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Global reconstructions of Cenozoic seafloor ages: Implications for bathymetry and sea level

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Abstract

Although accurate estimates of Cenozoic seafloor ages will serve to further our understanding of the relationship between mantle dynamics, plate tectonics, and a variety of surficial geological processes, it is difficult to estimate ages of subducted seafloor. However, given the near-constancy of surface velocities within a tectonic stage, we can estimate Cenozoic plate ages, even for subducted lithosphere. We reconstruct seafloor ages based on the Cenozoic plate reconstructions and absolute rotation poles of Gordon and Jurdy [R.G. Gordon and D.M. Jurdy, Cenozoic Global Plate Motions, J. Geophys. Res. 91 (1986) 12389–12406.]. For the western Pacific, we explore alternative models based on the reconstructions of Hall [R. Hall, Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations, J. Asian Earth Sci. 20 (2002) 353–434.]. Both reconstructions indicate an increase in average seafloor age since the early Cenozoic, resulting in an increase in the volume of ocean basins and a decreased sea level since the Early Cenozoic. These trends are more pronounced for the Gordon and Jurdy [R.G. Gordon and D.M. Jurdy, Cenozoic Global Plate Motions, J. Geophys. Res. 91 (1986) 12,389–12,406.] reconstruction because the Hall [R. Hall, Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations, J. Asian Earth Sci. 20 (2002) 353–434.] reconstruction retains older seafloor in the western Pacific, which approximately halves the predicted sea level decrease since the early Cenozoic (250 vs. 125 m compared to geologic estimates of ~150 m). These changes in sea level occur despite decreases in oceanic lithosphere production rates of only about 20% in both models. Thus, the changing distribution of seafloor age has a larger effect on sea level than changes in spreading rates or ridge lengths. These reconstructions can also be used to estimate past heat flow, the volume of subducted buoyancy and changes in the bathymetry of the Cenozoic ocean basins.

Keywords: Cenozoic sea level; ridge volume; global seafloor age reconstructions; spreading rates; subduction rates; plate tectonic reconstructions

1. Introduction

Plate tectonic processes shape the Earth's surface and record the thermal and dynamical evolution of the planet. Magnetic anomalies on the ocean bottom, which record primary information on the direction and speed of plates over the past ~180 Myr, likely provide the best record of the recent tectonic history of the Earth. Seafloor magnetic anomalies also constrain ages for oceanic lithosphere, which, because of the relationship between the age and the secular cooling of the oceanic lithosphere [3–5], determines the large-scale bathymetry of the

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ocean and provides an estimate of the thickness of oceanic plates. The thickness and density of plates control the amount of buoyancy entering the mantle at subduction zones, and hence exert important controls on plate and mantle dynamics [6–8]. Furthermore, the geographical distribution of oceans and their depths can profoundly impact environmentally important factors such as relative sea level (e.g., [9–12]), the Carbonate Compensation Depth (CCD), which will affect the amount of carbon sequestered on the ocean floor and by extension carbon recycling into the mantle, and more generally the nature of oceanic circulation (e.g., [13]). For the present-day, seafloor ages are measured independently from bathymetry although both are obtained by both sea going and satellite measurements. If we are to understand the long-term temporal evolution of systems ranging from tectonic to climatic, knowledge of the distribution of the ages for the oceanic floor is desirable for times in the past.

Unfortunately, the continuous consumption of oceanic lithosphere via subduction presents us with a fundamental problem: we cannot measure the age of the seafloor in the past, not even by proxy. In this paper, we present a model for the distribution of seafloor ages in the Cenozoic in approximately 5 Myr intervals. Two previous studies provided a basic set of seafloor ages in the Cenozoic stages. Lithgow-Bertelloni and Richards [8] estimated the ages of non-continental area for 4 different times in the Cenozoic (17, 34, 48, 64) by assigning the age of the nearest reconstructed isochron to the entire area between isochrons. This technique does not account properly for the age of any material that has been consumed at subduction zones in the last 65 Myr of Earth's history. (Hereon, we refer to this material as "paleosubducted", because the subduction process must be reversed in order to reconstruct ages for this material for times in the past.) In other words, Lithgow-Bertelloni and Richards [8] assigned the age of the oldest isochron to any material paleosubducted at the time of their age reconstruction. Wen and Anderson [14] estimated these ages by dividing the distance between paleosubducted seafloor and corresponding ridges by spreading rates. This approach cannot account for asymmetric spreading or changes in spreading rate through time. Both Lithgow-Bertelloni and Richards [8] and Wen and Anderson [14] did not self-consistently rotate all points of the sphere, but rather relied on existing plate boundary reconstructions and reconstructed isochrons. Conrad and Gurnis [15], in a more sophisticated work, reconstructed ages in the Southern Atlantic and Indian basins by rotating present-day seafloor ages [16] backward in time using the poles of rotation of Norton and Sclater [18] for the breakup of Gondwanaland. However, they did not attempt a global model, nor did they deal with paleosubducted material. Heine et al. [19] have recently reconstructed the past ages and bathymetry of Tethyan seafloor assuming symmetrical spreading.

In this work we choose a different methodology. We choose to reconstruct the ages of the seafloor by applying the basic relationship between distance, time and velocity to compute age differences between points with known ages today (extant) and points exhumed from the mantle whose ages are unknown (paleosubducted), over short distance and time ranges. If the motion history of a plate is relatively well known, the age difference between two points on this plate can be computed using the distance between them (in the direction of the velocity vector) divided by the magnitude of the velocity. Therefore, if the age of one of the two points is known, the age of the other point can be accurately determined. One underlying assumption in our work and previous studies is that plates move with nearly constant speed during each stage, the very definition of a tectonic stage.

Our study presents several advantages on previous work: 1) completeness: we create a global set of reconstructed seafloor ages that includes an assignment of model ages to previously subducted material, 2) consistency: plate boundary locations (particularly ridges) coincide with the position of the 0 age isochron, and 3) accuracy: our assignment of ages for paleosubducted material takes into account asymmetric spreading and the local spreading rate at any given stage.

We present below our general methodology in more detail and the results of our reconstructions of seafloor ages for the Cenozoic at approximately ~5 Myr intervals. We discuss the implications of our models by further analyzing the average age of the seafloor, the total volume of ocean basins, lithospheric production rates at different times, and the concomitant inferences of sea level. Our results shed light on a recent controversy over the changes in lithospheric production (or their constancy) in the last 180 Myr [10,20–23]. In more general terms the models we produce can be used as a baseline for the analysis of variations in heat flow [6], subducted lithospheric buoyancy [8], and hence mantle dynamics.

