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Reconstructions of Cenozoic Seafloor Ages: Implications for Sea Level

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Reconstructions of Cenozoic seafloor ages: Implications for sea level

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Abstract

Accurate estimates of seafloor ages in the recent geological past, will further our understanding of the relationship between mantle dynamics, plate tectonics, and a variety of surficial geological processes. Unfortunately, it is difficult to estimate directly ages for subducted seafloor. Given the near-constancy of surface velocities within a tectonic stage, we can use the relationship between velocity and distance to estimate plate ages for times in the recent past, even for subducted lithosphere. We reconstruct seafloor ages for the entire Cenozoic based on the plate reconstructions and absolute rotation poles of Gordon and Jurdy [1]. For the western Pacific, we explore alternative models based on the reconstructions of Hall [2]. Both reconstructions show an increase in average seafloor age since the early Cenozoic, resulting in an increase in the volume of ocean basins and decreased sea level today. 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 since the early Cenozoic (250 m 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 per cent. 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 the heat flow, the amount of subducted buoyancy and possibly climatic variability associated with factors determined by the age and bathymetry of the oceans, including the carbon cycle.

1. Introduction

Plate tectonic processes shape the Earth's surface and record the thermal and dynamical evolution of the planet. There is probably no better record of the last 180 My of Earth's tectonic history than the magnetic anomalies on the ocean bottom. This record gives us the primary tectonic information on the direction and speed of plates for the Cenozoic and late Mesozoic, upon which we base regional and global paleogeographic reconstructions. 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 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 five million year 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 will not account properly for the age of any material that has been consumed at subduction zones in the last 65 My of Earth's history. We refer to this material from hereon as "unsubducted" (schematically portrayed in Figure 1) because the subduction process must be reversed in order to reconstruct ages for this material for times in the past. Lithgow-Bertelloni and Richards [8] assigned the age of the oldest isochron to any material unsubducted at the time of their age reconstruction. Wen and Anderson [14] estimated these ages by dividing the distance between unsubducted seafloor and corresponding ridges by spreading rates. This approach is very sensitive to asymmetric spreading and 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 unsubducted material. Recently Gaina et al. [19] have also started reconstructing past seafloor ages and bathymetry, using magnetic anomalies and fracture zones.

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 and those whose ages are unknown, 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. Between stages the appearance or disappearance of plates in the baseline reconstructions coincides, at times, with the formation or extinction of ridges.

Our study presents several advantages on previous work: 1) completeness: we create a global set of reconstructed sea-floor 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 3) accuracy: our assignment of ages for unsubducted 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 My 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 My [20; 10, 21]; 22; 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. We also believe that variations in seafloor bathymetry may, at least locally, affect inferences of paleoclimate, via coupling effects between ocean bathymetry, oceanic circulation and climate.

2. Plate Reconstructions and Sea-floor 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, a complete set of plate boundaries, and the present-day isochrons on the seafloor shown in Figure 2.

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 would be older than 64 My today, we need the plate motion history and plate boundaries of the Mesozoic stages preceding the last stage of the Cenozoic. In this case we make use of the Mesozoic boundaries and poles of rotations compiled in Lithgow-Bertelloni and Richards [8]. Poles of rotations 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-day seafloor ages, 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, likely produced by different episodes of back-arc spreading and difficult to extrapolate from neighboring present-day anomalies.

3. Methodology

We determine past seafloor ages by rotating points on a 1° x 1° latitude-longitude grid backward in time according to the motions of Earth's tectonic plates. Each point is defined as oceanic or continental, and oceanic points are assigned an age based on present-day magnetic anomalies [Müller et al, 1997]. These ages are augmented for several back-arc basins and the Arctic Ocean with the Sclater et al. [17] ages. Material is rotated back in time in steps of ~5 million years. At every 5 My time interval we determined the plate boundaries using the following assumptions: a) The 0 million year isochrons define the ridges; b) transforms connect ridge segments; c) subduction zones are attached to continental margins, unless we have independent evidence of the contrary. The first assumption needs no explanation. 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 as 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 My, 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]. The second problem is more complex and has two main facets. The plate boundaries at the time between stages often do not coincide; different stages often differ not only by the position of plate boundaries, but also by the appearance of new plate boundaries and new plates. It would be difficult to account for such new plate occurrences solely by rotating the present-day anomalies back in time. To solve both of the issues mentioned above, we take special care to insure self-consistency and continuity at the boundary between stages. To do this we rotate the boundaries corresponding to two adjacent stages to the stage boundary. We then re-determine the plate boundaries to eliminate inconsistencies and to account 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) to 10 Ma.

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. Assigning ages to this material requires age assignments for seafloor that has not subducted.

Using finite stage poles we rotate each point on the surface of the Earth from time T_1 to time T_2, where T_2 is the time of interest (older than T_1) and T_1 is a time for which seafloor ages have already been estimated. At T_2, the age at any point on the non-unsubducted lithosphere is the age of the lithosphere at T_1 that rotates on to this 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 degrees of a grid point of T_2. This is the technique developed by Conrad and Gurnis [15].

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, so that we may properly assign ages to the unsubducted material. To find the age of point A (age_A) at time T_2 (Figure 2) we:

(a)Find the nearest neighbor (within 0.8° angular distance) point B on the same plate whose age (age_B) is known;

(b)Use age_B as an initial crude approximation of age_A to be updated later;

(c)Find all points (C) with known age (age_C), within 5 times the nearest neighbor distance (at most 4°);

(d) Find the stage pole (${}_{\mathbf{ageC+T2}}\mathbf{P}_{\mathbf{ageB+T2}}$) that describes the motion of the plate from ageC + T_2 to ageB + T_2 at time ageC + T_2, the time at which point C was created;

(e) Using the total reconstruction pole ${}_{\mathbf{ageC+T2}}\mathbf{P}_{\mathbf{T2}}$ to rotate pole (${}_{\mathbf{ageC+T2}}\mathbf{P}_{\mathbf{ageB+T2}}$) from ageC + T_2 to T_2 to find the stage pole ${}_{\mathbf{ageC}}\mathbf{P}_{\mathbf{ageB}}$ at time T_2;

