Modeling seafloor-spreading rates through time: A comment

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Demicco (2004) re-analyzes the relationship of area of ocean floor as a function of age versus age recently reviewed by Rowley (2002) and concludes, “the linear decrease in area versus age of ocean floor does not force a steady state view of sea floor spreading”. Neither Rowley (2002) nor Parsons (1982) argue that this linear relationship **requires** a constancy of the global rate of ridge production, but point out that a range of observables are consistent with such a model, and compelling evidence pointing toward more complicated models have not yet been brought forth. Specifically, Rowley (2002) showed, among other observations, that (1) the Pacific plate that should preserve evidence of faster spreading along the Kula-Pacific, Farallon-Pacific, Izanagi-Pacific, and Pacific-Phoenix ridges retains effectively no evidence of increased production during the Cretaceous (Figure 1), and (2) the fit of a model of cumulative area based on a constant production rate when compared with the cumulative areas of the independently dated isochrons has a slope of 0.9986 and with an R^2 of 0.9994 (Figure 2-reproduced from Fig. 3-inset of Rowley, 2002). Any alternative model has to account for these, among other, directly observable features.

Figure 1 – Here

Figure 2 – Here

The key aspect of Demicco’s re-analysis is to question whether subduction per unit time effectively subducts all ages of oceanic lithosphere equally as is assumed in the model of Parsons (1982) adopted by Rowley (2002). Demicco (2004) mischaracterizes the model by implying that at each time step there is **actually** subduction of an equal area of oceanic lithosphere irrespective of age, which he represents by the dashed line on Figure 2 in (Demicco, 2004). The model is actually predicated on the assumption that subduction at each time removes oceanic lithosphere as a random function of age independent of the areal extant of lithosphere of each age and a random area of each age up to the total area of that age present at that time. If both of the parameters controlling subduction of oceanic lithosphere are random, then over time, and in a statistical sense, the amount of oceanic lithosphere subducted of any given age is linearly proportional to age. Rowley (2002) justified adopting this model by computing the current and +5Ma and +10 Ma rates of subduction of ocean lithosphere as a function of age. This calculation demonstrates that there is no systematic bias in the subduction of oceanic lithosphere as a function of age. It is important to emphasize that this is a statistical statement and one of the purposes of Figure 2 in Rowley (2002) was to demonstrate that even over 10 m.y. there is expected to be considerable variability in highest and lowest rates of subduction of different ages of oceanic lithosphere. Thus, based on this data the evidence supports the hypothesis that over time lithosphere of all ages is statistically equally subducted per unit time. Rowley (2002) derived expected effects of stochastic sampling of the ages of lithosphere based on precisely these relations (See Figure 1 in Rowley, 2002). Thus the model advocated by Rowley (2002) rather than being prescriptive actually accounts quite reasonably for various sources of variability.

Demicco (2004) presents modeling results in which he explores whether it is possible to evolve from the Gaffin (1987) model of ridge production, as an example, to the presently observed area/age as a function of age distribution using genetic algorithms.

