Rate of plate creation and destruction: 180 Ma to present

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ABSTRACT

One of the primary measures of plate tectonics is the history of production of new oceanic lithosphere. As shown by B. Parsons, a direct estimate of the rate of plate creation can be derived from the area/age versus age distribution of the modern oceanic lithosphere. Inversion of the most recent area versus age data (digital isochrons by R.D. Müller et al.) yields a result that the rate of oceanic plate production has not varied significantly since 180 Ma from a mean rate of 3.4 km²/yr. Reconstruction of the cumulative area of subducted lithosphere over the past 90 m.y. is in excellent agreement with a fixed rate of ridge production. The conclusion that the rate of ridge production has not varied significantly contrasts markedly with most existing estimates in which the rate is modeled as decreasing by 50% or more since ca. 100 Ma. A constant rate of ridge production has important implications for models of sea level and $p(CO_2)$, among other phenomena that have been linked to variations in global rates of seafloor spreading.

Keywords: plate tectonics, sea-level changes, seafloor spreading, subduction.

INTRODUCTION

The rate of generation of new oceanic lithosphere is a fundamental parameter of plate tectonics. Given that the mean radius and hence volume of the Earth has been constant over at least the past 180 m.y., the rate of generation by seafloor spreading must equal the rate of destruction by subduction. The driving forces of plate kinematics directly control changes in the rate of generation and destruction, and hence any changes in rate provide an estimate of the variability of those forces over time. Beyond plate kinematics, changes in the

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rate of generation of new oceanic lithosphere have, for example, been implicated in controlling (1) long-term sea level (Kominz, 1984; Pitman, 1978), (2) ocean chemistry through changes in the hydrothermal exchange between the oceanic crust and sea water (Edmonds, 1992; Palmer and Edmonds, 1989; Richter et al., 1992), and (3) the global carbon cycle through the flux of CO_2 from ridge and arc-related magmatism (Berner, 1994). Estimates of the history of the generation rate of oceanic lithosphere have been made by (1) directly combining plate-reconstruction stage poles and ridge lengths to compute global spreading rates (Kominz, 1984; Pitman, 1978), (2) directly combining plate-reconstruction stage poles and trench lengths to compute global subduction rates (Engebretson et al., 1992), or (3) inversion of estimates of the long-term sea-level history (Turcotte and Burke, 1978; Gaffin, 1987). Although there are some similarities among all curves so produced (see McCauley and DePaolo, 1997), the differences are still large, as are the uncertainties. The primary problem underlying the direct determination of the ridge-production history from reconstructions is the inherent uncertainty in reconstructing now-subducted ridges and plates in the Pacific and Tethyan ocean basins. Production along these ridges, now entirely subducted, was responsible for all of the inferred increased production in the analyses of Kominz (1984) and Engebretson et al. (1992).

MODELING RIDGE PRODUCTION

Parsons (1982) explored the relationship between the area of preserved oceanic lithosphere per unit time versus age—hereafter referred to as the area/age versus age distribution—and the rate of oceanic lithosphere production. Parsons (1982) used the isochron map of Sclater et al. (1980) to estimate the area/age versus age distribution of the present oceanic lithosphere. He showed that the area/age versus age distribution of extant oceanic

lithosphere follows a basically triangular distribution (Fig. 1). The simplest governing relationship of such a system, adapted from Parsons (1982), is

$$\frac{dA}{dt} = -\frac{dD}{dt} = R_0\left(1 - \frac{t}{t_{max}}\right), \quad (1)$$

where dA/dt is the differential area (A) per unit time as a function of age (t), dD/dt is the differential destruction (D) of area of all ages per unit time as a function of age (t), R_0 is the rate of lithospheric production, and t_{max} is the maximum age of oceanic lithosphere. Integrating equation 1 with respect to t yields the cumulative areas of both preserved, $A(t)$, and subducted, $D(t)$, lithosphere as a function of age as given by equation 2:

$$A(t) = -D(t) = R_0 t\left(1 - \frac{t}{2t_{max}}\right). \quad (2)$$

Parsons's (1982) analysis of the data from Sclater et al. (1980) showed that the fit to a simple triangular area/age versus age distribution was quite good and that the cumulative area/age versus age relationship was well fit by a constant rate of lithosphere production. Parsons's (1982) elegant summary of these governing relationships and particularly his conclusions have largely, but not completely (Heller et al., 1996), been ignored in subsequent work.