(f) Compute the magnitude and direction of the fossil half-spreading rate at point A ($\mathbf{SR_A}$) using ${}_{\mathbf{ageC}}\mathbf{P}_{\mathbf{ageB}}$;

(g) Determine if $\mathbf{SR_A}$ is parallel to the vector distance between A and B ($\mathbf{d_{AB}}$) with the criterion that $|\cos(\alpha)|>0.8$, where α is the angle between $\mathbf{SR_A}$ and $\mathbf{d_{AB}}$;

(h) If the line that connects point A and point B is nearly parallel to $\mathbf{SR_A}$, then age_A is the distance in the direction of $\mathbf{SR_A}$ between the two points ($\mathbf{d_{AC}}$) divided by the magnitude of $\mathbf{SR_A}$; that is $age_A = age_C + d/|SR_A|$, which is a more accurate estimation of the age of point A than the crude approximation of step (b);

(i) Repeat the procedure for each point C that satisfies step (g) and average all the values to assign the age of point A.

Figure 3 is a 2-D cartoon meant to illustrate the method. All our calculations are properly done in spherical coordinates.

There are two major advantages of this method compared to those used in previous studies [8, 14]. First, the age of a point of unsubducted lithosphere 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 My [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. Secondly, by using multiple points as reference points for estimating the age we build a certain 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 unsubducted material. For example, when slabs from neighboring plates are unsubducted, there is not sufficient information to determine plate boundaries between these pieces of contiguous seafloor. The 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 lead to inconsistencies between past stage poles and the present day seafloor isochrons we use in this study. Ideally, if poles of rotations 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 poles of rotations to fit all parts of isochrons. In this case we correct for the negative ages by dividing all the area adjacent to the spreading ridge and up to 10 My old, into many small segments with boundaries parallel to the ridge segment. We determine the minimum age (age_{min}) in each section, which is nearly always that of the point on or closest to the ridge segment of interest. If the age of any point in the section, age_x, is less than 10 Ma it is corrected by $age_{xnew} = S*(age_x + |\ age_{min}\ |)$, where $S = 10/(10+|age_{min}|)$. Essentially this is a linear interpolation of ages between the ridge and the 10 Ma isochron.

Finally a problem is presented by the interpolation of ages for areas with very little information. One example is the NE corner of the Australian Plate, which has very little age data. Another example is the Tethyan Ocean, which is believed to have existed between the continents of Gondwana and Laurasia since Late Permian and has almost completely disappeared today [26-27] Though our reconstructions suggest the location of ancient Tethyan seafloor, little information about the ancient positions of the ridges and motion history of the basins makes the determination of seafloor ages of Tethyan oceans impossible.

4. Reconstructed Ages

Figure 4 shows the reconstructed seafloor ages as well as plate boundaries and velocities in the hotspot reference frame at 10, 25, 37, 48, and 64 Ma. 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 the 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 America and South American plates as they move away from each other are assumed to be continental area and assigned to the North America plate. Openings between Eurasia and Africa are assumed to be the remnant of the Tethyan Ocean in that region [26-27].

The reconstructions of seafloor ages shown in Figure 4 are based on the global reconstructions of Gordon and Jurdy [1]. However, different plate-tectonic models may have significantly different implications for seafloor ages locally. For example, the young seafloor in the Philippine plate, which is likely the result of back-arc spreading, gives rise to very young ages for the western Pacific that are probably unrealistic (Figure 4). These young ages stem from the welding of the present-day Philippine plate area to the Pacific prior to 10 Ma in Gordon and Jurdy [1]. Combining the Pacific and Philippine plates is at odds with a variety of geologic and tectonic data and reconstructions in this region [2, 25, 31-33], and an analysis of seismic images

[34-36]. As an alternative model, we use the reconstructions of Hall [2] in the western Pacific. In this model, an expansion of the trench retreat models 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, 55 Ma. A series of ridges and subduction zones in this set of paleogeographic reconstructions, evidence for which remains in the volcanic record, allow for a much more complex distribution of ages in the W. Pacific and also much older ages from Australia to Japan (Figure 5). In applying the Hall [2] reconstruction, we did not include the North New Guinea plate originally proposed in Seno and Maruyama [31] because lack of data on plate boundaries and motion history makes rotations and interpolation of seafloor ages inside the plate impossible. Instead, we treat the region as part of the Pacific Plate in the early Cenozoic. We choose Hall [2], because previous work has shown that the 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 (Figure 6). 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 panel of Figure 6, 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 [2] the average age of the Pacific seafloor is nearly constant within the expected error of the reconstructions (5 My change in the last 65 My). The maximum age of the seafloor also depends strongly on the ages inferred for the western Pacific. It increases strongly in the last 65 My (from 130 to 180 My today) for the Gordon and

Jurdy [1] models. For the Hall [2] model it decreases by less than 30 My 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 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 ignored.

Both the Gordon and Jurdy [1] and Hall [2] models show a decrease in lithosphere production rate by ~20% since the early Cenozoic (Figure 7). This is not a major decrease in lithospheric production rate, and is only minimally affected by the choice of plate boundaries in the Pacific. It may very well lie within the uncertainty inherent to the age of magnetic anomalies and the poles of rotations [23] It is clearly not nearly as dramatic as the changes in average age of the seafloor for both models. 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 seems to be a peak in productivity in the Cenozoic starting around 48 Ma in the Pacific, which propagates to the Indian and Atlantic basins at later times. The clear time lag in the peak appearance in different basins suggests a causal link through a global process, such as mantle flow, which can correlate plate motions. In the Pacific 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 of time (Figure 8), we see that they are clearly similar. This serves as a check on our results as well as 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 changes to the container volume of the ocean basins, and thus will result in changes in sea level. We calculate 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 average to calculate the change in average ocean basin elevation with respect to the present-day. 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 (Figure 9). This estimate ignores volume changes associated with changes to the area of each ocean basin. For the most part, shrinkage of one basin (the Pacific) is 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 (Figures 4 and 5), we must exclude the Tethyan seafloor area from the seafloor volume calculation. Thus, our ridge volume estimates (Figure 9) exclude changes in volume associated with basin area changes.