2. Plate reconstructions and seafloor ages

Three types of data are needed for reconstructions of seafloor ages at each chosen Cenozoic stage: a global set of absolute poles of rotation, plate boundaries, and the present-day seafloor isochrons (Fig. 1).

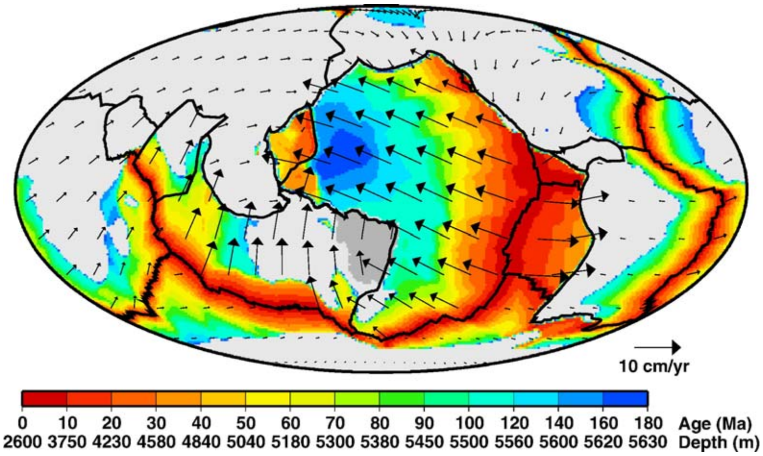

Fig. 1. Distribution of seafloor ages interpolated from the magnetic anomaly map of Müller et al. [16]. Ages for the Philippine plate, the Arctic Ocean and other back-arc basins are from Sclater et al. [17]. Bathymetry (depth) is determined from the depth–age relation of Ref. [4].

For this study we limit ourselves to the global set of plate reconstructions and poles of rotation of Gordon and Jurdy [1], supplemented by new reconstructions in the southwest Pacific by Hall [2]. The Cenozoic is divided into six tectonic stages (0–10, 10–25, 25–43, 43–48, 48–56 and 56–64 Ma) using tectonic events as natural dividing points. We use Gordon and Jurdy [1] only as a baseline for information on the number of plates and plate boundaries. In practice we re-determine all plate boundaries at every reconstructed age. In doing so we ensure that ridges and 0 Ma isochrons match exactly. To reconstruct seafloor that today would be older than 64 Myr, we need the plate motion history and plate boundaries of Mesozoic stages, and therefore make use of boundaries and poles of rotation compiled by Lithgow-Bertelloni and Richards [8]. Poles of rotation for periods older than 120 Ma are assumed to be the same as those in the 100–119 Ma interval of Lithgow-Bertelloni and Richards [8].

For the present, we use the dataset of Müller et al. [16], augmenting the coverage of areas without age data by extrapolating from the present-day anomalies, except for the seafloor NE of Australia, where the age of the seafloor is uncertain. The seafloor in this area was likely produced by different episodes of back-arc spreading, which makes extrapolation of ages from neighboring present-day anomalies difficult.

We must emphasize that choosing the reconstructions of Gordon and Jurdy [1] is essential to the robustness of the results, and is not an arbitrary choice. While, regionally there exist updated plate boundaries, and/or poles of rotation, Gordon and Jurdy [1] is the only global, complete and self-consistent set of plate reconstructions, published or available for the Cenozoic. Gordon and Jurdy's [1] global reconstructions in the hotspot reference frame, ensure that we do not introduce errors in the determination of past seafloor ages related to inconsistencies in the choice of reference frame, determination of plate boundaries, or closure of plate motion circuits. Nonetheless, in areas such as the western Pacific, where radically different reconstructions do exist, we choose to explore the effects of alternative plate boundaries on lithospheric production, ocean volume and sea level, as a qualitative measure of uncertainty, despite the perils of mixing plate boundaries and poles of rotations from different sources.

A rigorous analysis of the errors would require the existence of error ellipses for the poles of rotation of each plate for all times in the past, and formal estimates of uncertainty in the position of past isochrons. As these are not yet available, a formal error analysis is beyond the scope our study.

3. Methodology

We determine past seafloor ages by rotating points on a $1° \times 1°$ latitude–longitude grid backward in time from the present-day according to the motions of Earth's tectonic plates. To start, each point is defined as oceanic or continental, and oceanic points are assigned an age based on present-day magnetic anomalies [16]. These ages are augmented for several back-arc basins and the Arctic Ocean with the ages of Sclater et al. [17]. Material is rotated back in time in steps of ~5 Myr. At every 5 Myr time interval we determined the plate boundaries using the following assumptions: a) the 0 Myr isochrons define the ridges; b) transform faults connect ridge segments; c) subduction zones are attached to continental margins, unless we have independent evidence of the contrary. The second and third imply that as we go back in time we lose information on large transform boundaries, and that we may overestimate the ages of certain oceans if we miss some intra-oceanic subduction zones.

As in all stage reconstructions, the boundaries in Gordon and Jurdy [1] are drawn at the time corresponding to the age of the chron used in the reconstruction (stage 10–25 Ma: chron 5, 17.5 Ma; stage 25–43 Ma: chron 13, 37 Ma; stage 43–48 Ma: chron 21, 43 Ma; stage 48–56: chron 21b, 48 Ma; stage 56–64 Ma: chron 27, 61 Ma). This presents us with two problems. The first is that the magnetic and geochronological time-scales have been revised since 1986: anomalies have been re-picked and the dates on the time-scale have been improved by more accurate dating. Over the time period of 64 Ma the errors associated with the time-scale revisions are minimal and no more than 3 Myr for the oldest stage. To take into account these changes, we revise the age of the chrons used in Gordon and Jurdy [1] to coincide with the ages for the same chrons in Müller et al. [16] by comparing to the updated geomagnetic scale of Cande and Kent [24]. Second, the plate boundaries migrate and new plates and new boundaries may appear during each stage interval. Thus, when the boundaries of consecutive stages are expressed at the time that links neighboring stages, plate boundaries often do not coincide. To insure self-consistency and continuity at the boundary between stages, we rotate the boundaries corresponding to two adjacent stages to the stage boundary. We then re-determine the plate boundaries by interpolating between nearby, but non-overlapping, plate boundaries and by accounting for new plates. For example at 10 Ma (the boundary between the present-day stage (0–10 Ma) and the 10–25 Ma stage) we rotate present-day boundaries back to 10 Ma, and the 10–25 boundaries forward in time from the age of the chron 5 (17.5 Ma) to 10 Ma. The resulting plate boundaries (Figs. 3A, 4A) are the reconciliation of the plate boundaries rotated from these two time periods [1].