The current paper explores the relationship between the preserved area per unit time versus age distribution and the rate of oceanic lithosphere production by using (1) the most recent compilation of age of oceanic lithosphere (Müller et al., 1997), (2) the relationship between age and cumulative increase in area subducted determined with reconstructions, and (3) an analysis of existing plate-production curves relative to expectation of the preserved area/age versus age distribution in equilibrium with them.
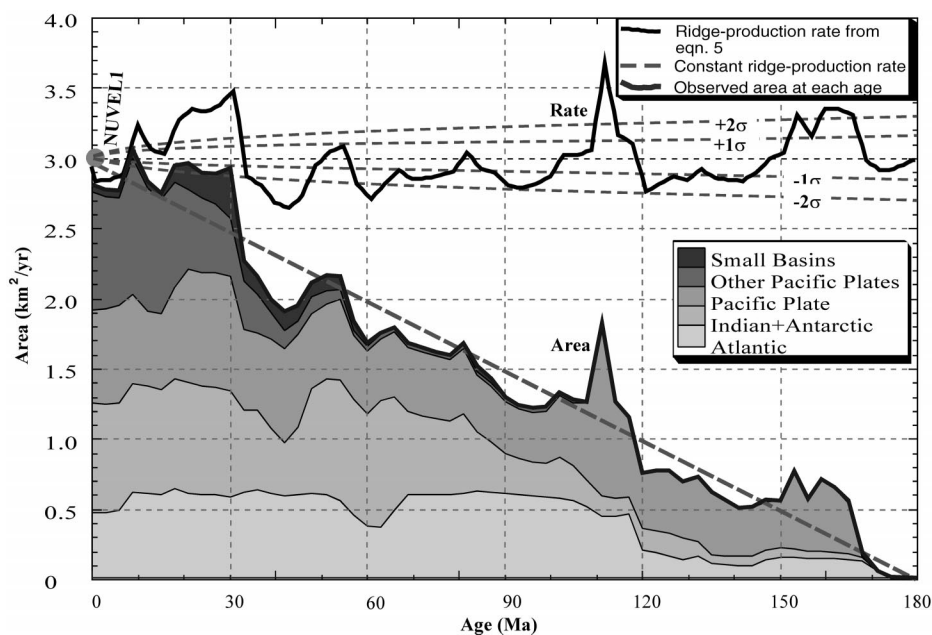
Figure 1. Curves of area/age vs. age and production rate vs. age derived by direct inversion using equation 5. Straight dashed curve shows the linear regression of the area vs. age data expressed in equation 3. The Müller et al. (1997) age grid has 6-minute spatial resolution and covers the area north of 72°S. Thus, the data cover an area of ~4.95 × 10^{8} km², including ~1.95 × 10^{8} km² assigned to continental crust and ~3.00 × 10^{8} km² assigned to oceanic crust. Of the grids cells assigned to oceanic crust, ~2.85 × 10^{7} km² (= ~9.5%) are considered to have undetermined ages in this analysis, including both the Amerasian Basin and Gulf of Mexico as each has been assigned a single age over its entire area (Müller et al., 1997). The sloping curve labeled "Area" is the area/age vs. age distribution derived from a slightly edited, updated version (http://beryl.es.su.oz.au/pub/agegrid/age_1.5.bint.gz, downloaded 24 August 1999) of Müller et al. (1997). Editing involved changing assigned values along the prime meridian and dateline in the middle of continents to continent values, as well as some grids in Ellesmere Island. Implicit in the analysis is that the grid cells that are unassigned are equally distributed in age. Large dot labeled NUVEL1 is the lithosphere-production rate derived from inversion of augmented rotation parameters in Gordon (1995) and corresponding ridge lengths. The ±1σ and ±2σ curves are estimates of the expected variability based on stochastic processes affecting the age-related subduction of lithosphere. Black curve labeled "Rate" is the ridge-production rate derived from the area/age vs. age distribution by using equation 5. Variously shaded areas for Atlantic, circum-Antarctic + Indian, Pacific, and small basins show their contributions of to the area/age vs. age distribution.

DATA—OBSERVATIONS OF THE AREA/AGE VERSUS AGE DISTRIBUTION

Figure 1 plots the area/age versus age distribution of ~88% of the present-day oceanic lithosphere as determined from Müller et al. (1997). Simple linear regression of the area/age versus age data confirms Parsons's (1982) fit of the observations to a triangular distribution. The best-fit equation is

$$\frac{dA}{dt} = 2.96 - 0.016t, \qquad (3)$$

with $R^2 = 0.932$ and where t is in km²/yr; equation 3 yields a corresponding t_{max} of 182 m.y. that is not different from the observed t_{max} of 180 m.y. Note that R_0 derived from the regression underestimates the total ridge production, reflecting the fact that areas amounting to >12% of the area of the oceans are excluded from the area data.

Equation 1 models the process as a source term R_0 and a destruction term R_0t/t_{max}. Thus, according to this model, at each time there is equal destruction of oceanic lithosphere of all ages from 0 to t_{max}; the sum of destruction per unit time equals R_0, and hence, with increasing age, the rate of decrease of area by subduction is linear with a slope of R_0/t_{max}. This model is equivalent to stating that, statistically, there is equal destruction of oceanic lithospheric area of all ages irrespective of the areal extent of each age of oceanic lithosphere. Parsons (1982) assessed the validity of this relationship by examining the destruction rate as a function of age and concluded that the observed pattern was consistent with this expectation. Figure 2 shows the current rate of destruction of oceanic lithosphere, as well as rates 5 and 10 m.y. into the future (denoted +5 and +10 m.y., respectively), holding current NUVEL1A angular velocities unchanged. Although there is considerable variability in the rates of destruction of oceanic lithosphere of various ages, it is clear that there is no consistent bias in the destruction rate of lithosphere of different ages that would lead to a model different from equal destruction rate independent of age. Note that this result counters the commonly espoused view that older lithosphere is more likely to be subducted than younger. In the present world there is no such relationship.