Because the average age of the ocean floor has increased during the Cenozoic (Figure 6), the volume of each ocean basin's ridge system has decreased during this time (Figure 9). 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 denudation. Our calculated sea-level curves caused by changes in ridge volume (Figure 9) are shown in Figure 10 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 are more reflective of observations.

6. Discussion

Both the Gordon and Jurdy [1] and Hall [2] reconstructions show changes in lithospheric production rates 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 My. 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 m 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 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 implication 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 [40] 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. This demonstration that large ocean basin volume changes can occur despite small changes in lithosphere production rates contrasts

Rowley's [21] assertion that a constant ridge production rate necessarily leads to constant ocean basin volume and sea level. This is clearly not the case. The primary reason is that lithospheric production is the product of ridge length and spreading rate, a convolution that might hide more dramatic changes in each component. 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.

Rowley's [21] conclusions have vast implications for geodynamics, well beyond our conventional wisdom regarding relative sea-level change in the late Mesozoic and early Cenozoic [9-10, 41]. Constancy in sea-floor spreading rates would suggest a much steadier plate-tectonic regime and a substantially reduced influence of tectonics on the carbon cycle for example. The time-dependence of mantle convection over time scales of 100-120 My is at odds with constant spreading rates.

In more general terms it seems important to study lithospheric production rates and changes in sea level by using all geologic information available and not only the history reflected in the extant magnetic anomaly record. The application of an analysis of the present-day snapshot of seafloor ages to past times [21], assumes that there is equal probability of destruction for oceanic floor of all ages and that such destruction always occurs at the same rate. This is evidently not true for the present-day [22] and not for the past as demonstrated by a cursory visual inspection of our maps. This assumption also neglects the dynamics of the Earth. Younger lithosphere is more buoyant and not as likely to be subducted; when it finally is, it is likely to encounter greater resistance and subduct at slower speeds. By contrast, old, dense lithosphere should subduct more rapidly [20], which should increase plate velocities, and spreading rates, for entire oceanic plates such as the Pacific [42].

Undoubtedly past plate reconstructions and poles of rotations inferred from the seafloor magnetic record, continental paleomagnetism, and hotspot tracks can contain large uncertainties. The 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. Rowley [21] contends that the explanation for the difference between the previous studies and his conclusion is due to the inherent uncertainty in reconstructing now-subducted ridges in the Pacific and Tethyan ocean basins. Our results show that when the ages of these now-subducted ridges in the Pacific are much 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 Tethyan Ocean basins is quite small on the global scale and it is unlikely to affect 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. We found that the distribution of seafloor ages, and the average age changed significantly from the early Cenozoic to present-day. We also find that the assignment of ages depends regionally quite strongly on the choice of reconstruction, as does the maximum age of the seafloor at any given time.

Our further analysis of average seafloor age, total volume of ocean basins and oceanic lithospheric production rate based on the reconstructed seafloor ages yields very interesting results and confirms generally held notions that seafloor production and sea level were higher in the past. 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, 42-43]. 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 that depend on this knowledge include those related to mantle flow driven by subducted buoyancy such as the geoid and dynamic topography [8,37]. 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] might 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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Figures and Figure Captions:

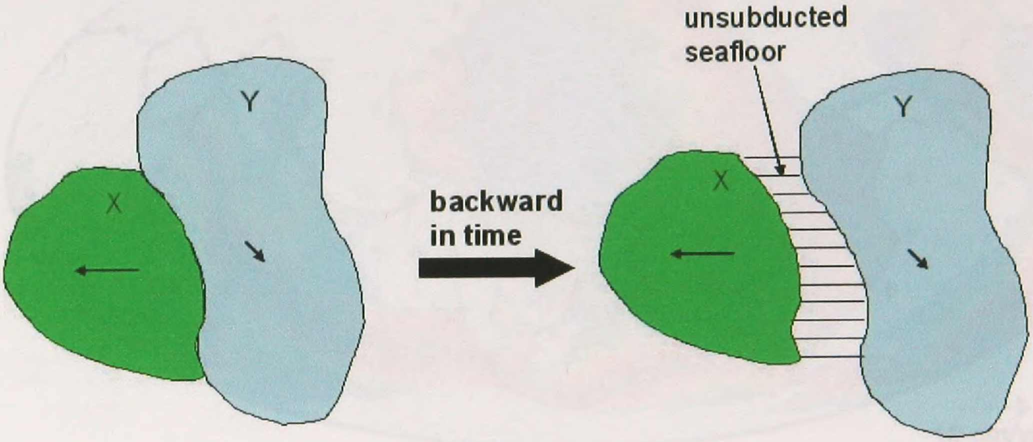

Figure 1: Schematic illustration of the appearance of unsubducted seafloor (horizontal lines) between two converging plates (X and Y) as they are rotated back in time. This material resides in the mantle at present. Its age at the time of consumption is unknown and must be assigned to obtain an accurate estimate of the distribution of seafloor ages in the past. The arrows represent the direction and speed at which plate X and Y would move away from each other as we rotate each point on the plate back in time.