To reconstruct seafloor ages for a given time in the past T_2, we start with plate ages from a more recent time T_1 for which the seafloor age is known. Using finite stage poles, we rotate each point on the surface of the Earth from time T_1 to time T_2. At T_2, the age at any point is the age of the lithosphere at T_1 that rotates on to that point, minus the duration from T_1 to T_2. Because points that are rotated from time T_1 generally do not fall exactly upon the grid points at time T_2, we interpolate among all points that, when rotated from T_1, fall within 1.5° of a grid point of T_2. This is the technique developed by Conrad and Gurnis [15].

As we go back in time, young seafloor is "sucked" back into ridges and large portions of the seafloor have no known age because they have been exhumed from subduction zones (Fig. 2A). We assign ages to this "paleosubducted" seafloor using the age of nearby seafloor with known age and paleo-spreading rates that applied at the time that seafloor was created. This technique is depicted in Fig. 2A and B, and described below and in the flow diagram of Fig. 2C.

Once plate boundaries have been obtained and ages determined for most of the seafloor, we assign each point on the surface to the plate whose boundaries encircle that point. To find the age of at a paleosubducted point A ($\mathrm{age_A}$) at the time of interest T_2 (Fig. 2A) we first find the nearest neighbor (within 0.8° angular distance) point B on the same plate whose age is known. We use the age at that point ($\mathrm{age_B}$) as an initial crude approximation of $\mathrm{age_A}$ to be updated later. Next, we find all points C with known age ($\mathrm{age_C}$) that are within 4° of point A (Fig. 2A). Because they are typically closer to their originating ridge, most points C were created at that ridge at a time ($\mathrm{age_C}+T_2$) after point A was created. Therefore, if we assume constant motion for the relevant plate (plate R, onto which points A and C were created) between the creation of points C and point A, we can extrapolate from the ages at a few of these points C to determine $\mathrm{age_A}$. To accomplish this extrapolation, we need to determine the half-spreading rate $\mathrm{SR_A}$ that applied at the time of point A formation (Fig. 2B), as well as which of the points C lie on a line (AC) that begins at point A and is nearly parallel to $\mathrm{SR_A}$ (perpendicular to the isochrons) (Fig. 2A). We determine $\mathrm{SR_A}$ by first determining the stage pole (${}_{\mathrm{age_C}+T_2}\mathrm{P}_{\mathrm{age_B}+T_2}$) for plate R at the time of point C formation ($\mathrm{age_C}+T_2$). This defines the fossil half-spreading rate $\mathrm{SR_C}$ at that time (Fig. 2B). To express this fossil half-spreading rate at point A and at the time of interest T_2, we use the total reconstruction pole for plate R, ${}_{\mathrm{age_C}+T_2}\mathrm{P}_{T_2}$, to rotate the stage pole ${}_{\mathrm{age_C}+T_2}\mathrm{P}_{\mathrm{age_B}+T_2}$ to the time of interest T_2 (Fig. 2C). Now we can use this new stage pole, ${}_{\mathrm{age_C}}\mathrm{P}_{\mathrm{age_B}}$, to calculate $\mathrm{SR_A}$ for each point C (Fig. 2A). We choose the set of points C for which $\mathrm{SR_A}$ is nearly parallel to AC (such that $|\cos(\alpha)|<0.8$, where α is the angle between $\mathrm{SR_A}$ and AC). For each of these points, we divide the distance between points A and C by $\mathrm{SR_A}$ and add the result to the age at point C to extrapolate for the age at point A. We use the average $\mathrm{age_A}$ computed from each eligible point C to assign an age for point A (Fig. 2C).

There are two major advantages of this method compared to those used in previous studies [8,14]. First, the age of a point of paleosubducted lithosphere