An alternative approach to modeling the area/age versus age distribution is to rewrite equation 1 in order to track the cumulative decrease in the area per unit age due to subduction, as in equation 4:

$$A_t = A_{0(t)} - \int_0^t D \, dt, \qquad (4)$$

where A_t is the preserved area of age t, $A_{0(t)}$ is the area originally created at time t and hence equal to R_t, and the integral is the destruction history, D, of lithosphere of age t between the present and time t. In the triangular distribution of Parsons (1982) D is a constant $= R_0/t_{max}$. Evaluating the integral in equation 4 with respect to t yields the cumulative loss of lithosphere with age; this loss grows as $\frac{1}{2}Dt^2$. Although there is considerable scatter in Figure 2, there is no obvious trend and hence the rate of destruction is compatible with this assumption. Equation 4 and equation 1 yield identical results if R_0 is constant. An alternative might be that $D \propto A_t$ as would be typical, for example, of radioactive decay. This alternative would result in an exponential relationship of the form $D = A_{0(t)}\exp(-\lambda t)$ with $\lambda \approx 0.0111$ yr⁻¹, corresponding to a half-life of ~62.4 m.y. Such a form would significantly deviate from the observed area/age versus age distribution: >13% of the oceanic lithosphere would be expected to be older than 180 m.y. (Parsons, 1982). The combination of lack of a clear
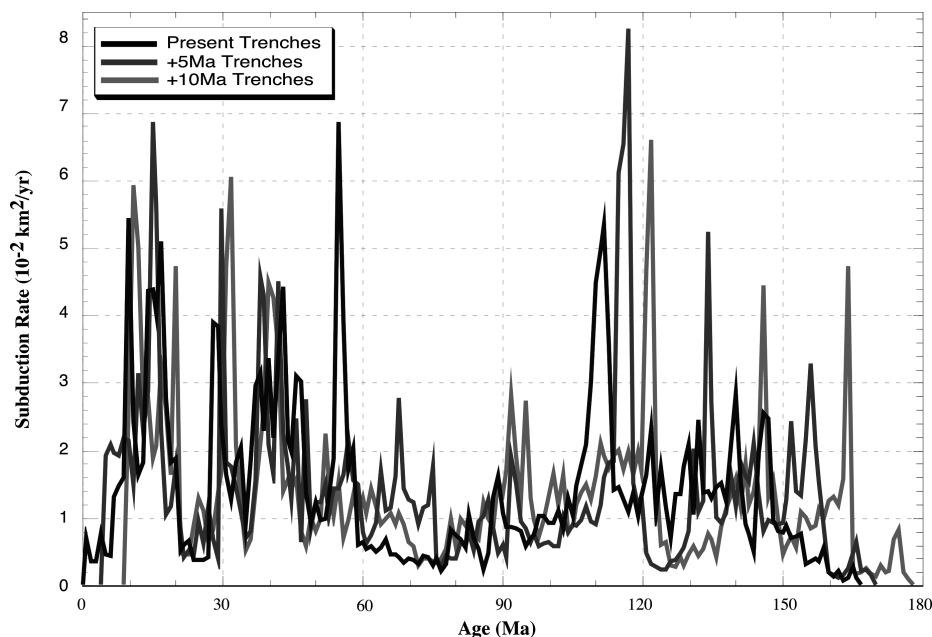
Figure 2. Rate of subduction of oceanic lithosphere by age in 1 m.y. bins for the present and for +5 m.y. and +10 m.y. in the future. Derivation of present rates used NUVEL1 angular velocities (Gordon, 1995) applied to the age grid along current trenches. Future rates, assuming no change in rotation parameters, were derived by determining the age plus age offset and summing the areas by those ages of the grid cells along trajectories defined by the NUVEL1 rotation parameters (Gordon, 1995) at angular distances from the current trenches corresponding to +5 and +10 m.y.

trend in the area of subduction with age and linear fit to the area/age versus age distribution strongly supports the model of Parsons (1982).

DIRECT INVERSION OF THE OBSERVED AREA/AGE VERSUS AGE DISTRIBUTION TO RATE

It is possible to explicitly calculate a history of production, R_t as a function of time that would exactly reproduce the observed area/age versus age data if it is assumed that subduction consumes an equal area of oceanic lithosphere of all ages. If equation 4 is recast so that we can use the observed area/age versus age distribution A_t to determine R_t then

$$R_t = A_t - \sum_{i=1}^{t} \frac{R_i}{t_{max}} dt, \qquad (5)$$

where R_i/t_{max} has been substituted, in a discretized form, for D. In order to solve equation 5 for all times in the past, we only need to know A_t and R_i at $t = 0$, which equals A_0. For all older ages, we can successively step backward in time, computing the rate of production corresponding to the preserved area/age versus age distribution. The only unknown in

equation 5 is whether t_{max} has been constant over time. The value of t_{max} today is readily determined from the maximum age of oceanic lithosphere and is equal to 180 m.y. It is not clear how t_{max} should have varied in association with the progressive opening of the Atlantic and circum-Antarctic oceans. The value of t_{max} in the Atlantic and Indian Oceans has clearly been increasing with time. Simultaneously the area of the Pacific has been progressively reduced. This areal reduction might be taken to imply that t_{max} in the Pacific should be decreasing and just happens to be essentially identical in age with the Atlantic and circum-Antarctic Ocean basins. As is clear from equation 5, if t_{max} increases, the incremental rate of reduction in area per unit time is reduced, resulting in a corresponding decrease of R_i/t_{max}. A lower bound on t_{max} can be established by the fact that oceanic lithosphere that is 180 m.y. old today is still preserved and hence $t_{max} + t - 180 \geq 0$ must always have been true for the past 180 m.y. Otherwise all lithosphere older than $t_{max} + t$ would have been subducted. This bound is obviously most stringent in more recent intervals unless t_{max} was very small at some time in the past. The next section contains further discussion of t_{max}

in connection with several existing models of lithospheric production over time.