In his analysis Demicco (2004) explicitly requires that subduction zones must subduct, by more than a factor of 2, precisely those ages produced by the highest global rates. Theoretically there is nothing that precludes this and hence Demicco (2004) is correct in pointing out that alternative models are possible. Demicco (2004) does not describe the actual equations by which his system evolves and therefore it is difficult to explicitly analyze it. In the model system described by Rowley (2002) with a fixed total area of oceanic lithosphere there must intrinsically be a relationship between the rate of production and the maximum age of lithosphere from equation 2 of Rowley (2002). If there is more young oceanic lithosphere reflecting higher rates of production there must be a corresponding decrease in old lithosphere resulting in a decrease in the maximum age of preserved lithosphere at any given time. The system cannot arbitrarily maintain a fixed maximum age of lithosphere at 180 m.y. as assumed Demicco (2004). Rowley (2002) exploited this to demonstrate that, for example, in the Gaffin (1987) model, the high rate of production in the Cretaceous results in a maximum predicted age of oceanic lithosphere preserved today that is about 50 m.y. younger than observed in the Atlantic and Indian Oceans where one might argue they might be preserved and the Pacific Ocean. Note that if regions are arbitrarily assumed to be conserved, and hence treated as unsubductible, the rate of destruction increases in direct proportion to the rate of conserved lithosphere production, thus further decreasing the probability of preserving old lithosphere in the Pacific. In Demicco's model in which high rates of production do not effect the maximum age of the lithosphere, because he assumes it remains constant, the area/age as a function of age distribution must become concave up with a very long (>50 m.y.) tail at older ages. This contrasts with the approximately triangular distribution observed today or convex up distribution as would be expected from a model in which subduction removes lithosphere randomly in age and area (see Rowley, 2002 Figure 5c). This concave up distribution reflects the significant over (relative to age independent) subduction of young oceanic lithosphere while leaving the older end of the age spectrum isolated from subduction. Were subduction to behave this way it would violate the assumptions used by Gaffin (1987) to produce his ridge production curve in the first place. If subduction preferentially removes young oceanic lithosphere then this would significantly reduce changes in the younger part of the age spectrum of the oceans and hence sea level as modeled by Gaffin (1987); however based on my own attempts to replicate Demicco's model parameters there is still some correlation between high rate and younger mean age of ocean lithosphere, and hence a predicted change in mean depth of the oceans as a function of time.

It is important to point out that Demicco (2004) does not perform any analysis based on the observable system to provide a compelling case in support of why subduction should preferentially subduct particular age tracts over others. In fact, it is worth noting that Figure 2 in Demicco (2004) shows rates of subduction at 20 Ma of given ages if oceanic lithosphere, for example around about 130 to 140 m.y. that are a factor of 2 greater than any rate of subduction observed today, even though Gaffin's rate is only slightly more than 10% higher at 20 Ma than today. Note also that adjacent age bins in his model have zero or near zero rates of subduction. This ignores the fact that, to first order, the distribution of ages along trenches are smooth and continuous and hence it is not likely that subduction zones would subduct discrete, and discontinuous age tracts, rather than the pattern reflected in Figure 2 of Rowley (2002), based on modern rates.

Demicco (2004) uses genetic algorithms to find the optimal solution that evolves the Gaffin (1987) production curve and into the present area/age as a function of age distribution (see Figure 1A of Demicco, 2004). After 1000 iterations Demicco's model does not, in fact, converge on a result that satisfies this simple constraint. However, it is inherently possible to write the prescription such that each iteration yields precisely a solution to the problem as described by Demicco (2004). The important question then is how variable is each model iteration in terms of the path taken. Monte Carlo simulations demonstrate that (1) the mean age of lithosphere as a function of age varies only trivially ($2\sigma << 1.0$ Ma), and (2) there can be virtually no subduction of older lithosphere following the period of rapid production prior to 60 Ma as subduction seeks to maintain a relation between production and t_{max}, but can not due to the model assumption that t_{max} remains fixed. Figure 3 is an example of a typical iteration reflecting Gaffin's production rate at 20 Ma and the distribution of the ages of subducted lithosphere. Similar patterns are repeated, although offset in age, for all intervals from 60 Ma to the Present and for all iterations of the model. This pattern is a robust feature of all solutions satisfying constraints as stipulated by Demicco (2004). Note that this does not resemble the present-day pattern shown in Figure 2 of Rowley (2002).

