

Mid-Cretaceous seafloor spreading pulse: Fact or fiction?

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ABSTRACT

Two main hypotheses compete to explain the mid-Cretaceous global sea-level highstand: a massive pulse of oceanic crustal production that occurred during the Cretaceous Normal Superchron (CNS) and the “supercontinent breakup effect,” which resulted in the creation of the mid-Atlantic and Indian ocean ridges at the expense of subducting old ocean floor in the Tethys and the Pacific. We have used global oceanic paleo-age grids, including now subducted ocean floor and two alternative time scales, to test these hypotheses. Our models show that a high average seafloor spreading rate of 92 mm/a in the Early Cretaceous that decreased to 60 mm/a during the Tertiary, with peaks of 86 mm/a and 70 mm/a at 105 Ma and 75 Ma ago, respectively, correspond to the two observed sea-level highstands in the Cretaceous. Calculations using GTS2004 produce lower seafloor spreading rates during the same period and diminish the mid-Cretaceous spreading pulse. Global ridge lengths increased in the earliest Cretaceous but stayed relatively constant through time. However, we find that the average age of the ocean basins through time is only weakly dependent on the choice of time scale. The expansive mid- and Late Cretaceous epicontinental seas, coupled with warm climates and oxygen-poor water masses, were ultimately driven by the younger average age of the Cretaceous seafloor and faster seafloor spreading rather than a vast increase in mid-ocean ridge length due to the breakup of Pangea or solely by higher seafloor spreading rates, as suggested previously.

INTRODUCTION

A major debate in geosciences is centered on causes that led to substantial global sea-level fluctuations through time. Dramatic changes that occurred during mid-Cretaceous time (120–80 Ma ago), such as prolonged magnetic field stability, large igneous province (LIP) eruption, a sea-level highstand, variations in atmospheric CO₂, and anoxia, have been linked to a massive pulse of rapid seafloor spreading (Larson, 1991b). However, Heller et al. (1996) argued that proxies of mid-Cretaceous seawater geochemistry do not correlate with the postulated increase in seafloor spreading activity and explained the Cretaceous rise in global sea level through natural changes in the age-area distribution of oceanic lithosphere due to cycles of continental breakup and amalgamation.

Three additional factors play a significant role in controlling ocean volume change through time, namely the generation of oceanic LIPs, oceanic sedimentation (Miller et al., 2005), and changes in total oceanic crustal area. Rowley (2002) and Cogne et al. (2006) suggested that changes in global sea level are mostly due to episodic creation of volcanic plateaus rather than changes in global seafloor spreading rates and are based on the assumption that the age-area distribution of oceanic lithosphere has remained constant since the breakup of Pangea. However, recent studies (Becker et al., 2009; Demicco, 2004; Müller et al., 2008b) have shown that the present-day age-area distribution cannot be used to infer ocean basin history, suggesting non-steady-state production of oceanic crust through time.

We aim to address the mid-Cretaceous spreading pulse controversy by computing the age-area distribution of oceanic lithosphere, mid-ocean ridge lengths, crustal production, and seafloor spreading rates since the Early Cretaceous. We follow the methodology of Müller et al. (2008b) and use an associated plate rotation model (Müller et al., 2008a; Steinberger and Torsvik, 2008; Torsvik et al., 2008). Our approach differs from previous studies primarily due to our detailed reconstruction of all known ocean basins from the Early Cretaceous to present rather than a simple extrapolation of the present day, which may provide misleading results. Ultimately such models are relevant for separating eustatic from regional tectonic controls on basin sedimentation, enhancing our fundamental understanding of how stratigraphic cycles form in sedimentary basins.

OCEANIC CRUST EVOLUTION SINCE THE CRETACEOUS

Larson and Pitman (1975) provided the idea of a mid-Cretaceous spreading pulse after they found evidence of a vast mid-ocean ridge system in the Pacific Ocean in the mid to Late Cretaceous. Subsequent detailed mapping of magnetic M-sequence anomalies in the NW Pacific confirmed this observation (Nakanishi and Winterer, 1998). Larson (1991b) pioneered the idea that the spreading pulse was triggered either by a superplume originating from the core-mantle boundary (Larson, 1991a) or by an elevation of the 670 km boundary due to a sudden slab penetration into the lower mantle (Larson and Kincaid, 1996).

