quite difficult for the paleo-Pacific (e.g. [22–24]), a large part of which has also been subducted. In order to circumvent this problem, we have based our reconstructions, on a first-order, more conservative model. This model is based on the generally accepted ideas of Sclater et al. [19] and Parsons [25], that the currently observable seafloor age distribution results from (1) a triangular $\{dA/dt\}$ distribution arising from constant crustal production at the global scale and (2) subduction of oceanic lithosphere which is independent from the age of the crust. Because neither the global ridge lengths [2,4], nor the spreading rates [3–5] on these ridges have significantly varied in the past, we assume that this seafloor age distribution can be extrapolated to the last 180 Myr for Panthalassa. Practically, we modelled the average, or the old, whole Panthalassa ocean (including Tethys with its north India and north Africa margins, Mongol–Okhotsk and paleo-Pacific oceans) as an average ocean having a maximum crust age of 180 Ma at each time step, with a surface/age balance similar to the present-day global one, and a subduction rate independent from the lithospheric age. In contrast, we directly determined the evolution, from 180 Ma to Present, of the oceanic basins volume generated by the new oceans (Atlantic, Indian, oceanic part of Antarctic; AIA for short in what follows) from the measurement of surface/age structure currently observable in these oceans (Fig. 1c). Finally, we determined the volumes of oceanic basins by using two different depth vs. age relationships (i.e. [26,27]).

The balance of oceanic basin volume changes due to Panthalassa subduction and newly generated volumes in the AIA oceans, given a constant global oceanic surface (Fig. 1d to g), produces the relative sea-level changes illustrated in Fig. 2a and b. The red curves are derived from the assumptions discussed above. The blue ones include plateau formation and ice cap growth as explained below. Figures a and b correspond to the two depth vs. age models. The first, obvious fact in these figures is that our simple model predicts sealevel rise during the Cretaceous, stabilization between ~ 100 and 50 Ma, and a fall since ~ 50 Ma. The model curves (red and blue curves in Fig. 2a and b) are in phase with the eustasy curve of Haq et al. ([28]; dashed black lines) and its first-order variation (solid black lines). We further point out that even the shapes (overall dissimetry) of the curves are in close agreement, with a relatively slow rise of sea-level before 100 Ma and a sharper fall after 50 Ma (Fig. 2). This confirms the results of Heller and Angevine [8] and Heller et al. [7] and underlines the important fact that Pangea breakup does have a eustatic effect which is in first order agreement with observations as summarized by Haq et al. [28].

However, amplitudes predicted by our original model (red curves in Fig. 2) are not in close agreement with observations. Indeed, modelling the effects of Pangea breakup alone leads to only ~ 90 to ~ 110 m of relative sea-level change (Fig. 2a and b). Although the largest amplitude (Fig. 2b) is obtained when using the geochemically based age vs. depth relationship of Humler et al. [27], it hardly exceeds 110 m. We thus follow Harrison [29] and Heller et al. [7] in arguing that other significant phenomena, not directly linked to oceanic crust dynamics, might enhance the magnitude of these changes: these are the emplacement of oceanic plateaus between 120 and 70 Ma, which may have led to an additional ~ 60 m sea-level rise, and the growth of ice caps in the past 40 Myr which may have caused a ~ 80 to ~ 60 m fall in sea-level [29]. Other minor effects (e.g. sedimentary fluxes, continental crust thinning before ocean opening, continental crust reduction in collision