If it is assumed that t_{max} has remained constant at 180 m.y., the area/age versus age distribution derived from the Müller et al. (1997) data together with R_t derived with equation 5 is as shown in Figure 1. The average rate over the past 3 m.y. estimated from the area/age versus age distribution is comparable with that derived by using augmented NUVEL1 (Gordon, 1995) rotation parameters and corresponding ridge lengths. There is a fair degree of short-term (m.y.) variability implied in the area/age versus age data that does not appear to be compatible with the good correlation between the 3 m.y. NUVEL1 rates and the decadal rates derived from GPS studies (Gordon, 1995). Close examination of the Müller et al. (1997) data reveals that much of the variability between 0 and 10 Ma is from the Cocos plate; this finding reflects uncertainties in the assignments of anomalies on this plate (Klitgord and Mammerickx, 1982). Thus, it appears appropriate to use longer-term means rather than the ~1 m.y. resolution of the Müller et al. (1997) data. For the present purposes, a 3 m.y. bin size is employed, anchored at the present by using the NUVEL1 result.

The area/age versus age distribution is well fit by an essentially unchanging rate of generation of seafloor spreading over the past 180 m.y. Direct inversion of the area/age versus age data implies that rates have on average not varied by more than ±10% from the 180-m.y.-long average of 3.0 km²/yr, which is not different from the value resulting from simple linear regression analysis. Once again, this value underestimates the total ridge production by at least 12%. This conclusion was surmised by Parsons (1982) on the basis of the close fit of the cumulative area/age versus age data from Sclater et al. (1980) when compared with the results of equation 2. Figure 3 reproduces this comparison with the modern data.

What part of the variability in the preserved area/age versus age distribution and the corresponding variability in the rate of ridge production reflects the fidelity with which subduction follows an age-independent pattern rather than variability in rate? In other words, to what degree does the variability displayed in Figure 1 reflect stochastic variability in the sampling of the age of the subducting oceanic lithosphere? In order to assess this question, a 5000-iteration Monte Carlo simulation of deviations of the area per unit age from the linear solution was computed as a function of age. In the simulation, each iteration starts with a linear fit described by equation 1, is stepped forward in time for $t > t_{max}$ steps, re-
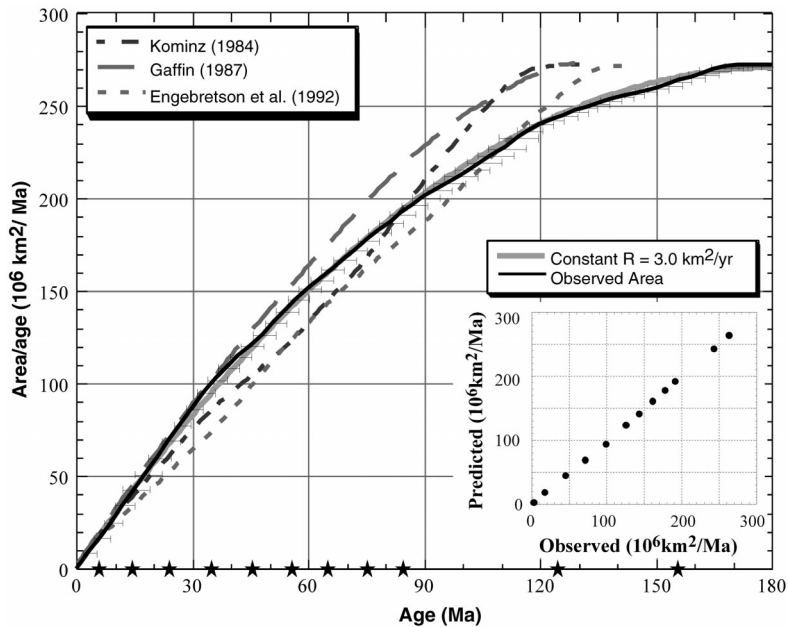
Figure 3. Cumulative area/age vs. age relationships of various models of lithosphere-production history. Black curve with error bars is the cumulative area as a function of age of observed oceanic lithosphere derived from the Müller et al. (1997) data. The error bars are standard errors of each 3 m.y. bin. The black stars represent the calibration points used by Cande and Kent (1995) and Gradstein et al. (1994) in their interpolations of the reversal history to time. The thick gray curve is based on equation 2 and assumes constant production at the 180-m.y.-long average rate of 3.0 km²/yr. The three superimposed curves of dashed lines for cumulative area/age vs. age distributions derived from solutions of equation 5 are based on proposed lithospheric-production histories of Kominz (1984), Gaffin (1987), and Engebretson et al. (1992). The inset graph plots the observed cumulative area corresponding to each of the calibration tie points used by Cande and Kent (1995) and Gradstein et al. (1994) vs. the predicted cumulative area of oceanic lithosphere at each of the tie points; a constant production rate of 3.0 km²/yr is assumed. The slope of a linear regression of these points is 1.00 with $R^2 = 0.999$.