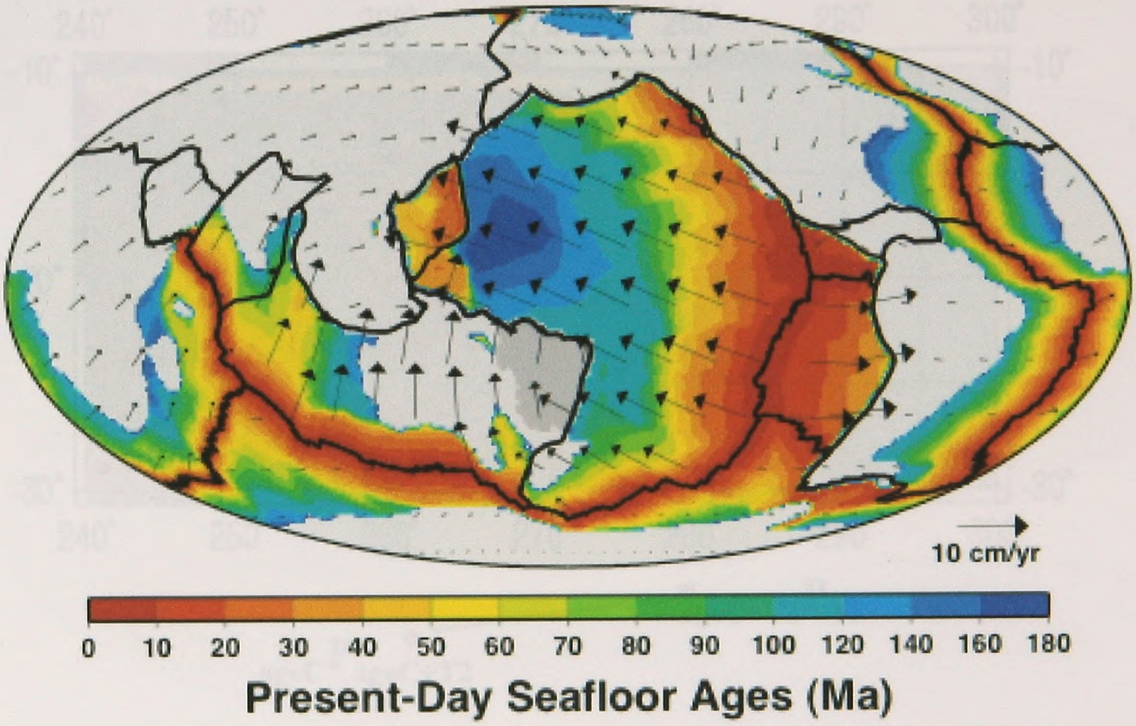

Figure 2. Present-day distribution of seafloor ages interpolated from the magnetic anomaly map of Müller et al. [6]. Ages for the Philippine plate, the Arctic Ocean and other back-arc basins from Sclater et al. [17].

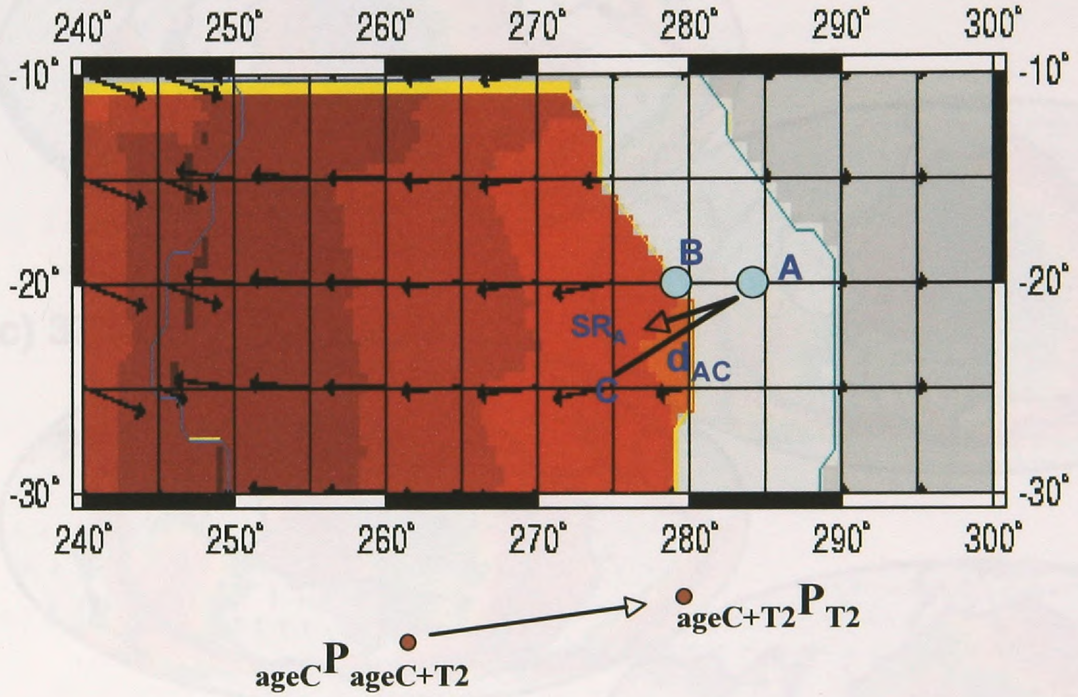

Figure 3. Schematic illustration of the methodology used to determine the age of unsubducted seafloor (light gray). Colors correspond to seafloor of known age, dark gray to continental areas following Figures. For any point A whose age is unknown we follow the procedure outlined in Section 3, points (a)-(i). Point B is the nearest neighbor with known age within 0.8 degrees angular distance. Point C is one of many points of known age within 4 degrees, then used to find a more accurate age of point A if the distance $\mathbf{d_{AC}}$ is parallel to the spreading rate direction at the time point A was generated. $_{\mathbf{ageC}}\mathbf{P}_{\mathbf{ageC+T2}}$ is the stage pole that describes the motion of the plate at $age_C + T_2$, when point C was created. $_{\mathbf{ageC+T2}}\mathbf{P}_{\mathbf{T2}}$ is the total reconstruction pole used to compute the fossil half-spreading rate at point A ($\mathbf{SR_A}$).