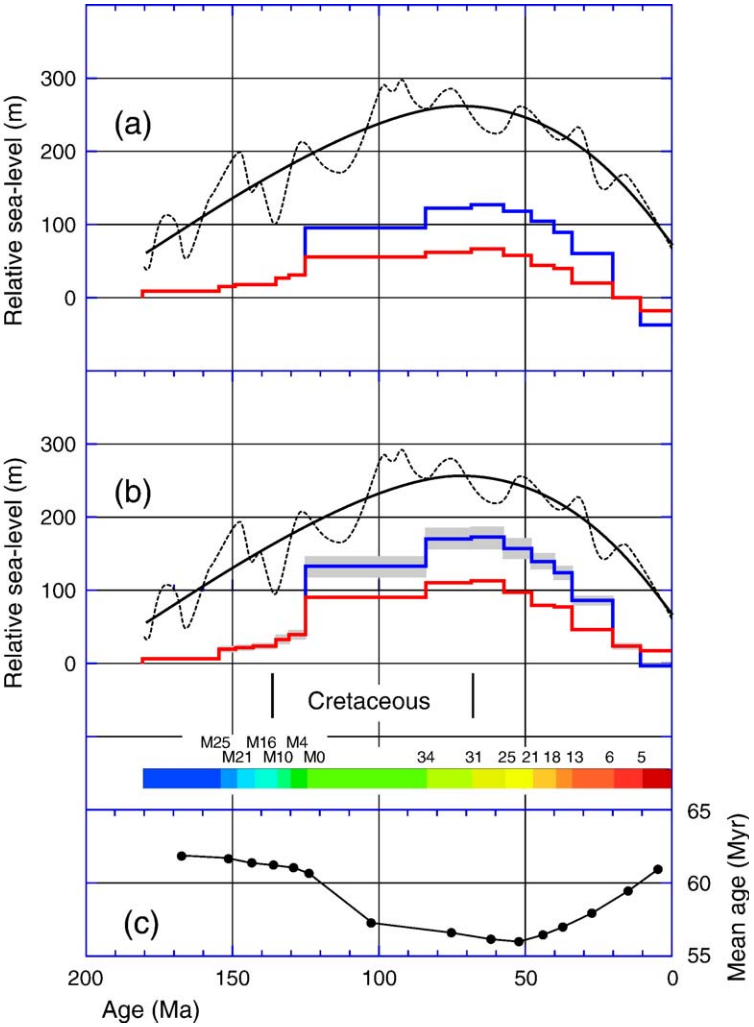


Fig. 2. (a) and (b) curves of relative sea-level (in m, left scale) from 180 Ma to the Present; black dotted curves: digitization of Haq et al. [28], in Hardenbol et al. [30], relative sea-level curve; black solid curves: 3rd-order polynomial adjustment on the first-order sea-level variation; red curves: model of sea-level variation due to Pangea breakup as proposed in this paper, using the depth vs. age models of (a) Stein and Stein [26] and (b) Humler et al. [27]; blue curves: same as previous ones, but adding plateau and ice cap growth as suggested by Harrison [29] and Heller et al. [7]; the grey area in (b) suggests the uncertainty on these models; these are relative curves, which explains the offset between experimental (black) and modelled (red and blue) curves; in our model, we have taken the zero line of sea-level at an age of 180 Ma, whereas Haq et al. [28] chose 60 m of height for the present-day "zero" sea-level. (c) Global weighted mean age of oceanic lithosphere (in Myr, right scale) as modelled from 180 Ma to the Present; uncertainties are less than 0.2 Myr. Color bars follow the isochron color scale of Müller et al. [10] modified for Gradstein et al. [36] magnetostratigraphic scale.

zones, etc…) may be involved. Adding plateaus and ice cap growth effects increases predicted model amplitudes (blue curves in Fig. 2a and b) to ~ 170 to ~ 180 m respectively, with an uncertainty on the order of ±15 m. It should be noticed, however, that these simple calculations do not take into account any isostatic effects (e.g. [29]) which could lower down sea level amplitude by about 30%. Further error could arise from our simplifying assumption of a constant average surface/age structure of Panthalassa through time. More detailed assumptions on the structure of the paleo-Pacific may further improve the correlation. Another reason for mismatch could be due to inaccuracy of the eustasy chart [28,30] which is far from being universally accepted (e.g. [31]), and we finally note that the ~ 100–150 m amplitude of sealevel variations we propose appear consistent with other proposed models of Sahagian et al. [32] and Miller et al. [33]. Altogether, therefore, we conclude that first-order sea-level changes seem to be primarily driven by a mechanical effect (ocean lithosphere balance in surface/age distribution through times), to which are added the effects of oceanic plateau production and ice cap growth, without the need to resort to changes in the rates of oceanic crust production (e.g. [2–4,34]).

Furthermore, we point out that the mechanism of Pangea breakup predicts that the oceanic lithosphere as a whole should exhibit an episode of rejuvenation, due to the opening of young oceans, followed by progressive ageing of the new oceans. To test this idea, we have computed the mean age of the oceanic lithosphere as the sum of the ages of individual crustal segments bounded between pairs of successive isochrons, weighted by the area percentage of each of these segments, for each reconstruction interval from 180 Ma to the Present. The resulting weighted mean age varies between 56 and 62 Myr, and is clearly anticorrelated with sea-level changes (Fig. 2c). We note that the ~ 6 Myr amplitude of mean age variation we obtain in measuring the oceanic segments is in good agreement with the one proposed by Heller and Angevine [8] on the basis of their model. Here again, we observe a good phase correlation between the two signals, with slow increasing sea-level correlated to slow decreasing mean lithospheric age, and the sharper sea-level fall correlated to sharper increasing age.