moving area as a random function of age such that the area removed equals the area added at each step. At the end of each iteration, the deviation at each million-year age increment is computed as the simulated area minus linear area. The frequency distribution was then used to define $\pm 1\sigma$ and $\pm 2\sigma$ curves (Fig. 1) that provide estimates of the expected stochastic variability as a function of age. Comparison of the rate estimates with these curves (Fig. 1) suggests that much of the variability at older times is not statistically significant. However, the marked increase in implied lithosphere-production rates between 34 and 8 Ma clearly exceeds the $\pm 2\sigma$ confidences. Analysis of the Müller et al. (1997) data (Fig. 1) reveals that much of the increase between 34 and 8 Ma is associated with lithospheric production in small ocean basins such as the South China Sea, Philippine Sea, and Scotia Sea. The age distributions in these basins are unevenly covered in this data set, potentially

resulting in an additional source of nonstochastic variability. It is therefore unclear whether this peak in production between 34 and 8 Ma reflects a real increase and decrease in production or nonrandom sampling of ocean-floor age and corresponding nonrandom distribution of areas of the ocean lacking age assignments. The marked increase in rate in the late Early Cretaceous centered at ca. 112 Ma is another anomaly (Fig. 1). This spike occurs entirely within the Early Cretaceous Quiet Zone within the Pacific plate and thus is not explicitly constrained by reconstructions of observed magnetic reversals. Instead, it is likely an artifact of modeling changing rotation poles implied by changing curvature of fracture zones and the marked angularity of the anomalies bounding the quiet zone, but without explicit control on the age distribution of oceanic lithosphere within the quiet zone.

Equations 1 and 2 explicitly incorporate the fact that both incrementally and cumulatively,

the rate of production and destruction of lithospheric area must be equal. If the world is reconstructed (including both oceanic and continental lithosphere) to an arbitrary time, t, in the past, all oceanic lithosphere younger than t is subtracted, and the surface area that has been subducted between the present and t is tabulated, it should grow according to equation 2. We can thus compare the rate of increase of subducted area with the simple model of constant ridge production. Figure 4 shows a comparison between these and demonstrates that cumulative increase in area of subducted lithosphere is completely consistent with a constant rate of ridge production over the past 90 m.y. Note that we are not concerned with the age distribution of the reconstructed oceanic lithosphere, and hence the result shown in Figure 4 constitutes an independent assessment of the ridge-production history at least to 90 Ma. In addition, it should be noted that this assessment incorporates both the effects of subduction as well as shortening in the Himalaya-Tibet and Alpine orogenic systems, but does not take into account shortening or extension in Pacific-facing areas such as the Andes or Laramide shortening in the Western Cordillera of North America or later Tertiary extension in the Great Basin. These constitute small errors that do not significantly affect the conclusion. This aspect of the model is not extended back beyond 90 Ma because it is not possible to directly link the motion of the Pacific plate to the rest of the plate circuit at older times; this lack of linkage would introduce unknown uncertainties into the reconstructions of this area and hence into any estimate of subducted area.

A critical issue that needs to be addressed is the degree to which the conclusions drawn are dependent upon the time scale used. This issue is particularly important because the ages assigned to the magnetic reversal time scale, and employed by Müller et al. (1997), assume a constant rate of spreading (Cande and Kent, 1995; Gradstein et al., 1994). Thus, it might be thought that the analysis presented here simply restates the assumption underlying these time scales. Cande and Kent's (1995) analysis has minimized implied changes in rates along profiles of many, but not all, ridge segments by using >9 dated calibration points, between which ages are linearly interpolated. Gradstein et al. (1994) assumed that the rate remained constant along a single profile; they used only two tie points between which linear interpolation of ages was done. Figure 3 highlights all of the tie points used in the Cande and Kent (1995) and Gradstein et al. (1994) time-scale assessments. Here the
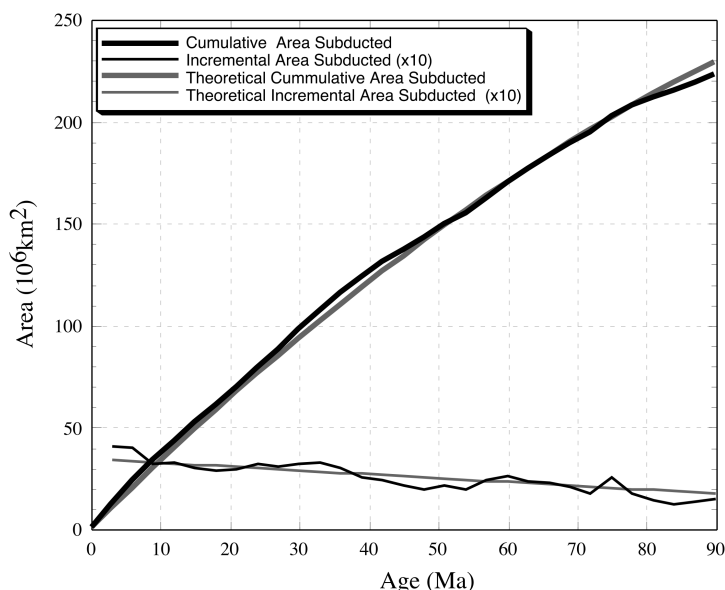
Figure 4. Comparison between the cumulative area of subducted lithosphere from the present to 90 Ma and that predicted by equation 2 with a constant rate of production of 3.4 km²/yr. Black curves are the cumulative and incremental areas as a function of age based on reconstruction, and gray curves are based on equation 2 and the assumption of a constant rate of ridge production.