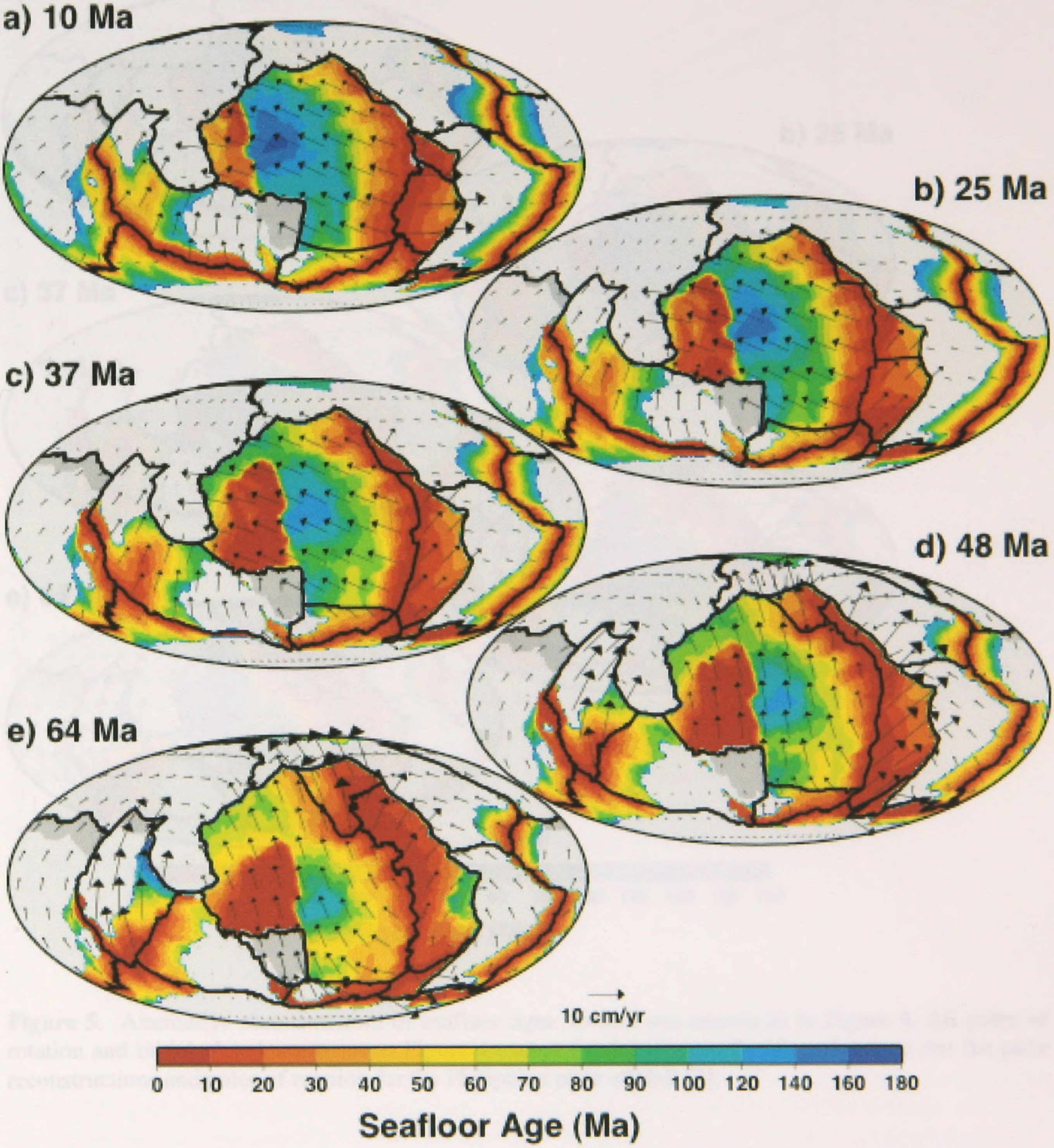

Figure 4. Global reconstructions of seafloor ages for 10, 25, 37, 48 and 64 Ma derived from the Gordon and Jurdy [1] model. Light grey indicates continental areas and dark grey areas with insufficient information to determine ages. Solid black lines are the plate boundaries determined at each time period. Arrows represent the absolute plate motion at the time of reconstruction. Note the very young ages in the western Pacific.