Seafloor spreading rates have mainly been assessed using global tectonic reconstructions (Hays and Pitman, 1973; Kominz, 1984), sea-level changes (Gaffin, 1987), subduction history (Engebretson et al., 1992), and the present-day seafloor age distribution (Conrad and Lithgow-Bertelloni, 2007). Kominz (1984) attempted to evaluate plate generation rates for the past 80 m.y. using a global tectonic model and concluded that spreading rates decreased since the Late Cretaceous. Gaffin (1987) found a smoother decrease in spreading rate from 120 Ma ago to present when inverting the Vail et al. (1977) sea-level curve. Similar results were obtained by assessing the subduction history of the Circum-Pacific realm (Engebretson et al., 1992). Larson (1991b) introduced oceanic plateau volumes to the model of Kominz (1984) and reported an increase in crustal production by 50% to 100% from 125 to 80 Ma ago. This spectacular increase was believed to be due to higher spreading rates and extensive formation of LIPs. Heller et al. (1996) later criticized this idea, instead proposing that asymmetries in spreading, increases in ridge length, and changes in the age-area distribution of oceanic lithosphere were responsible for changes in the mid-Cretaceous oceanic basins. Conrad and Lithgow-Bertelloni (2007) computed average half spreading rates from the present-day age grid (Müller et al., 1997) using a length-weighted approach and found rapid changes in Cenozoic spreading rates.

To test these hypotheses, we use a comprehensive kinematic model that incorporates (1) Cretaceous to present plate reconstructions based on a global database of marine geophysical data interpretations (including the Arctic oceans and backarc basins), (2) reconstructed spreading histories of the Pacific, Phoenix, Izanagi, Kula, and Farallon plates and the plates involved in the Tethys domain, and (3) a merged moving hotspot (Late Cretaceous to present) and true polar wander (TPW)-corrected (Steinberger and Torsvik, 2008; Torsvik et al., 2008) (Early Cretaceous) reference frame, resulting in a set of global oceanic age grids (Müller et al., 2008a; Müller et al., 2008b). Our age grids differ from those presented in

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Müller et al. (2008b) for times prior to 100 Ma ago due to our switch to a TPW-corrected reference frame. In addition, we test two alternative time scales—CK95G94 (Cande and Kent, 1995, between present and 83 Ma ago; Gradstein et al., 1994, for older times) and GTS2004 (Gradstein et al., 2004)—which are substantially different in terms of the duration of the Cretaceous Normal Superchron (CNS) and, therefore, in terms of the amplitude of any mid-Cretaceous seafloor spreading pulse.

Global gridded data of oceanic crustal age, crustal production, and lengths of the paleo-mid-ocean ridge system have been used to extract information on active oceanic seafloor spreading since the Cretaceous in five-million-year intervals (Fig. 1). Mid-ocean ridge lengths were computed (Fig. 1C) by separating the fracture zone and ridge segments. In order to analyze the evolution of oceanic area due to the Pangea breakup, we have computed separate values for all parameters in the Pacific and the rest of the world (Fig. DR1 in the GSA Data Repository¹). Global spreading rate gridded data for the past 140 m.y. were also computed using our global set of finite reconstruction rotations (Fig. DR2). However, as described in Conrad and Lithgow-Bertelloni (2007), extracting mean spreading rate values along the active ridge using an age/area-based cutoff is biased toward faster-spreading ridges. We find this bias is a factor of two. Consequently, we calculated spreading rate values from crustal production and ridge lengths. All spreading rate values quoted are full spreading rates.

We observe a steady increase in the age of oceanic lithosphere from the Late Cretaceous (42 m.y.) to the present day (64 m.y.), representing a 22 m.y. increase in mean crustal age (Fig. 1A). This change from substantially younger ages in the Cretaceous to older ocean floor at present correlates with the transition from high sea level in the Cretaceous to progressively lower sea level throughout the Cenozoic (Fig. 1E). We find that the mean paleo-age of oceanic lithosphere is only very weakly dependent on the choice of time scale, with a maximum difference of only 2 m.y. (Fig. 1A).

As the mean age of the global oceanic crust increased through time (Fig. 1A), a general decrease in crustal production is observed from Late Cretaceous to present, from 4×10^6 km²/Ma at 80 Ma ago to $<3 \times 10^6$ km²/Ma in the late Tertiary (Fig. 1B). In the Early to mid-Cretaceous, the choice of time scale produces differing results: CK95G94 shows higher crustal production rates of 5×10^6 km²/Ma, whereas GTS2004 has a maximum of 3.9×10^6 km²/Ma in the mid-Cretaceous. A sudden decrease in global oceanic crustal production occurred between 120 and 115 Ma ago and between 75 and 50 Ma ago due to the subduction of the Meso-Tethys ridge system and the Izanagi-Pacific ridge, respectively.