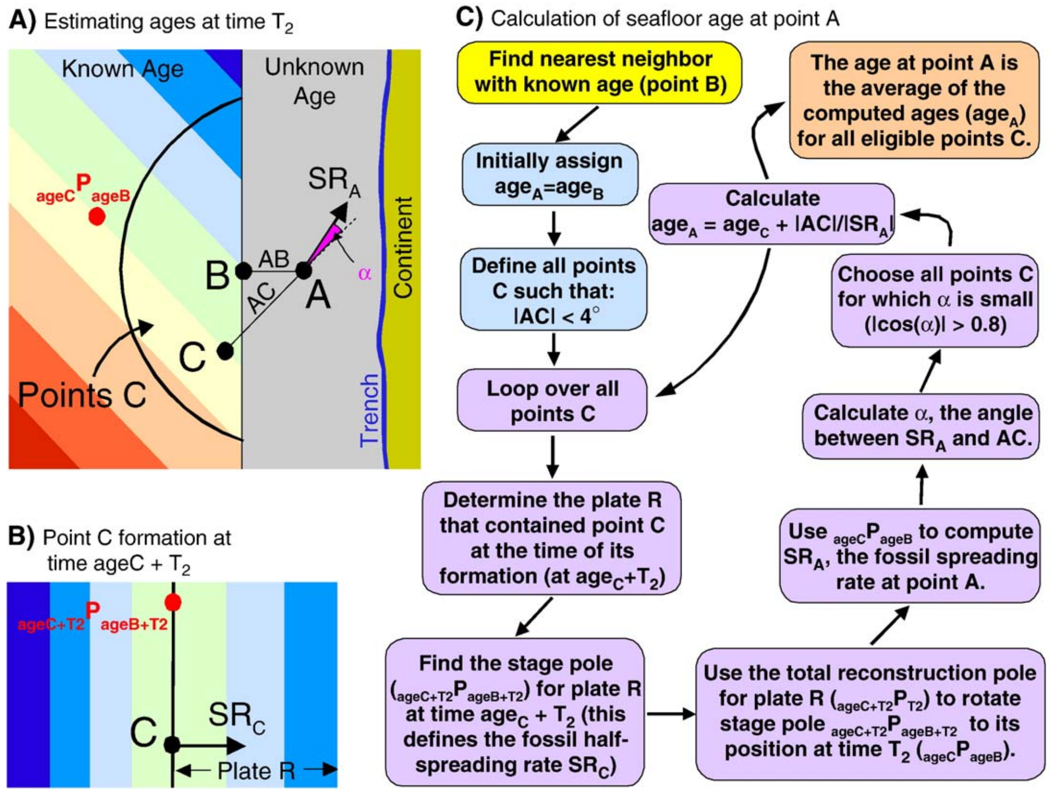

Fig. 2. Diagrams (A and B) and flow chart (C) showing the method by which we estimate the age of "paleosubducted" seafloor that has been exhumed from subduction zones (grey area in A) as the seafloor age reconstruction proceeds backward from a time T_1 with known ages to an earlier time T_2. To estimate the age at a given point A, we define a set of nearby points C with known ages and extrapolate from the ages of these points to find the age of point A (part A). We determine the fossil half-spreading rates required for this extrapolation (SR_A) by examining the half-spreading rates at the time point C was created, which are described by the stage pole ${}_{\mathrm{age_C}+T_2}P_{\mathrm{age_B}+T_2}$ (part B). By rotating this pole to its position at time T_2, we obtain the new stage pole, ${}_{\mathrm{age_C}}P_{\mathrm{age_B}}$, which defines the fossil half-spreading rate at point A (part A). The direction of SR_A is used to determine which points C will be useful for extrapolation of ages to point A. The magnitude of SR_A provides the age gradient needed for this extrapolation (part C).

can be estimated using the ages of seafloor close to it, rather than the 0 Ma isochrons at the time. In other words, we are able to account for the proper changes in spreading rate or ridge geometry for times at which global plate reconstructions are available (the last 120 Myr [8]). Furthermore, by re-determining spreading centers and using absolute motion poles we are able to account for any instance of asymmetric spreading that is evident in the magnetic anomaly record. This is because we extrapolate for unknown ages using the half-spreading rates that applied at the time of plate formation, which are not necessarily half of the total spreading rate at the time (see the example in Fig. 2B, where asymmetrical spreading is present, but does not affect our determination of the half-spreading rate SR_C). Secondly, by using multiple points as reference points for estimating the age we build redundancy that can significantly improve the accuracy of our estimates.

There are some clear shortcomings and limitations inherent in our method and in any attempt to assign ages to paleosubducted material. For example, when slabs from neighboring plates are exhumed, there is not sufficient information to constrain any possible plate boundaries between pieces of contiguous seafloor. Any boundaries determined in these cases are rather speculative and are likely highly inaccurate.

Another problem lies in our assumptions that ridges and transform faults follow 0 Ma isochrons and that subduction zones are attached to continental margins. These approximations neglect ridge-jumps and intra-oceanic subduction. The latter especially, will not necessarily be valid for many regions, i.e. the northern Australian Plate and SE Asia [2,25]. They should be regarded as only first-order approximations when not enough data are available for global reconstructions.

Some problems arise from the uncertain nature of reconstructed poles of rotations, which leads to inconsistencies between past stage poles and the present-day seafloor isochrons we use in this study. Ideally, if poles of rotation fit seafloor isochrons perfectly, the 0 Ma isochrons on adjacent plates should match each other perfectly. However, this is often not the case. In practice, we found persistent gaps between the reconstructed position of the present-day seafloor anomaly and the 0 Ma isochrons at that time, especially in the eastern Pacific region. The ages interpolated for these gaps are negative because they are "ahead of" the 0 Ma isochrons. This type of problem is, unfortunately, unavoidable because it is virtually impossible to find a complete set of rotation poles to fit all parts of isochrons. In this case, we correct for the negative ages by dividing all of the area between the spreading ridge and the 10 Myr isochron, into many small sectors with boundaries perpendicular to the ridge segment. We then linearly interpolate ages between the ridge and the 10 Ma isochron.

A final problem is presented by the interpolation of ages for areas with very little age information, such as the NE corner of the Australian Plate and the Tethyan Ocean, which existed between Gondwana and Laurasia since the Late Permian, but has almost completely disappeared today [26,27]. Though our reconstructions suggest the location of ancient Tethyan seafloor, we have little information about the positions of ancient ridges and the motion history of basins, despite some recent progress [19].

4. Reconstructed ages

We reconstruct seafloor ages, plate boundaries and velocities in the hotspot reference frame at 10, 25, 37, 48, and 64 Ma (Figs. 3, 4). These results have an approximate resolution of 100 × 100 km. We have also reconstructed ages for other times (5, 15, 20, 30, 43, 52, 56, and 60 Ma), approximately every 5 Ma.

Several assumptions about specific regions are made in these reconstructions. First, India is assumed to collide with Eurasia at ~57 Ma [28–30] and the southern boundary of Eurasia is fixed to the other parts of the plate. Any opening between the North American and South American plates as they move away from each other is assumed to be within continental area and assigned to the North American plate. This is a choice of convenience, given the complicated tectonic history of the Caribbean plate and the presence of shallow continental carbonate platforms in the region. Openings between Eurasia and Africa are assumed to be the remnant of the Tethyan Ocean in that region [26,27].

Although our reconstructions of seafloor ages (Fig. 3), are primarily based on the global reconstructions of Gordon and Jurdy [1], different plate-tectonic models may locally influence reconstructed seafloor ages significantly. Young seafloor on the Philippine plate, for example, which is likely the result of back-arc spreading, gives rise to very young and probably unrealistic ages for the western Pacific (Fig. 3). These young ages stem from Gordon and Jurdy [1] welding of the present-day Philippine plate area to the Pacific prior to 10 Ma. However, it is now apparent that combining the Pacific and Philippine plates is at odds with a variety of geologic and tectonic data [2,25,31–33], as well as seismic images [34–36] for the region. As an alternative model, we use the reconstructions of Hall [2] in the western Pacific. In this model, an expansion of the trench retreat scenario of Seno and Maruyama [31], the Philippine plate rotated to its present position from a location to the north of the present-day New Hebrides, Papua New Guinea arc, over the past 55 Ma. A series of ridges and subduction zones in this set of paleogeographic reconstructions, evidence for which remains in the volcanic rock record, allow for a much more complex distribution of ages in the western Pacific and also much older ages from Australia to Japan (Fig. 4). In applying the Hall [2] reconstruction, we did not include the North New Guinea plate originally proposed in Seno and Maruyama [31] because a lack of data on plate boundaries and motion history makes rotations and interpolation of seafloor ages inside the plate impossible. Instead, we treat this region as part of the Pacific plate in the early Cenozoic. We choose Hall [2], because previous work has shown that these proposed tectonic boundaries and extrapolated slab subduction would agree better with regional seismic tomography studies [34–36].