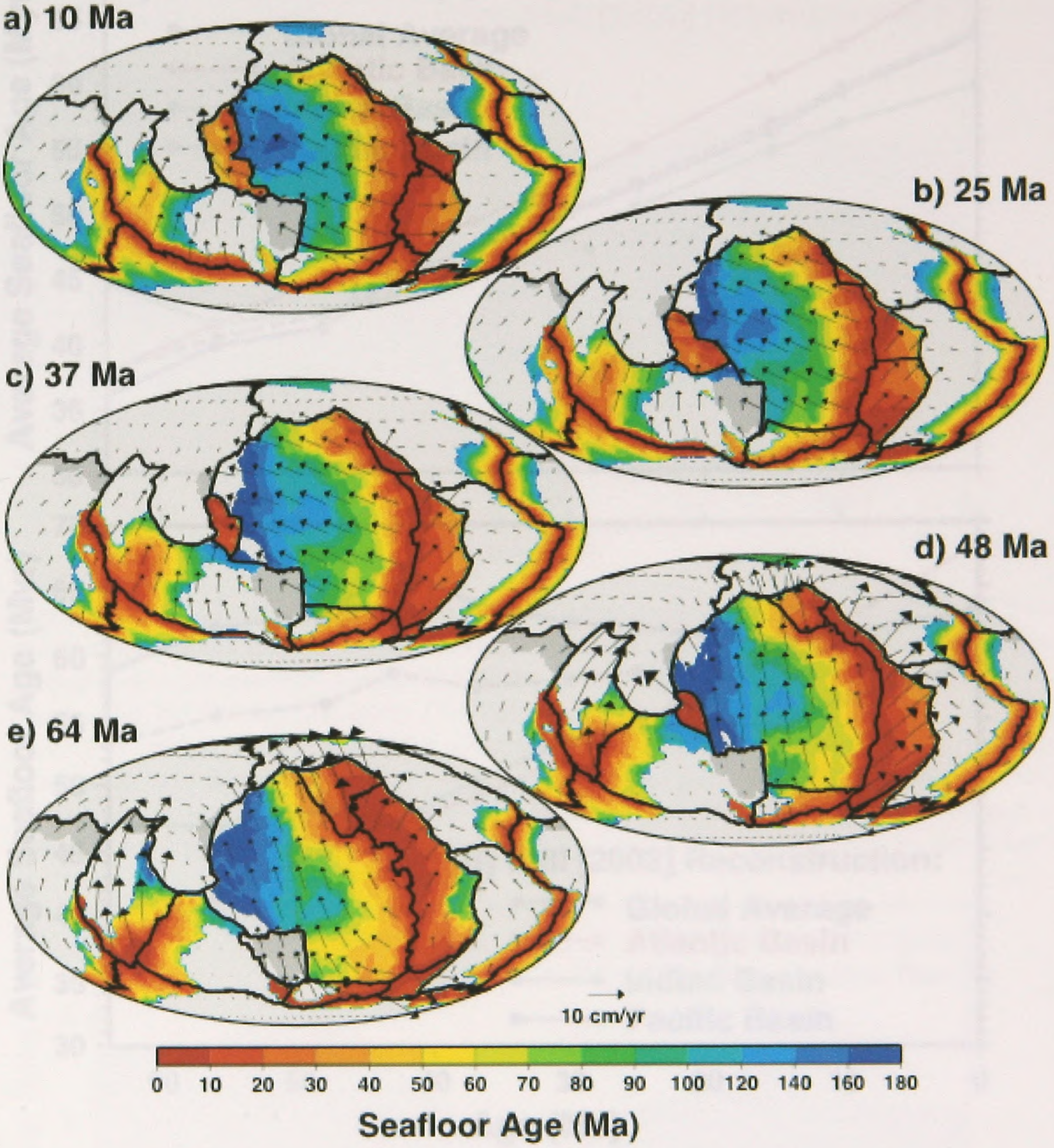

Figure 5. Alternative reconstruction of seafloor ages. Colors and arrows as in Figure 4. All poles of rotation and initial plate boundaries as Figure 4 except for the western Pacific, where we use the plate reconstructions and poles of rotation for the Philippine plate of Hall [2].

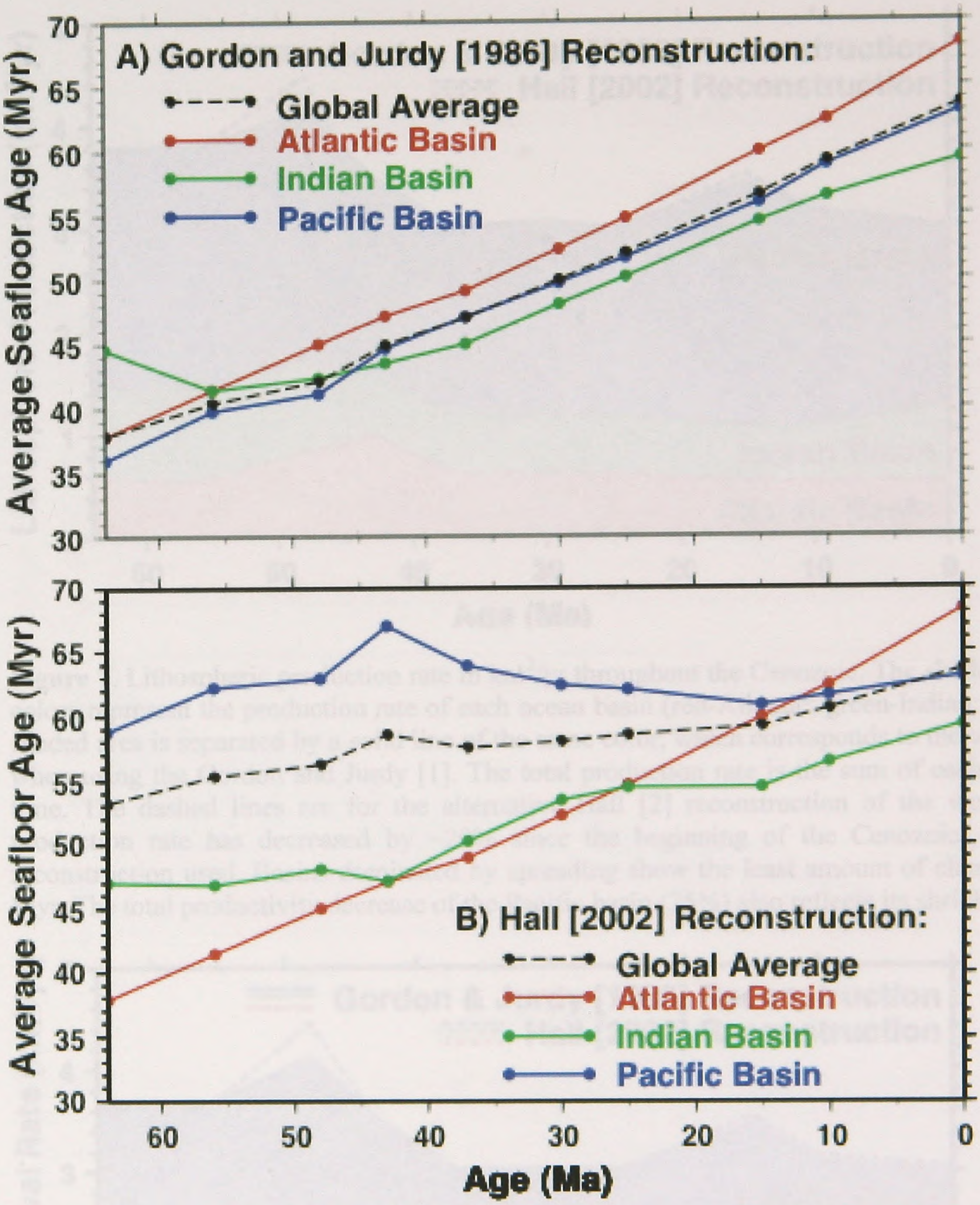

Figure 6. Average age of the seafloor for the distributions of ages shown in Figures 4 (top panel) and 5 (bottom panel). In both panels, the dashed black line is the global average, and the colored lines the average for different basins (red-Atlantic, blue-Pacific, green-Indian). The average age increases 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 [2] 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.