integral properties described by equation 2 can be used to show that the global rate analysis is independent of the underlying assumption used to construct these time scales. Because the cumulative areas of lithosphere equal to and younger than the age of each tie point can be reasonably determined, then, if the global rate of production is constant, this area should grow as predicted by equation 2. Figure 3 demonstrates that the observed cumulative areas and that predicted by constant rate at the ages of each calibration point are identical within uncertainty. Thus, even though we know virtually nothing about rate during the Early Cretaceous Quiet Zone, the cumulative area increase between the beginning and end of the zone are completely compatible with a globally constant rate of lithosphere production. Similarly, the fact that only one profile and two tie points determine the ages within the pre–Early Cretaceous Quiet Zone Cretaceous and Jurassic (Gradstein et al., 1994), the close fit of the cumulative areas with a constant rate of production implies that this conclusion can be extended globally as well.

EXISTING MODELS OF LITHOSPHERIC PRODUCTION

A number of models have been proposed over the past 20 yr that describe the lithosphere-production history based on various direct and indirect assessments. Several of these models are briefly reviewed in terms of proposed production histories, predicted area/age versus age distributions, and predicted variations in t_{max} as a function of age.

Given a proposed lithosphere-production history, it is possible to derive the corresponding predicted area/age versus age distribution. Each proposed history has the rate at time t from 180 Ma to present. If necessary, the rate is held constant between the oldest age provided in the model and 180 Ma. The area underlain by oceanic lithosphere is assumed to remain fixed and to equal that of the assigned portion of the age grid. This area is equal to the cumulative area at t_{max}, which from equation 2 is $A(t_{max}) = \frac{1}{2}R_0 t_{max} = 271.5 \times 10^6$ km², which is the area covered in the Müller et al. (1997) grid. This value corresponds with $R_0 = 3.02$ km²/yr and $t_{max} = 180$ m.y. For any given starting rate at 180 Ma, R_{180} (specified in km²/yr), the corresponding $t_{max(180)} = 2 \times 271.5$ km²/R_{180}, which in turn specifies a triangular area/age versus age distribution derived from equation 1. For each subsequent time t, new lithosphere is created at a rate R_t and removed at a rate $R_t/t_{max(t)}$ from each million-year age bin, where $t_{max(t)}$ for all subsequent times is defined as the X (age) intercept of the iteratively computed area/age versus age distribution. Plots of the expected area/age versus age distribution can be made at any arbitrary time including the present (Fig. 5), as can both cu-

mulative preserved-area and subducted-area curves that can be compared with observations, as well as $t_{max(t)}$ as a function of age (Fig. 6) for any model of R_t.

Kominz (1984) undertook perhaps the first comprehensive examination of the lithosphere-production history following Pitman's (1978) initial analysis. Kominz (1984) compiled mean spreading rates and ridge lengths over the past 140 m.y. to derive her estimate of the lithosphere-production history shown in Figure 5A. The corresponding area/age versus age distribution predicted by her proposed lithosphere-production history is also shown. Her lithosphere-production history predicts (1) less area than observed between 55 and 3 Ma (Fig. 5A), (2) a factor-of-two more lithosphere than observed between 109 and 80 Ma (Fig. 5A), and (3) a current $t_{max} = 130$ Ma (Fig. 6) as opposed to 180 Ma.

Engebretson et al. (1992) used a combination of relative plate motions and reconstructions of subduction zones in a presumed fixed-hotspot frame of reference to assess the time history of subduction. The underlying rationale was that subduction boundaries are better-conserved features than mid-ocean ridges and hence the area of consumption per unit time is better recorded than ridge production. The lithosphere-production history reconstructed by Engebretson et al. (1992) is shown in Figure 5B. Their production history predicts (1) only about two-thirds the area observed between 37 Ma and the present (Fig. 5B), (2) the area of lithosphere between 136 and 37 Ma to be overestimated by as much as 50% (Fig. 5B), and (3) current $t_{max} = 142$ Ma (Fig. 6) as opposed to 180 Ma.

Finally, Figure 5C provides the same comparison for the lithosphere-production history modeled by Gaffin (1987) on the basis of inverting the Vail et al. (1977) sea-level curve to a lithosphere-production history (see Pitman, 1978; Kominz, 1984). His production rate predicts (1) about the correct area compared with observation between 32 and 0 Ma (Fig. 5C), (2) more lithosphere (by as much as 50%) than observed between 103 and 32 Ma (Fig. 5C), and (3) a current $t_{max} = 130$ Ma (Fig. 6) as opposed to 180 Ma.