Figure 3- Here

Demicco (2004) argues that the simplest model that accords with all of the directly observable data should not be favored, ignoring Occum's Razor, in favor of an alternative model for which there are no directly observable data to support it. This alternative model is required to function such that, by chance, the outcome results in a cumulative area/age as a function of age distribution that accords almost perfectly with the simple model of constant global rate of oceanic lithosphere production (Figure 2). Although Demicco (2004) is correct to state that a constant global production rate model does not uniquely satisfy the observed area/age as a function of age data, he does not provide a compelling case based on directly observable properties of the systems as to why more complex models should be favored. Demicco (2004, p. 485) lists observations that indicate that modern rates of ridge production vary spatially. The examples given are simply a manifestation of plate behavior on a sphere reflecting variable plate-scale force balances within a global system limited by the very slowly evolving mean viscosity of the mantle and hence limited over short time scales (100's m.y.) by mantle flow consistent with this mean viscosity.

Demicco (2004) cites as compelling evidence supporting a view of time varying global production of oceanic lithosphere indirect, model-based correlations with various aspects of atmospheric and oceanic chemistry. Demicco (2004) states "there has been a growing consensus that global sea level, global climate, seawater chemistry (Lowenstein et al., 2001); (Horita et al., 2002), atmospheric carbon dioxide (Berner and Kothavala, 2001), nonskeletal carbonate mineralogy (Sandberg, 1983), evaporite mineralogy (Hardie, 1996), and perhaps evolution of shellbuilding organisms (Stanley and Hardie, 1998) have all varied through time more or less in lockstep. The ultimate driver of these global cycles is thought to be secular variation in the rates of ocean-floor spreading and concomitant increases and decreases in global volcanicity" returning to Fischer's (1982) paper in which this view is espoused. However, this list ignores the underlying source of these correlations, that being the paper by Gaffin (1987) that provides the long-term ridge production curve used in all of the above modeling studies to drive atmospheric and ocean chemistry and their correlates. The important point here is that Gaffin's curve is not based on an observable record of ridge production. Instead it is based on the "hypothesis that long term (10^8 yr) eustatic sealevel change is due primarily to changing ridge volume" (p.596) following the model of Pitman (1978) and Kominz (1984). Gaffin (1987) uses the Vail et al. (1977) Phanerozoic sea level curve, which is not actually sea level but a continental flooding curve, to derive his estimate of seafloor production rate. In his analysis Gaffin (1987) demonstrates a close correlation, although not a one to one mapping, of sea level and his estimate of ridge production (see Gaffin, 1987, Figure 5, p. 608) and Figure 4. Thus the consensus regarding the links between seafloor production and sea level, and derivative correlations to atmospheric and ocean chemistry that forms the fundamental basis for Demicco (2004) discomfort with the analysis of Rowley (2002) conflates data and models. Sea level from Vail et al. (1977) drives Gaffin (1987) seafloor production (hence these are correlated) that then is used to drive models of atmospheric (Berner, 1994) and ocean chemistry (Hardie, 1996) against which various data are compared, hence these too inherently correlate among themselves and with both ridge production and sea level as mapped by Vail et al. (1977). What underlies these correlations is not an observed record of seafloor production rate but a hypothesis that relates Vail et al. (1977) sea level curve to ridge production. It is worth pointing out here that in his more recent work (Berner and Kothavala, 2001) no longer depends upon time variation in global ridge production to drive time variations in the global carbon cycle.

Figure 4- Here

This is not the place to raise issues with the Pitman (1978) hypothesis linking sea level and global ridge production, but the fact remains that any property that correlates well with Gaffin (1987) ridge production model will correlate well with Vail's sea level curve. Thus these correlations do not provide compelling arguments that should require the discarding of the simplest model related to ridge production in favor of a more complex model for which there is no actual observational support.

In summary, Demicco (2004) correctly points out that the triangular area/age as a function of age distribution does not require a constant rate of global ridge production. This was never claimed by Rowley (2002) but a number of directly observable properties of the current system are completely compatible with this simple model. In fact, there are no directly observable data that imply a more complex model as advocated by Demicco (2004). Further, the Gaffin (1987) model used by Demicco (2004) is not based on an observable record, but instead is a model that correlates inferred sea level variation, also not directly observable, and ridge production. There is therefore no directly observable record that necessitates or compels an interpretation in which ridge production varies over time. Before we toss out the simplest and most consistent model for more complex ones there needs to be compelling evidence negating the viability of the simplest model.