Cumulative global mid-ocean ridge lengths show peaks at 120–110, 100, and 70 Ma ago (Fig. 1C). A continuous mid-ocean ridge developed between West Africa and South America between 100 and 95 Ma ago (Torsvik et al., 2009); new ridges were created at ca. 83 Ma ago in the Mascarene Basin (Storey, 1995), Tasman Sea (Hayes and Ringis, 1973), and between West Antarctica and the Pacific (Larter et al., 2002); and a plate tectonic reorganization in the Pacific (after 78 Ma ago) resulted in the formation of the Kula plate, leading to an increase in the global seafloor spreading system. Although the long-term trend of mid-ocean ridge lengths has remained relatively constant, there is an increase in the Early Cretaceous from 53,000 km to 64,000 km (Fig. 1C) primarily driven by the development of ridge systems in the Tethys and Atlantic Oceans (Fig. DR1).

The mean global spreading rate displays a pronounced change from higher seafloor spreading rates in the Late Cretaceous (~70 mm/a) to much

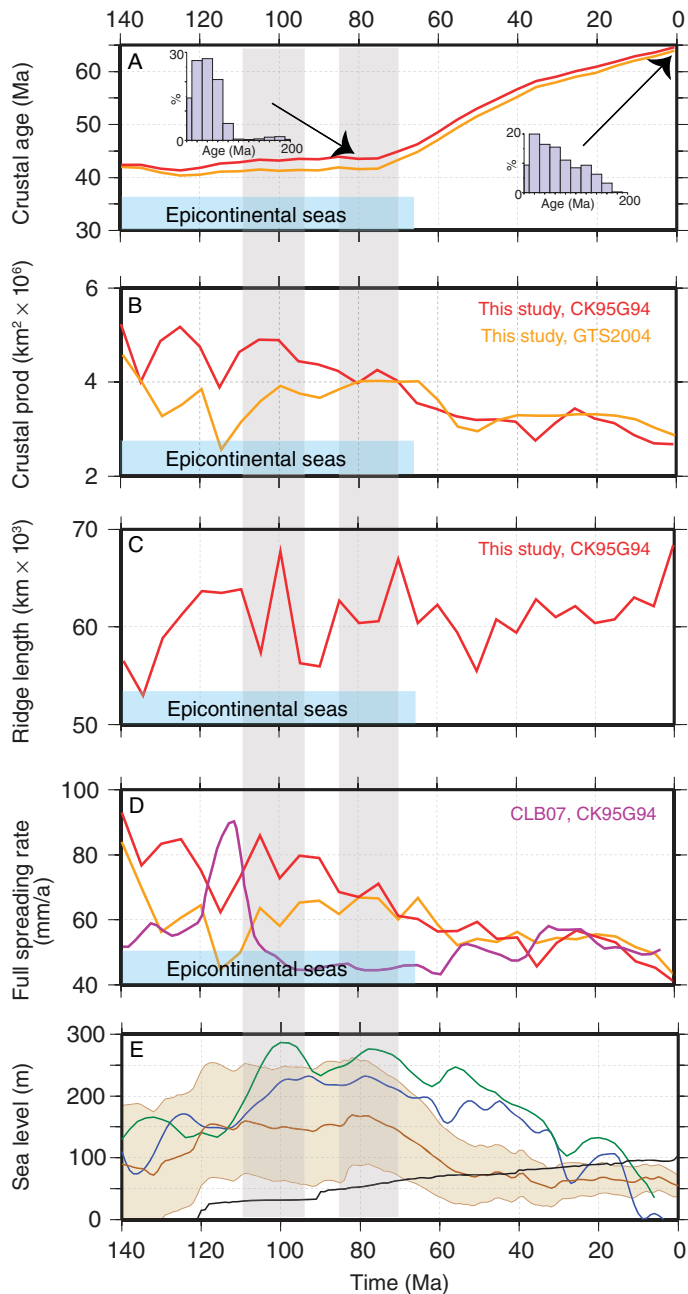


Figure 1. Cretaceous to present changes in global oceanic floor geometry and correlations with global eustasy. **A:** Mean crustal age using CK95G94 (red) and GTS2004 (orange). Histogram inserts show percentage of crustal age (20-million-year bins) at 80 Ma ago (upper left) and present (lower right). **B:** Mean oceanic crustal production using CK95G94 (red) and GTS2004 (orange). **C:** Mid-ocean ridge lengths using CK95G94 (red). **D:** Mean global seafloor spreading rates using CK95G94 (red) and GTS2004 (orange). Purple line taken from Conrad and Lithgow-Bertelloni (2007) for comparison. **E:** Selected published sea-level curves and estimated mean sea-level rise due to LIP emplacement (black). Dark green—Haq and Al-Qahtani (2005); blue—Haq et al. (1987); brown—Müller et al. (2008b) with associated error envelope. Gray bands highlight the two major Cretaceous sea-level highstands.