The discordance between these proposed lithosphere-production curves and both the model of constant production or the model derived from the direct inversion of the area/age versus age distribution is also apparent in the cumulative histories shown in Figure 3. This comparison simply emphasizes the misfit of these models with the observed area/age versus age distribution. As can be seen in Figure 3, the deviations of area as a function of age
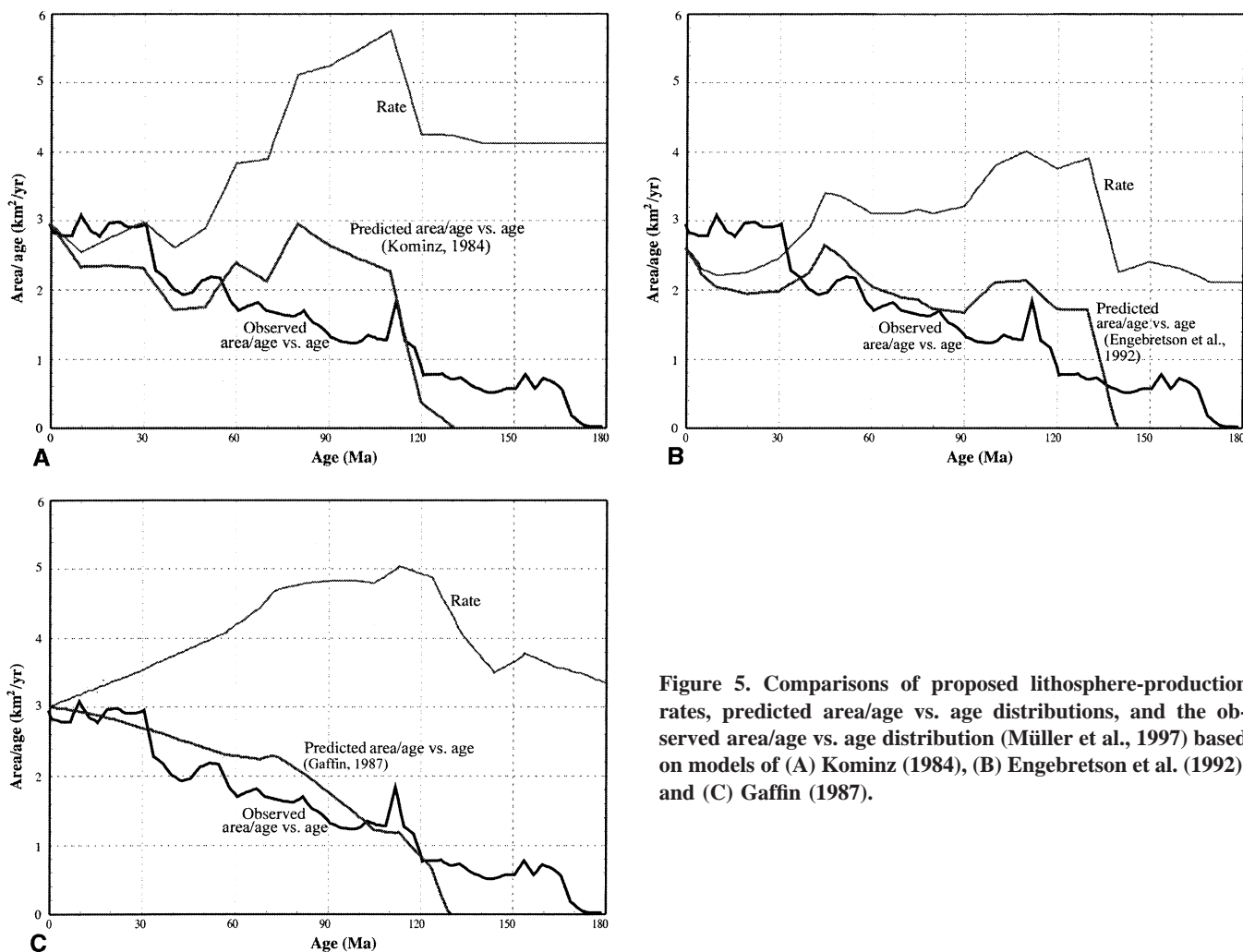
Figure 5. Comparisons of proposed lithosphere-production rates, predicted area/age vs. age distributions, and the observed area/age vs. age distribution (Müller et al., 1997) based on models of (A) Kominz (1984), (B) Engebretson et al. (1992), and (C) Gaffin (1987).

in each of these models exceed the estimated uncertainties in age of the Müller et al. (1997) grid.

It should be clear from the foregoing comparisons that both differences between the predicted and observed area/age versus age distribution and predicted t_{max} versus observed t_{max} imply that none of the existing models of lithosphere-production history is compatible with the directly observable constraints.