5. Geophysical implications

Further analysis of our seafloor age reconstructions yields intriguing results. We estimate that the average seafloor age increased between ~20% and ~70% since the early Cenozoic (Fig. 5). This estimate is strongly affected by the amount of young oceanic lithosphere in the western Pacific region in the middle and early Cenozoic. The presence of this young ocean floor is a direct result of the assumption in Gordon and Jurdy [1] that the Philippine and Pacific plates were one plate during the period of time prior to 10 Ma, which implies that the young present-day seafloor inside the Philippine plate was from a region far east of its present-day location. Treating them as two separate plates as in Hall [2] leads to vastly different reconstructions of plate boundaries and seafloor ages. As shown in the bottom

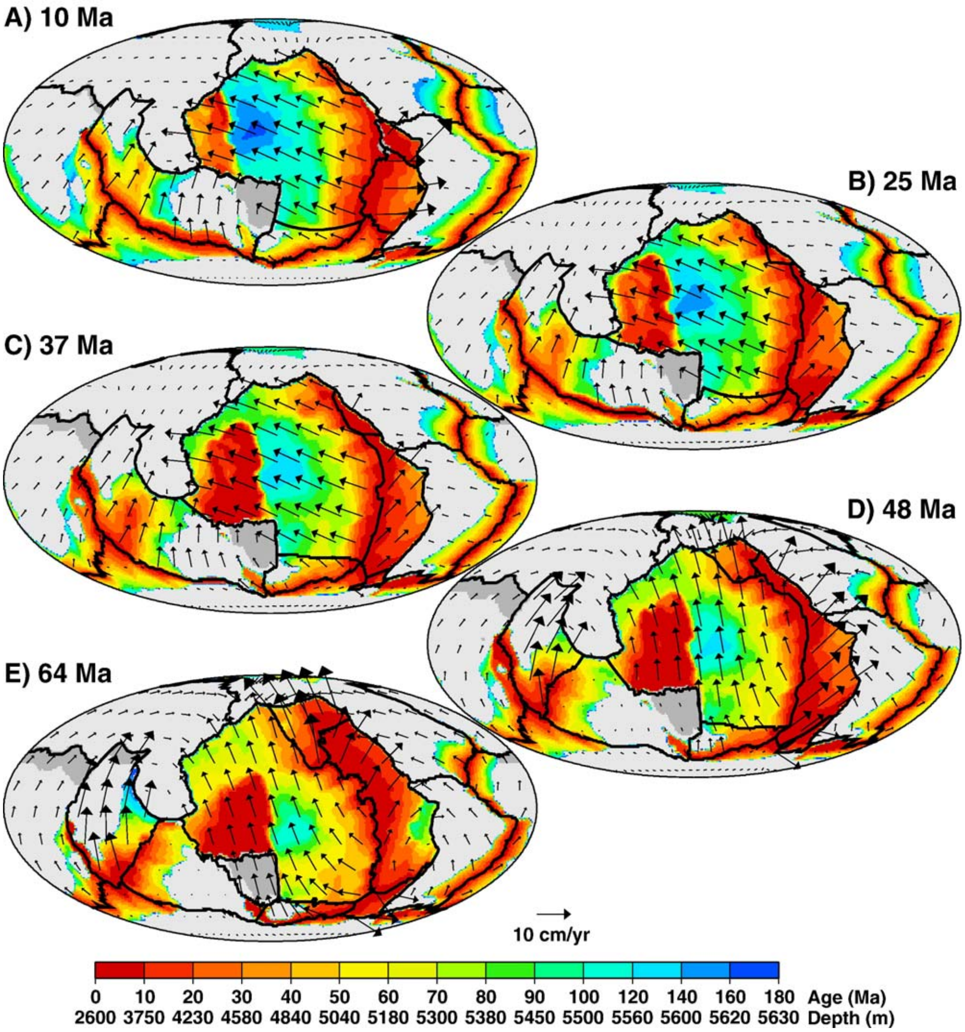

Fig. 3. Global reconstructions of seafloor ages (and inferred depths) for 10, 25, 37, 48 and 64 Ma derived from the Gordon and Jurdy [1] model. Light grey indicates continental areas and dark grey areas with insufficient information to determine ages. Solid black lines are the plate boundaries determined at each time period. Arrows represent the absolute plate motion at the time of reconstruction. Note the very young ages in the western Pacific.

panel of Fig. 5, the average seafloor age in this case increased by only 20%. The average age of the Atlantic seafloor has nearly doubled since the early Cenozoic, as the basin expanded, with smaller changes for the Indian and Pacific basins. The average age for the Indian and Pacific basins depends on the ages inferred for the western Pacific. When using Hall's [2] model the average age of the Pacific seafloor is nearly constant within the expected error of the reconstructions (5 Myr change in the last 65 Myr). The maximum age of the seafloor also depends strongly on the ages inferred for the western Pacific. It increases strongly in the last 65 Myr (from 130 to 180 Myr today) for the Gordon and Jurdy [1] models. For the Hall [2] model it decreases by less than 30 Myr in the same period of time.

5.1. Lithospheric production

We estimate changes in the rates of lithosphere production at ridges and consumption at subduction zones during the Cenozoic by integrating spreading rates along the length of diverging plate boundaries at each stage and within each oceanic basin (Atlantic, Indian and Pacific, as well as the Tethyan convergence for the subduction removal rate). To avoid overemphasizing transpressive and transtensional transform boundaries, we eliminate convergence or divergence rates that are