lower rates at present (~40 mm/a) (Fig. 1D), mirroring the change from a sea-level highstand in the Late Cretaceous to lower sea level in the Tertiary (Fig. 1E). However, spreading rates in the Early to mid-Cretaceous differ significantly depending on time scale: the mid-Cretaceous seafloor spreading pulse is diminished using GTS2004. The fastest seafloor spreading

¹GSA Data Repository item 2009166, Figure DR1 (separate values for all parameters in the Pacific area and the rest of the oceanic area) and Figure DR2 (global seafloor spreading rate gridded data), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

rates observed using GTS2004 are 82 mm/a at 140 Ma ago and 66 mm/a at 80–75 Ma and 65 Ma ago. This is in contrast to seafloor spreading peaks of 92 mm/a, 84 mm/a, 86 mm/a, and 79 mm/a at 140, 125, 105, 95–90, and 75 Ma ago, respectively, using CK95G94 (Fig. 1D). The ~20 mm/a decrease in spreading rate amplitude during the mid-Cretaceous using GTS2004 does not necessarily suggest that the mid-Cretaceous seafloor spreading pulse is fiction, as the Aptian age in GTS2004 is still very contentious (see “Discussion”). CK95G94 remains our preferred time scale. Spreading rates declined to below 60 mm/a in the early Cenozoic (60 Ma ago) until the present day. Our results contrast substantially with the seafloor spreading calculations of Conrad and Lithgow-Bertelloni (2007), who give spreading rates of ~90 mm/a at 110 Ma ago, dropping off to less than 45 mm/a between 100 and 60 Ma ago, and a stair-stepped increase to less than 60 mm/a at 35 Ma ago (Fig. 1D).

Our global analysis of crustal age, ridge length, crustal production, and spreading rate using the two alternative time scales reveals that, irrespective of time scale, the increase in mean age of the oceanic lithosphere from the Late Cretaceous to present reflects a profound long-term change in the age-area distribution of oceanic lithosphere through time. This change is relatively independent of both ridge length and seafloor spreading rates and mainly reflects the aging of the ocean basins formed after the breakup of Pangea. While the mid-Cretaceous sea-level highstand (110–95 Ma ago) is apparent when using CK95G94, it is diminished when GTS2004 is applied due to the longer stage of the CNS. The initial increase in length of the mid-ocean ridge system during the Early Cretaceous due to the breakup of Pangea and formation of the Indian and Atlantic ocean ridges did contribute to an increase in sea level during this time but remained relatively constant afterwards (Fig. 1C).

DISCUSSION

Deriving global seafloor spreading histories invariably involves two major sources of uncertainty: the difficulty in reconstructing the intricate spreading history of the Pacific and Panthalassa ocean basins and uncertainties associated with the time scale used to map oceanic crustal age distribution (Kominz, 1984; Heller et al., 1996). We believe our choice of method, with attached uncertainties and time scale comparison, is more appropriate to tackle ocean floor evolution than the relatively simplistic approach of extrapolating currently preserved ocean floor to estimate age-area distributions in the past.

Errors in Mid-Ocean Ridge Reconstructions

The mean error of our modeled present-day oceanic crustal age is approximately ± 1.4 m.y. We scale our error analysis for ocean basin reconstructions such that the mean reconstruction error of subducted ocean floor is 10 m.y., a fourfold increase in the combined uncertainties reflecting errors in mid-ocean ridge location and geometry (Müller et al., 2008b). The assumptions inherent in our model are addressed in Müller et al. (2008b). The most likely elements missing from our reconstruction of mid-ocean ridges are additional ridges whose geometry and evolution are currently not well constrained. These include spreading ridges in the Pacific postulated by Taylor (2006), as well as backarc basins that may have existed in the Cretaceous (e.g., Rocas-Verdes Basin in South America [Dalziel, 1981] and a backarc north of Greater India [Aitchison et al., 2000]). The present-day percentage of backarc spreading centers is ~10% of the global total. Including this value in our calculations would increase the Cretaceous ridge system by ~6500 km and decrease spreading rates by ~2.5 mm/a, leaving our conclusions unchanged.