## 4. Robustness of the mean oceanic crust age vs. sealevel relationship

We therefore conclude that a significant part of first order sea-level change is primarily controlled by the mean age of the oceanic lithosphere. We now test the robustness of this inference viz. some of our underlying assumptions. For instance, we have assigned Panthalassa, which is largely unknown in this respect, a constant average lithospheric age of 62 Ma through geological time since 180 Ma (the rest of the Global Ocean being measured via the actual isochron patterns) i.e. the present-day value. Because Tethys, Mongol–Okhotsk, and large parts of the Pacific oceans have disappeared, and the overall surface has decreased by ~ 50% between 180 Ma and the Present in going from Panthalassa to the Pacific, we have no means to check the detailed age structure of this ocean in the past. In other words, because some of our more important conclusions are based on a strong assumption on Panthalassa surface/age structure (thus, mean age), we need to explore the sensitivity of our conclusions to this assumption further.

We have therefore tested the effects of different models of mean age evolution of Panthalassa crust (Fig. 3a), on the shape of the global oceanic mean age curve (Figs. 2c

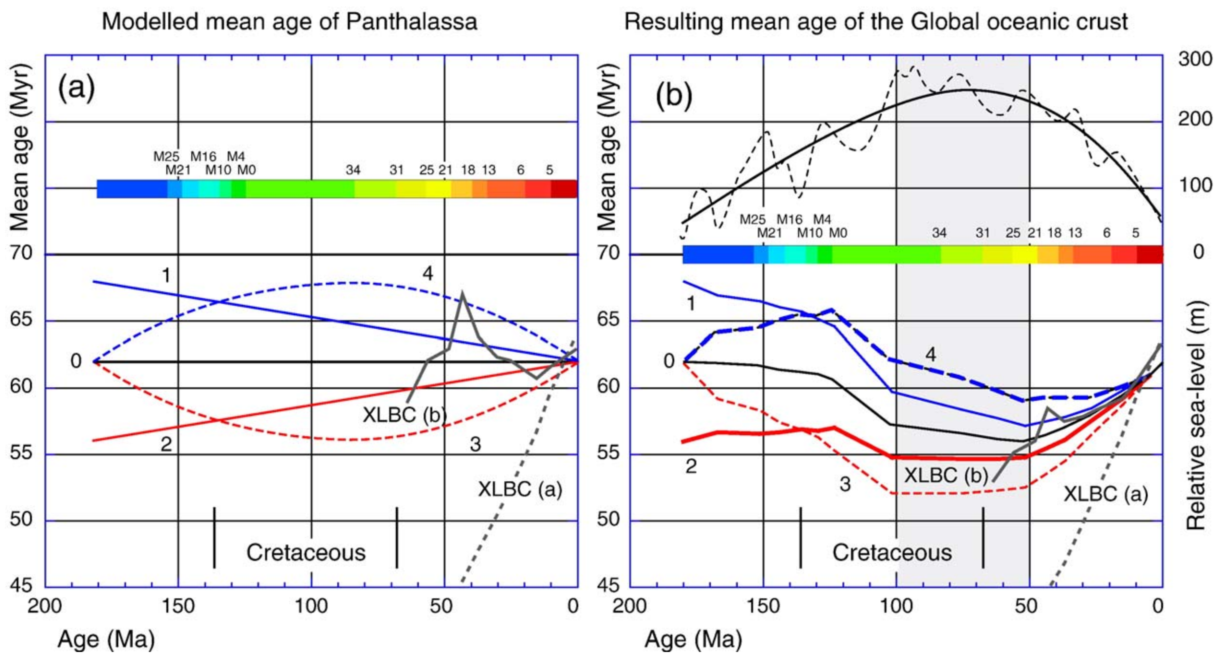


Fig. 3. (a) Curves of modelled Panthalassa crust mean age (in Myr) as a function of geological age (in Ma) following Models 0 to 4 (see text); grey dotted XLBC(a) and continuous XLBC(b) curves: paleo-Pacific mean age deduced from Gordon and Jurdy [23] and Hall [35] respectively (after Fig. 5(a) and (b) of Xu et al. [24]). (b) Bottom: Global oceanic crust mean age (in Myr) as a function of geological age (in Ma) resulting from Models 0 to 4 (see text); Top: first-order sea-level in meters (black dotted curve) following Haq et al. [28], and smoothed sea-level evolution from 180 Ma to the Present (black curve), as a function of age (in Ma); grey area underlines period between 100 and 50 Ma; color bars in (a) and (b) as in Fig. 2.