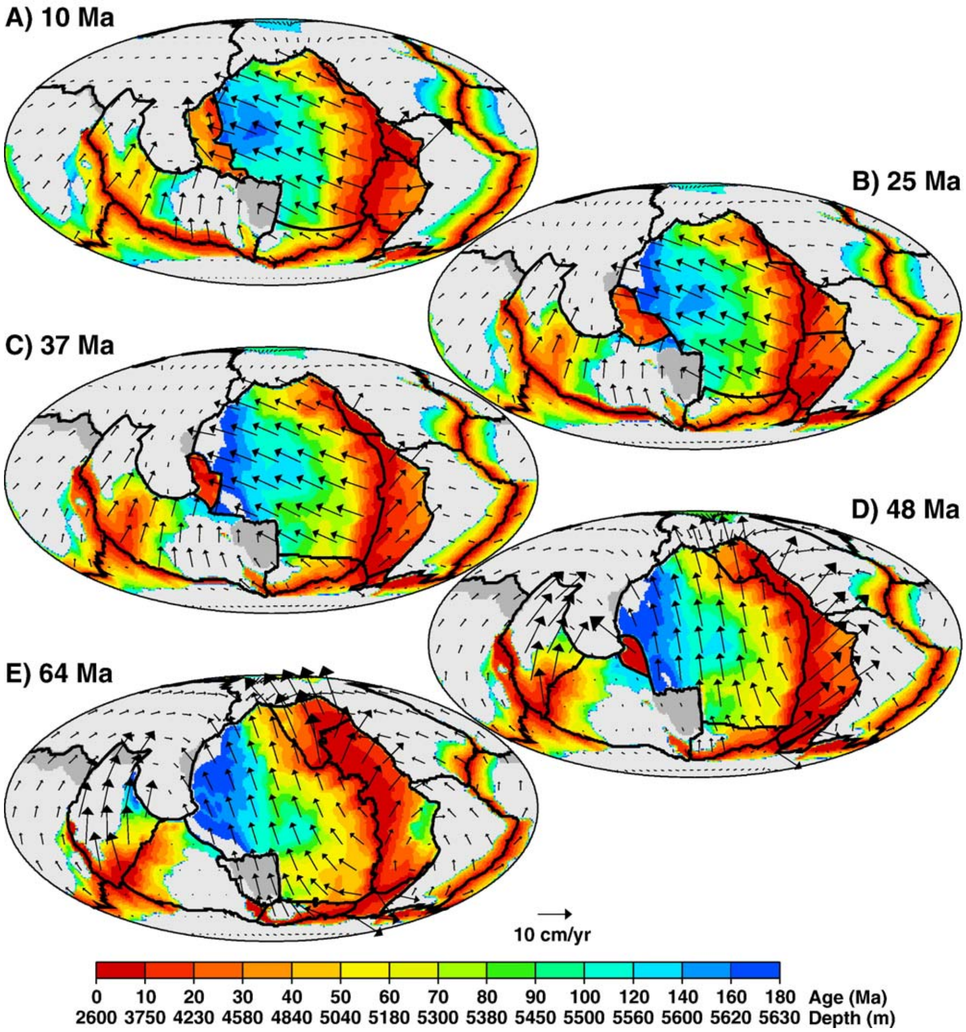

Fig. 4. Alternative reconstruction of seafloor ages. Colors and arrows as in Fig. 3. All poles of rotation and initial plate boundaries as Fig. 3 except for the western Pacific, where we use the plate reconstructions and poles of rotation for the Philippine plate of Hall [2].

less than 0.5 cm/yr [8,37]. Due to peculiarities in plate boundary geometry some plate boundary segments show the opposite sense of motion that is expected. These are not included in the integration.

Both the Gordon and Jurdy [1] and Hall [2] models show a decrease in lithosphere production rate by ~20% since the early Cenozoic (Fig. 6). This is not a major decrease in lithospheric production rate, and is only minimally affected by the choice of plate boundaries in the Pacific. This decrease may very well lie within the uncertainty inherent to the age of magnetic anomalies and the poles of rotations [23], and is clearly not nearly as dramatic as the changes in average age of the seafloor for the Gordon and Jurdy model [1]. The Cenozoic decrease in productivity is largely reflected in the Pacific [~25%] and Indian [~13%] basins, where subduction has occurred in the recent past, rather than the presently expanding Atlantic Ocean. It is worth noting that the geometry of the Atlantic ridge system has changed little during this time period compared to the dramatic changes in the Pacific and Indian oceans. It also worth noting that the curves are not smooth and that the rate of decrease in lithospheric production might be faster than anticipated. There appears to be a slight peak in productivity in the Cenozoic starting around 48 Ma in the Pacific, which seems to propagate to the Indian and Atlantic basins at later times. Although, this peak might not be beyond the uncertainty inherent in the reconstructions, we speculate that the time lag in the appearance of the peak in different basins suggests a causal link through a global process, such as mantle flow, which can correlate plate motions. In the Pacific

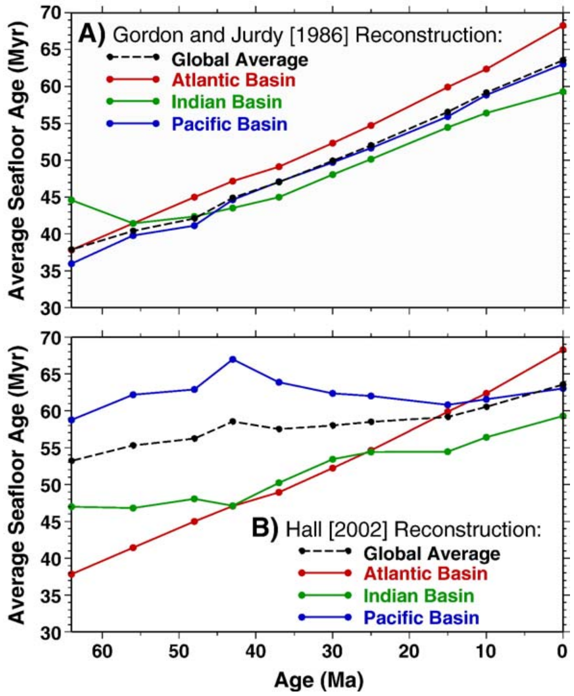

Fig. 5. Average age of the seafloor for the distributions of ages shown in Figs. 3 (top panel) and 4 (bottom panel). In both panels, the dashed black line is the global average, and the colored lines the average for different basins (red—Atlantic, blue—Pacific, green—Indian). The average age increases by nearly 70% and very smoothly throughout the Cenozoic on average, when using the Gordon and Jurdy [1] reconstructions. For individual basins the average increases ranges between 80% (Atlantic) and 50% (Indian). When using Hall's [2] model the change in average age is smaller due to the much older ages of the entire western Pacific. The global mean increases by only 20%. The average age of the Pacific basin is essentially constant within the expected errors. The changes in the Indian curve result from a small amount of western Pacific Ocean included in the definition of its boundaries. The Atlantic curve is, of course, exactly the same.

basin, it is likely that the extinction of the Farallon-Kula ridge at about 45 Ma marks the end of the peak in productivity we observe in the Cenozoic. Comparing the lithospheric production rates to the rates of seafloor removal of via subduction as a function time (Fig. 7), we see that they are clearly similar. This serves as a check on our results, as we expect production and consumption to be identical, and on the conclusion that productivity has decreased with time. The decrease in seafloor consumption rates is primarily a Pacific phenomenon, which is expected given the area decrease of the Pacific basin during the Cenozoic.