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Figure Captions

Figure 1. Area/age as a function of age for the Pacific Plate (gray line) for each 1 m.y. age bin from version 1.6 of the Müller et al. age grid data set (Müller and Royer, 2001). Note the extreme peak in area/age at 110 is within the Early Cretaceous Quiet Zone is an artifact of an incorrect interpolation of changing poles of rotation in this time interval in the Mueller et al. model. Rate curve (solid black line) derived from total area divided by interval length, where the intervals are defined by the independently dated magnetic reversals used in the Berggren et al. (1995) and Gradstein et al. (1995) time scales. Black squares indicate ages at which the average interval rate is calculated. Two vertical black lines indicate total measured effective length of Pacific isochrons from the Mueller et al. (1997) isochron data set. Effective length is the projected length measured relative to the interval pole of rotation. Since area per unit time divided by length is velocity the absence of a significant change in ridge length demonstrates that there is no evidence of a change in the mean spreading rate between the Early and Late Cretaceous.

Figure 2. Cumulative area of oceanic lithosphere at each of the independently dated isochrons used in the Berggren et al. (1995) and Gradstein et al. (1995) magnetic reversal time scales versus the cumulative area predicted by equation 2 of Rowley (2002) for the same ages and a constant rate of global ridge production.

Figure 3. Histogram of model rates of subduction of lithosphere as a function of age for a single iteration of a model replicating the constraints described by Demicco (2004). The model embeds the constraints that at time t, t_{max} = 180 m.y. and hence there must be preserved areas of oceanic lithosphere of all ages less than tmax, and, in t years the area/age as a function of age distribution must match present area/age as a function of age distribution. The absence of subduction from about 105 to 150 m.y. reflects the fact that areas of lithosphere in those age bins already equal the areas that are presently observed in the corresponding (i.e. age progressed) age bins and hence no further subduction of lithosphere of those ages is allowed. The modest subduction of older ages (>155 m.y.) in this model reflect model assumptions that insures that t_{max} is maintained at 180 m.y. and can therefore be arbitrarily increased or decreased by adopting different assumptions.

Figure 4. Correlation of sea level height and global ridge production from Gaffin (1987) at each 10 m.y. increment from 0 to 500 Ma with correlation coefficient of these parameters.