Mesozoic Time Scales

Two time scales were used to assess the mid-Cretaceous seafloor spreading pulse: CK95G94 and GTS2004. The choice of time scale has a significant effect on the duration of the CNS and magnitude of the

mid-Cretaceous spreading pulse. As observed by Heller et al. (1996), placing the CNS between 120 and 83.5 Ma ago (Gradstein et al., 1994) minimizes the pulse of rapid spreading rates compared to the time scale of Larson et al. (1982). The new GTS2004 places the CNS old limit at 124.6 Ma ago, making the CNS approximately 5 m.y. longer in duration compared with Gradstein et al. (1994), leading to a decrease in spreading rate of ~20 mm/a (Fig. 1D). However, the new GTS2004 calibration is still contentious. For example, Fiet et al. (2006) proposed an Aptian boundary at 113.7 Ma ago ± 0.4 Ma based on absolute dating combined with orbital chronology, whereas He et al. (2008) redated the Aptian boundary to 121.1 Ma ago ± 0.5 Ma based on $^{40}\text{Ar}/^{39}\text{Ar}$ dates from China. We retain CK95G94 as our preference until a better consensus is reached in calibrating the duration of the CNS. We believe our choice is a good compromise between a time scale that significantly increases the duration of the CNS and a time scale that significantly decreases that duration.

Oceanic Volcanic Plateaus

The evolution of global oceanic area and estimation of paleodepths (Müller et al., 2008b) showed that the contribution of oceanic LIP emplacement and sedimentation is not significant compared to the effect of oceanic basin volume change, although both these factors acted to decrease oceanic depth and thus increase global sea level. The uncertainty in LIP-related depth changes is on the order of ± 5 m (Müller et al., 2008b). An additional effect not considered in this analysis is the potential uplift of the seafloor before LIP eruption when the plume head arrives in the upper mantle, followed by a collapse during eruption. Based on estimates for the size (~500 km diameter) and density anomaly (~1%) of the plume head, we infer an ~2 m sea-level rise prior to eruption of a LIP, with an upper limit of ~5 m (corresponding to ~700 km diameter). We therefore argue that the timing and distribution of significant LIPs was not sufficient to significantly raise Cretaceous sea level (Fig. 1E).

The Cretaceous superplume hypothesis (Larson, 1991b) strongly relied on the assumption that the Pacific plate hosted twice as many volcanic plateaus than today by considering that they originated closer to mid-ocean ridges and hence split and later subducted or accreted. This assumption is prone to introduce errors into the calculations of global sea-level changes. The two largest volcanic plateaus, Ontong Java and Kerguelen, which account for over half of total LIP production since the Mesozoic (Coffin and Eldholm, 1994), erupted off-ridge not on-ridge, emphasizing the fact that restoration of LIP volumes has to take into account the past position of the volcanic plateau relative to the active mid-ocean ridge. Although evidence of obducted LIP fragments has been described for Circum-Pacific locations, most are older than mid-Cretaceous. In addition, the time of emplacement of the largest LIP (Ontong Java) preceded the highest mid-Cretaceous sea-level peak by at least 25 m.y. Based on our present knowledge of LIP emplacement and subsequent evolution, we conclude that LIPs are not likely to be the main factor to trigger global sea-level rise.

CONCLUDING REMARKS

Our analysis of the evolution of the global oceanic area since the Cretaceous shows that global average seafloor spreading rates were highest during the Cretaceous with substantial peaks occurring at 140, 125, 105, 95–90, and 75 Ma ago (using CK95G94, our preferred time scale). The GTS2004 time scale shows peaks in seafloor spreading at 140, 80–75, and 65 Ma ago but not during the mid-Cretaceous. Both time scales show a drop in seafloor spreading rates from the Late Cretaceous to less than 60 mm/a during the entire Tertiary. Although mid-ocean ridge lengths increased during the Early Cretaceous as a consequence of Pangea breakup, they remained relatively constant since the mid to Late Cretaceous, implying little long-term variation in ridge length. Emplacement of preserved volcanic plateaus contributed only moderately to the sea-level

rise. The choice of time scale has a significant influence over the presence/absence of the mid-Cretaceous sea-level pulse, requiring better calibrations of the age extent of the CNS. However, the average age, and therefore depth and volume, of the ocean basins is only very weakly dependent on the choice of time scale. Therefore, we conclude that the change from expansive mid- and Late Cretaceous epicontinental seas to substantially lowered global sea level in the Cenozoic was ultimately driven by a combination of decreasing spreading rates and aging ocean basins.

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