5.2. Sea level variations

Because the seafloor gets deeper as it ages, changes in the average age of the seafloor with time will result in

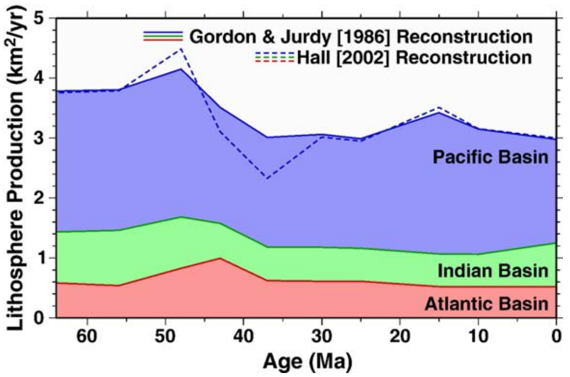

Fig. 6. Lithospheric production rate in km^2/yr throughout the Cenozoic. The shaded areas of different colors represent the production rate of each ocean basin (red-Atlantic; green—Indian; blue-Pacific). Each shaded area is separated by a solid line of the same color, which corresponds to the value of productivity when using the Gordon and Jurdy [1]. The total production rate is the sum of each shaded are at each time. The dashed lines are for the alternative Hall [2] reconstruction of the western Pacific. Total production rate has decreased by ~20% since the beginning of the Cenozoic, independent of the reconstruction used. Basins dominated by spreading show the least amount of change over the last 65 Myr. The total productivity decrease of the Pacific basin (25%) also reflects its shrinkage by subduction.

changes to the container volume of the ocean basins, and hence in sea level. We compute seafloor depths from our model ages using the age-depth model of Stein and Stein [4], and average the deviation of these depths relative to their present-day mean, to calculate variations in average seafloor elevation for each basin with respect to today. By multiplying this quantity by the area of each ocean basin, we estimate the change in volume of each basin's ridge system relative to the present-day (Fig. 8).

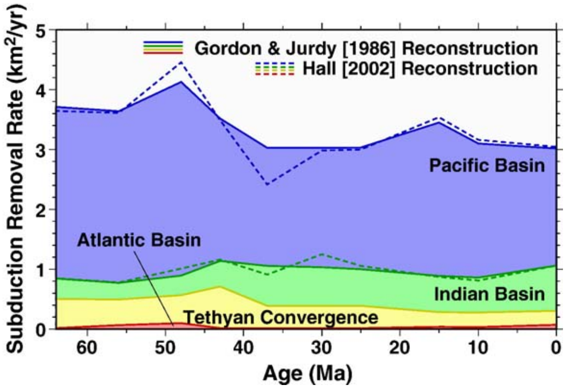

Fig. 7. The rate of lithospheric removal by subduction in km^2/yr. Colors and lines as in Fig. 6, except for the addition of a yellow band to account for the disappearance of the Tethyan basin. Peaks in subduction removal correspond to peaks in productivity as seen in Fig. 6.

This estimate ignores volume changes associated with changes to the area of each ocean basin. Shrinkage of one basin (the Pacific) is largely counterbalanced by the growth of others (Atlantic and Indian), but processes such as continent–continent collision (Tethyan closure) may generate unbalanced changes in ocean area. Volume changes associated with changes in the surface area of the oceans are ignored in other studies of sea level change (e.g., [9,10]) because the net growth or shrinkage of ocean area over time is not well constrained. Furthermore, because we do not know ages, and thus depths, for the reconstructed Tethyan seafloor (Figs. 4 and 5), we must also exclude the Tethyan seafloor area from the seafloor volume calculation. It is difficult to put quantitative bounds on the effect of continental collision or unknown ages for the Tethyan ocean on the total volume of the ocean basins. In terms of total area (not volume), we find that the decrease in continental area due to continental collision is on the order of ~5% of the ocean area during the Cenozoic and the Tethyan ocean represents less than 3% of the ocean area in the earliest Cenozoic.

Because the average age of the ocean floor has increased during the Cenozoic (Fig. 5), the volume of each ocean basin's ridge system has decreased during this time (Fig. 8). This volume decrease inevitably leads to a drop in relative sea level, as the decreasing volume of the ridge system provides the basins with new container volume that can accommodate larger amounts of water, causing less spillage onto the continental surface. We compute sea level following Kominz [10], who use the method of Pitman [9] to account for isostatic compensation of water column mass changes and continental inundation or exposure denudation. We do not include the effects of changes in geoid and dynamic topography through time on relative changes in sea level [40], because these contributions are difficult to compute for the past [41]. Our calculated sea level curves caused by changes in ridge volume (Fig. 8) are shown in Fig. 9 and compared to the observed sea level curves of Vail et al. [38] and Haq et al. [39]. Our results do not contain the shorter period (5–15 Ma) fluctuations of observed values, but nicely bracket the longer period (~100 Ma) observations. The change in relative sea level predicted using exclusively Gordon and Jurdy's [1] reconstructions is much too large, reflective of the very young ages of the western Pacific, due to the treatment of the Philippine plate. Hall's [2] reconstructions for this region lead to much older ages and hence smaller relative changes in sea level that better agree with observations.

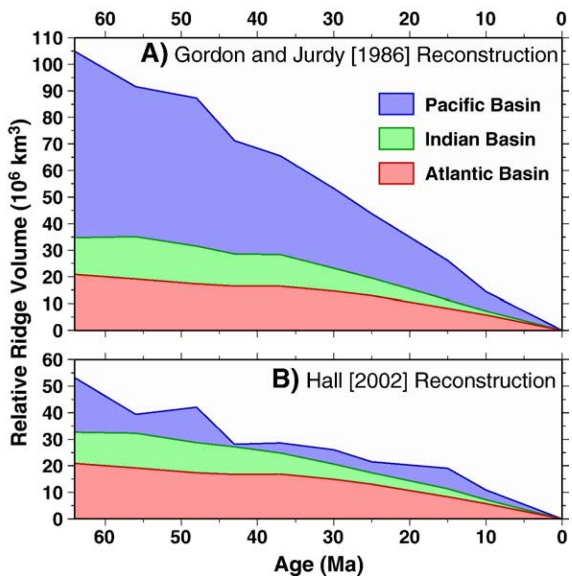

Fig. 8. Relative change in the ridge volume (km^3), with respect to today's value, throughout the Cenozoic (Top—Gordon and Jurdy [1]; Bottom—Hall [2]). Shaded areas and colors as in Figs. 6 and 7. Despite small changes in total lithospheric production, the total ridge volume (or ocean basin volume) has changed dramatically in the last 65 Myr. It has decreased (increased) between 50 and 100 10^6 km^3 depending on the age distribution of the western Pacific. Smoother variations are observed for ocean basins dominated by spreading, rather than subduction.