DISCUSSION AND CONCLUSIONS

Parsons (1982) elegantly summarized the potential of the area/age versus age distribution to address models of ridge-production history. He concluded that there was nothing in the then-current area/age versus age distribution that necessitated large changes in global production in the past 180 m.y. His analysis is confirmed here. The analysis is extended by two important additions: (1) that the cumulative area of subducted lithosphere based on

plate reconstructions grows as predicted by a model in which ridge production has remained fixed over this interval, and (2) that the predicted and observed cumulative areas at the specific calibration ages of the magnetic reversal time scales grow completely in accord with a constant rate of ridge production. The two rates 3.0 and 3.4 km²/yr derived herein are identical once consideration is given to the different data that they are fitting. The value of 3.0 km²/yr simply accounts for that proportion of the Earth covered in the age grid of Müller et al. (1997). The value of 3.4 km²/yr takes into account the unassigned areas of the oceans as well as the lithospheric shortening in the Himalaya-Tibet and Alpine system that together add a little more than 10% to the total. This higher value is the best estimate of the global rate of ridge production and in fact is not different from the 3.45 km²/yr originally derived by Parsons (1982).

A wide array of models of various aspects of marine geochemistry, atmospheric chemis-

try, and sea level are predicated in relation to lithosphere-production rate. In all these models, an assumed scaling exists between lithosphere-production rate and each property. For example, McCauley and DePaolo (1997) have shown that $p(CO_2)$ based on Berner (1994) (normalized to present) scales approximately as $R_t^{0.21}$. The isotopic composition of Sr in seawater is a balance between riverine input of radiogenic Sr and hydrothermal exchange of seawater with a less radiogenic, mantle-derived Sr (McCauley and DePaolo, 1997; Richter et al., 1992). The exchange of Sr isotopes between oceanic crust and ocean water is assumed to be linearly related to the lithosphere-production rate (McCauley and DePaolo, 1997; Richter et al., 1992). Finally, Pitman (1978), Kominz (1984), and Gaffin (1987) have modeled sea level as a function of lithosphere-production rate through its control of the area of lithosphere younger than 70 m.y.

The fundamental conclusion derived from the analysis of the relationship between the
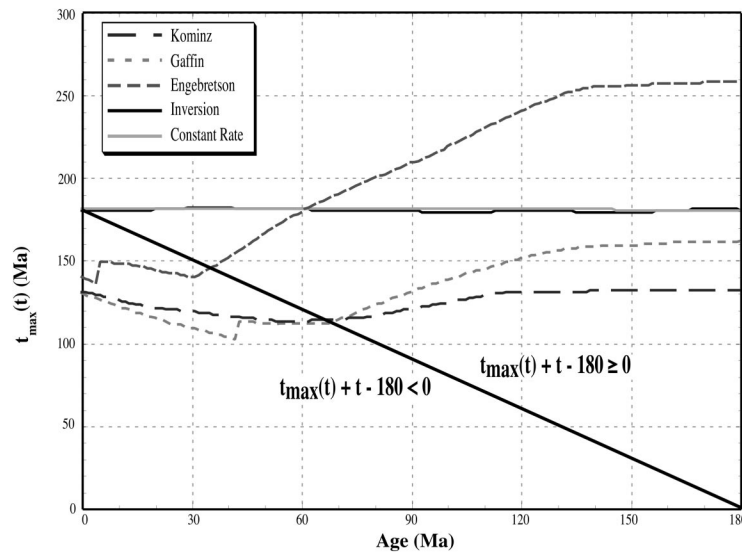
Figure 6. Predicted histories of t_{max} as a function of age required to satisfy each of the models of global ridge production investigated in this paper. Thick black diagonal line separates (1) the lower field in which $t_{max}(t)$ precludes existence today of ocean floor as old as 180 Ma that is observed today (and models incompatible with this constraint) from (2) the upper field containing models compatible with oceanic lithosphere of this age. Note that the horizontal black solid curve labeled "inversion" tests the assumption that t_{max} is fixed (as in equation 4) vs. forward model that accepts the rates derived from equation 4 as input and computes $t_{max}(t)$. The deviation of $t_{max}(t)$ shown by this horizontal black curve from the constant rate curve is ±1 Ma and, hence, this assumption is consistent with this model.

preserved area/age versus age distribution and rate of production is that the global rate of lithosphere production has not varied significantly since 180 Ma. If the rate of ridge production has not changed, then the mean age of the ocean lithosphere has not changed, and consequently, the mean depth of the oceans has not changed over the past 180 m.y. If the mean depth does not change, then the volume has not changed with the result that sea level could not have been affected in the way that Pitman (1978), Kominz (1984), or Gaffin (1987) have modeled it. If we accept this conclusion, then either these correlated properties have not varied significantly or other sources must be identified to drive long-term trends in them.

Delaney and Boyle (1986) argued that the amount of hydrothermal exchange between seafloor and oceans, and therefore presumably the rate of plate generation, had not varied by more than 30%–40% perhaps since 100 Ma on the basis of the limited temporal variability of Li/Ca ratios in foraminiferal shells. The analysis presented here is completely compatible with their assessment but would imply even more limited variability than they allowed for.

Finally, the conclusion that the mean rate of ridge production has not varied at least over the past 180 m.y. is an expected result. The global rate of ridge production is expected to correlate with the changes in the mean rate of heat production in the mantle. Given the long time scales needed to affect global heat production and the correlation of mantle viscosity to mantle temperature, the null expectation is that, on the short time scales (180 m.y.) that are within the data to address, there should have been little or no change. This is exactly what is found. The surprising result would have been for the data to necessitate that a significant change in global ridge-production rate had occurred—not the other way around.

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