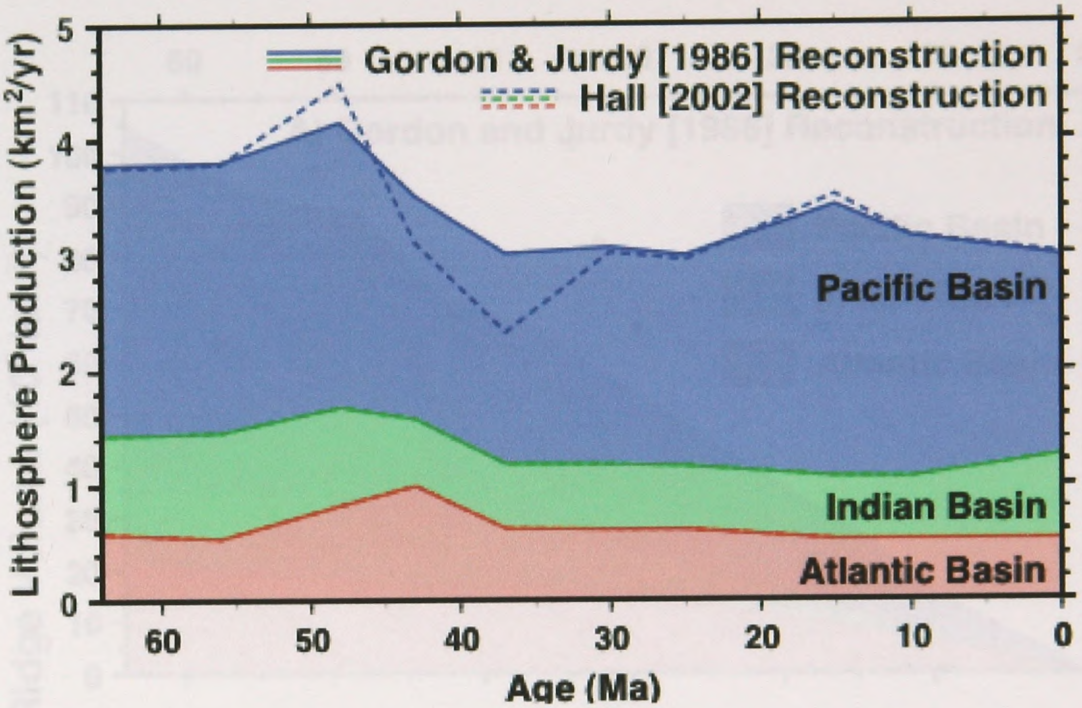

Figure 7. Lithospheric production rate in km^2/yr throughout the Cenozoic. The shaded areas of different colors represent the production rate of each ocean basin (red-Atlantic; green-Indian; blue-Pacific). Each shaded area is separated by a solid line of the same color, which corresponds to the value 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.

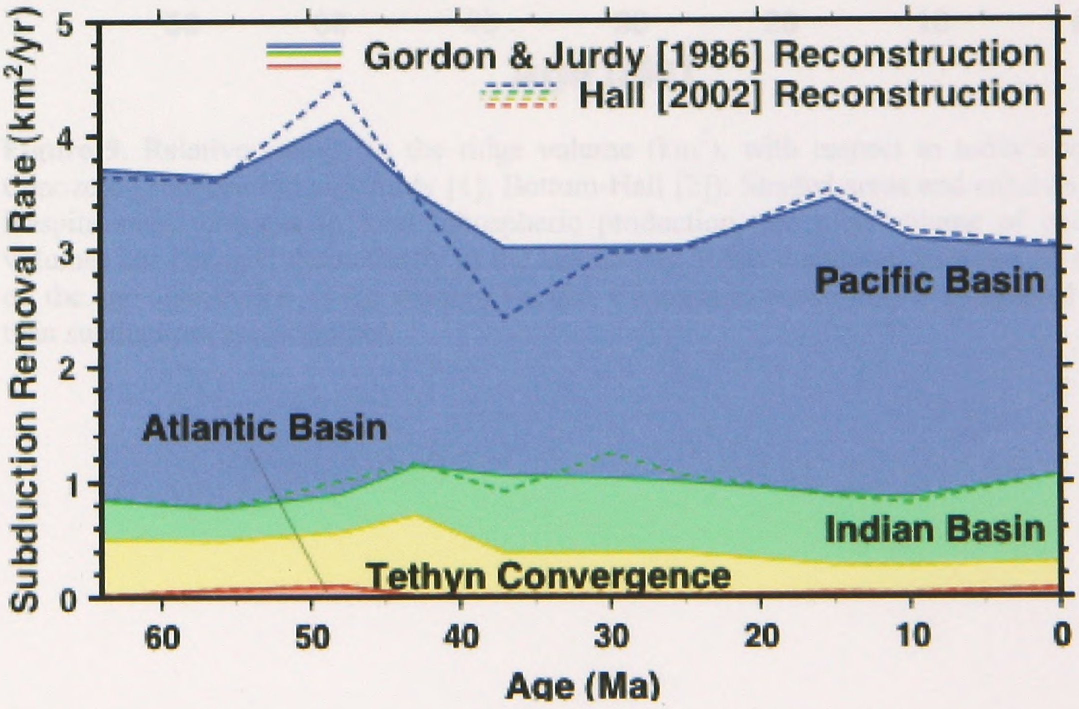

Figure 8. The rate of lithospheric removal by subduction in km^2/yr. Colors and lines as in Figure 7, except for the addition of a yellow band to account for the disappearance of the Tethyan basin. Peaks in subduction removal correspond to peaks in productivity as seen in Figure 7.