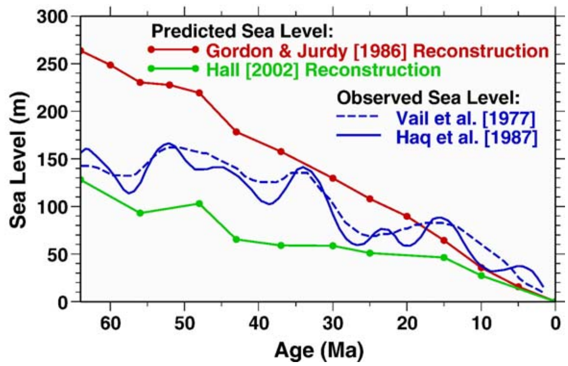

Fig. 9. Sea level curves as a function time, computed using the method of Pitman [9], shown for the seafloor ages in Fig. 3 (solid red line) and Fig. 4 (solid green line). The blue dashed [38] and solid [39] lines correspond to estimates based on areal extents of continental marine rocks [39] and seismic attributes of passive margin sedimentary sequences [38]. Older ages in the western Pacific obtained when using the Hall [2] reconstruction, halve the predicted sea level decrease in the last 65 Myr.

6. Discussion

Both the Gordon and Jurdy [1] and Hall [2] reconstructions show changes in lithospheric production rate in the Cenozoic that are in line with previous studies [10,12], which found that the lithospheric production rate decreased by about 20–30% since the early Cenozoic. Both studies show much greater variations prior to ~100 Ma, with a more muted variation in the last 65 Myr. Our observation of a ~20% decrease in lithospheric production rate, while perhaps not large, is greater than the constant lithospheric production rate argued for by Parsons [20] and Rowley [21]. Both reconstructions also show an increase in average seafloor age since the early Cenozoic, resulting in decreased ocean basin volume and increased sea level in the past. These trends are more pronounced for the Gordon and Jurdy [1] reconstruction because the Hall [2] reconstruction retains older seafloor in the western Pacific, which approximately halves the predicted sea level decrease (250 vs. 125 m compared to geologic estimates of about 150 m) since the early Cenozoic.

Our reconstructions of seafloor ages demonstrate that large changes in ocean basin volume, sufficient to explain observed variations in sea level, can occur despite only a small (~20%) decrease in lithospheric production rate. Furthermore, we have shown that variations in the treatment of the tectonic history of one corner of the Pacific basin leads to a change in the total volume of ocean basins of nearly a factor of 2. These results highlight the fact that, as noted by Parsons [20], ocean basin volume, and thus sea level, depends directly on the age distribution of the seafloor, which is only partly controlled by seafloor production rates. Instead, the seafloor age distribution depends critically on the tectonic evolution of the ocean basins. In the case of the western Pacific, the question of whether old lithosphere has been continuously subducting through the Cenozoic has dramatic implications for the seafloor age distribution, and sea level. On a basin-wide scale, the eastward migration, and eventual disappearance, of the Pacific–Farallon ridge system during the Cenozoic and Mesozoic [42] caused the ridge-trench distance in the Pacific to grow. This allowed for very old ages in the western Pacific today, even without a large global change in spreading rates.

The result that large ocean basin volume changes can occur despite small changes in lithosphere production rates contrasts recent work advocating that a constant ridge production rate leads to constant ocean basin volume and sea level [21]. Indeed, our calculated sea level curves suggest more profoundly that the changing distribution of seafloor age and changes in plate geometry have a larger effect on sea level than changes in net spreading rates.

Undoubtedly past plate reconstructions and poles of rotation inferred from the seafloor magnetic record, continental paleomagnetism, and hotspot tracks can contain large uncertainties. These uncertainties grow larger the further back in time we try to extend the analysis. Nonetheless, abandoning the history of plate motions may lead to larger errors in interpretation. For example, our results show that when the ages of now-subducted ridges in the Pacific are better estimated, a small change in lithospheric productivity is still evident in the Cenozoic alone, and it implies more than 100 m change in relative sea level. The area of Cenozoic Tethyan Ocean basins is quite small on the global scale and it is unlikely to have affected the overall averages computed here and in previous studies.

7. Conclusions

We have compiled a comprehensive model of seafloor ages in the Cenozoic that is based on present-day seafloor ages and plate-tectonic models for this time period. The distribution of ages and the average age of individual and global ocean basins changed significantly from the early Cenozoic to present-day. Regionally, the assignment of ages depends quite strongly on the choice of reconstruction, as does the maximum age of the seafloor at any given time.

Further analysis of average seafloor age, total volume of ocean basins and oceanic lithospheric production rate based on the reconstructed seafloor ages confirms generally held notions that seafloor production and sea level were higher in the early Cenozoic. The average seafloor age likely increased by more than 20% and less than 50% during the Cenozoic, and the total lithospheric production rate decreased by about ~20%. Differences between the two tectonic models (compiled from Hall [2] and Gordon and Jurdy [1]) only impact the average age and depth of the ocean but predict sea level lowering during the Cenozoic of between 250 and 125 m, which bracket observations of sea level drops of about 150 m during this time.

Our results represent a point of departure for investigations in a variety of fields in the Earth science, where assumptions about past processes depend on knowledge of the distribution of seafloor. For instance, the thickness and volume of subducted slabs, and hence the total subducted buoyancy in the mantle, can be more accurately estimated if we know slab ages at the time of subduction. This is likely to impact our estimates of the magnitude of the forces driving plate tectonics (e.g., [8,43,44]). Similarly, the location of ancient slabs and their signal in the mantle can lead to more sophisticated studies of slab dynamics and more quantitative comparisons with seismic images of the mantle at global and regional scales. Other dynamical quantities, such as the geoid and dynamic topography, depend on knowledge of slab density heterogeneity in the mantle [8,37], but are also influenced by active upwellings (e.g., [45]). Our models might also be used to predict oceanic heat-flow variations with time and estimate how each oceanic basin contributes to the heat-flow budget. Variations on the order of ~30% as seen in Sprague and Pollack [6] may have significant implications for thermal evolution models of the Earth. Finally, global reconstructions of this kind, with predictions for bathymetric changes and sea level changes can impact paleoclimate studies, through their consequences for deep seawater circulation history and coupling to the atmosphere.

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