and 3b). Model 0 (black line in Fig. 3a) is the one presented above, where the mean age of Panthalassa crust is assumed constant through times at 62 Ma, the present-day value of the global oceanic crust. Models 1 (blue line, Fig. 3a) and 2 (red line) involve linear decrease and increase, respectively, of the mean age of Panthalassa crust, from 180 Ma to the Present, with an empirical amplitude of 6 Myr. Models 3 (dotted red curve, Fig. 3a) and 4 (dotted blue curve) involve smoothly variable mean ages of Panthalassa, starting at 62 Myr at 180 Ma (same as Present), with respectively a decrease or an increase arbitrarily fixed at 90 Ma. Here again, the amplitude is empirically fixed at 6 Myr. These five, simple models are sufficient to test the response of global sea level variations to reasonable changes in Panthalassa age distribution.

We have next computed changes in the global weighted mean age of oceanic lithosphere predicted from these models of Panthalassa mean ages. Whichever model is used, the creation of new AIA oceans at the expense of the older one induces a significant, asymmetric dip in the curves of global mean age vs. time. Notwithstanding the model used, the minimum occurs between 100 and 50 Ma (grey area in Fig. 3b), i.e. the time of sealevel highstand (black curves, Fig. 3b), and the decrease in mean oceanic crust age before 100 Ma is slower than the rise after 50 Ma. These two features, which correlate with the smooth increase and sharper decrease of sea level during these periods, are robust whichever Panthalassa age model is used.

As could be guessed from inspection of Fig. 3, the (anti)correlation coefficient between observed first order sea level change and the prediction of Model 0 is high and significant, at −0.94. Models 1 to 4 lead to correlation coefficients ranging from −0.44 to −0.97. Of course, the minimum correlation is formed with Model 4, in which assumed Panthalassa age structure fully opposes the observed sea level change. Yet, even in this “worse case” scenario, the main features of Cretaceous younging followed by faster Cenozoic ageing of the global crust, and related sea level variations are preserved.

Indeed, models in which Panthalassa shows null to positive increases in mean age in the past (Models 0, 2 and 3, Fig. 3) better correlate with sealevel change. This is actually supported by detailed studies of oceanic structure in the Pacific. We have plotted the paleo-Pacific reconstructions of Xu et al. [24] for the last 65 Myr in Fig. 3 (grey curves), computed after the previous reconstructions of Gordon and Jurdy [23] (XLBC(a) dotted grey curve, Fig. 3) and Hall [35] (XLBC(b), continuous grey curve, Fig. 3). Although it shows some scatter around our model, the more recent XLBC(b) curve appears highly consistent with our study in the 0–65 Ma period, which supports the mechanism of ocean lithosphere rejuvenation due to Pangea breakup proposed here.

## 5. Conclusions

We believe that the main result from this study is that Pangea breakup controls a significant part of sea-level variations since 180 Myr, in line with the models of Heller and Angevine [8] and Heller et al. [7]. We based our results on direct computation of oceanic lithosphere surfaces encompassed between isochron pairs in newly formed oceans (Atlantic, Indian and oceanic part of Antarctic), assuming a model of surface/age structure for Panthalassa. Two key assumptions were that: (1) the newly formed oceans accreted at the expense of Panthalassa; (2) due to the difficulty of modelling the age structure of the subducted oceanic segments in Panthalassa, including the vanished Mongol–Okhotsk and Tethys oceans, and the largely consumed paleo-Pacific plates (including all or parts of Kula, Izanagi, Farallon and Cocos), we assumed an average age/surface distribution within this ocean similar to the present-day global one. The surface/age structure balance between this modelled Panthalassa and the observed, actual surface distribution of the Atlantic, Indian and Antarctic oceans/plates between 180 Ma and the Present is a major forcing mechanism which accounts for approximately half of first order sea-level change, due to the rejuvenation of the global oceanic lithosphere. There is no need to resort to a pulse in oceanic production in mid-Cretaceous times, consistent with the conclusions of Heller et al. [7]. Regardless of the model of age evolution of Panthalassa oceanic crust, rejuvenation of global lithosphere ages occurs between 100 and 50 Ma. This rejuvenation appears to be well correlated with first-order sealevel change in the last 180 Myr, and is therefore a candidate as a first-order forcing mechanism, accounting for ~ 90 to 110 m (~ 70%). However, first order sea-level change also results from the addition of two other important mechanisms, oceanic plateau production and ice caps development, contributing respectively ~ +60 m in the 120–70 Ma period, and ~ −60 to 80 m since 40 Myr. First-order sea-level change is probably a good proxy of mean oceanic lithospheric age, which has itself evolved in the past as a result of Wilson cycles of supercontinent fractionation and amalgamation.

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