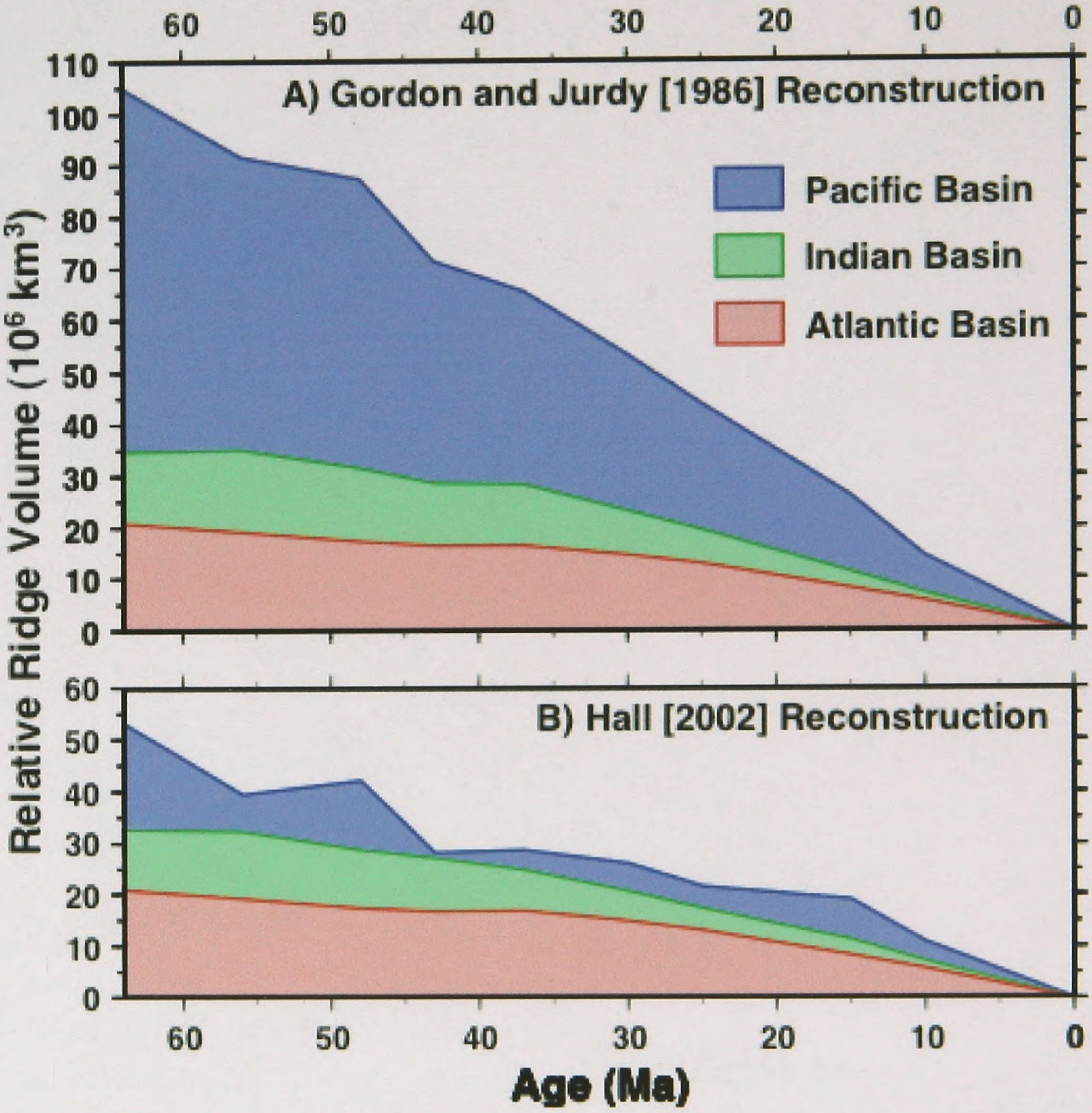

Figure 9. Relative change in the ridge volume (km^3), with respect to today's value, throughout the Cenozoic (Top-Gordon and Jurdy [1]; Bottom-Hall [2]). Shaded areas and colors as in Figures 7 and 8. Despite small changes in total lithospheric production, the total volume of ocean basins (or ridge volume) has changed dramatically in the last 65 My. It has decreased between 50 and 100% depending on the age distribution of the western Pacific. Changes in ocean basins dominated by spreading, rather than subduction, are smoother.

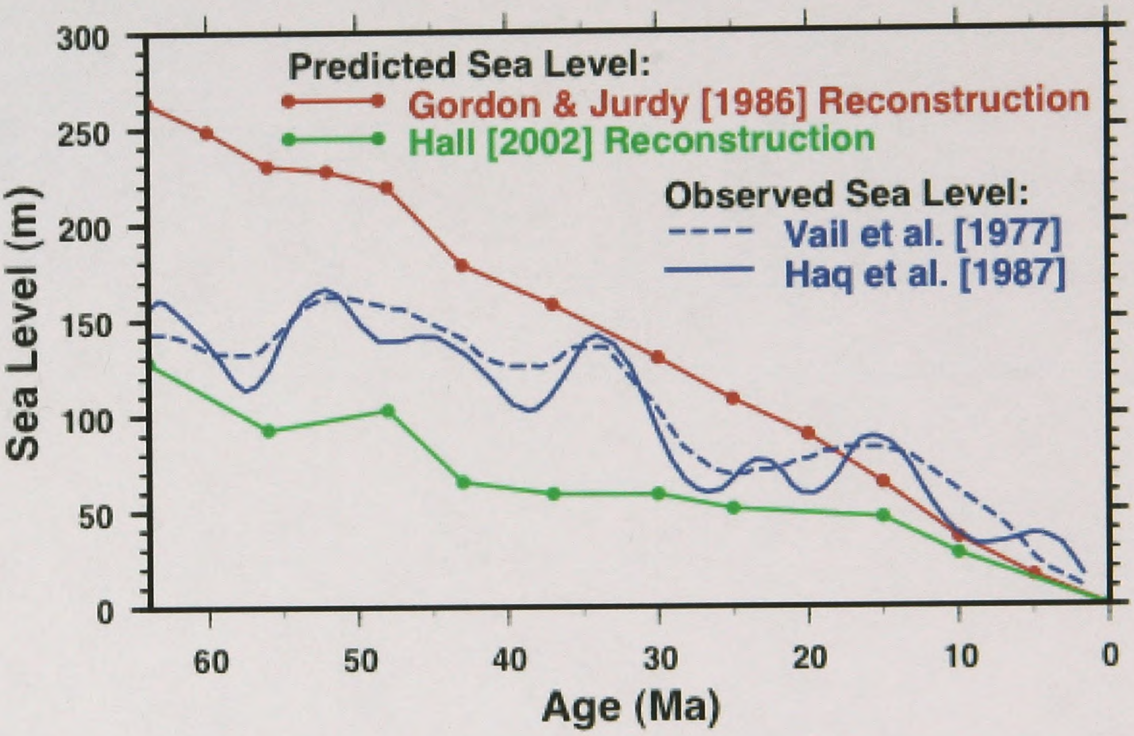

Figure 10. Sea level curves as a function time, computed using the method of Pitman [9]. Solid red line calculated given the seafloor ages in Figure 4; solid green line from the ages shown in Figure 5. The blue dashed [38] and solid [39] lines correspond to geological estimates. The older ages in the western Pacific obtained when using the Hall [2] reconstruction, halve the predicted sea-level decrease in the last 65 My.