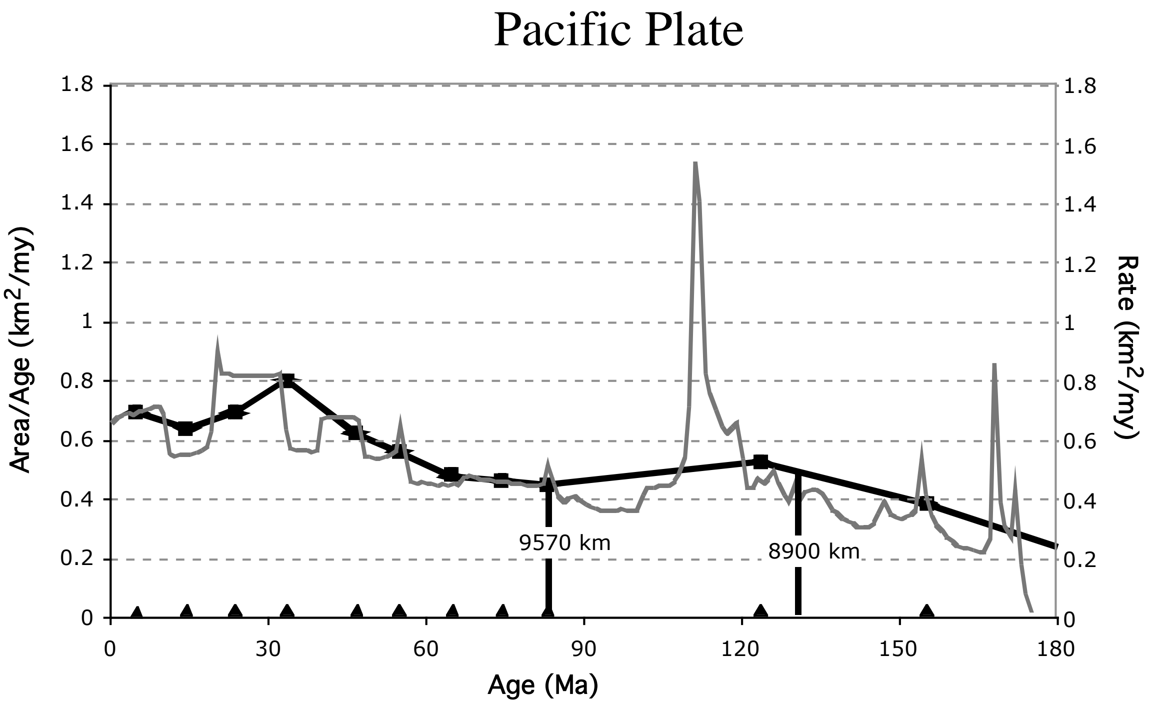

Figure 1

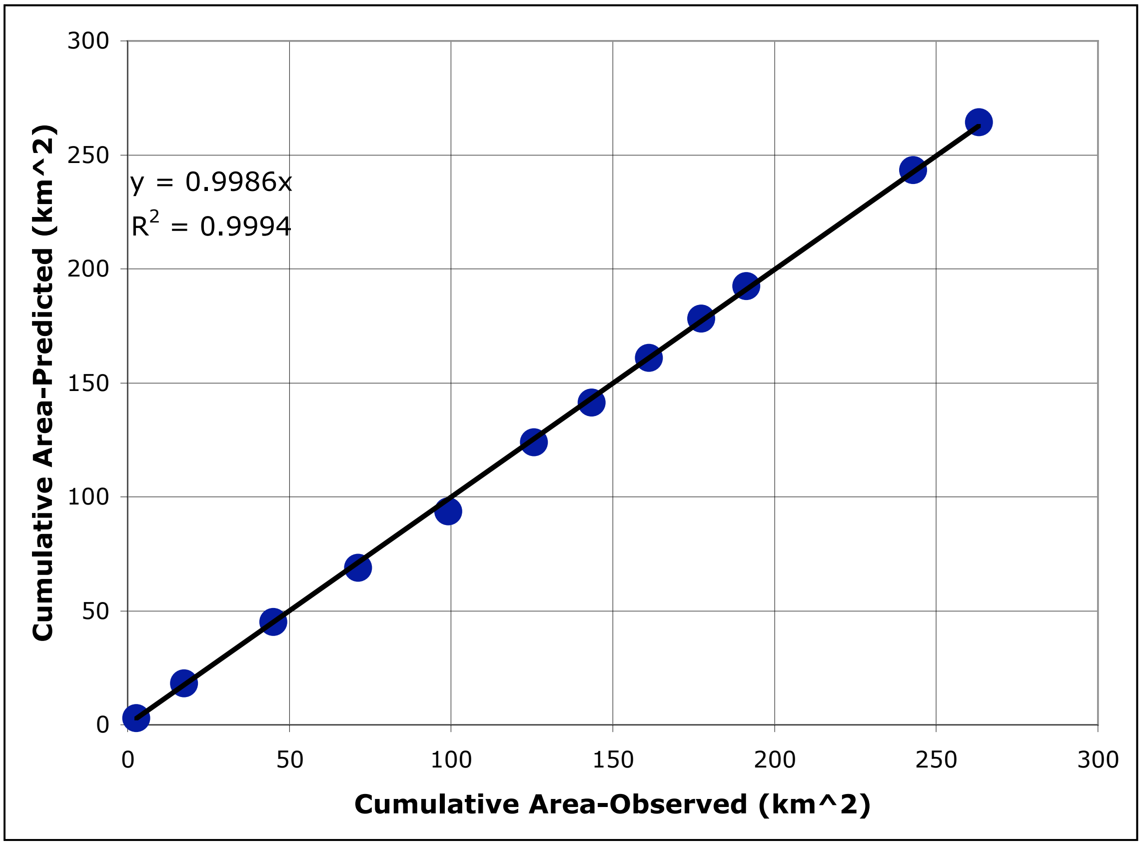

Figure 2

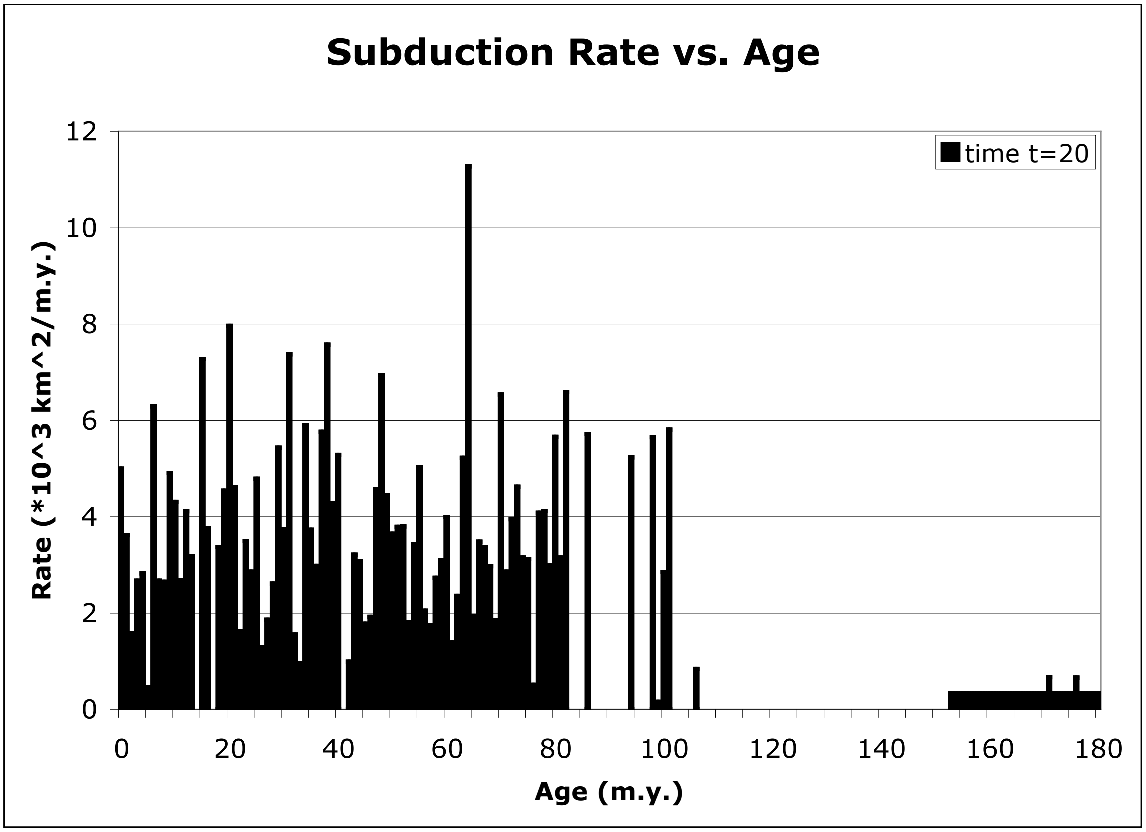
Subduction Rate vs. Age
12
10
8
6
4
2
0
Rate (*10^3 km^2/m.y.)
■ time t=20
0
20
40
60
80
100
120
140
160
180
Age (m.y.)

Figure 3

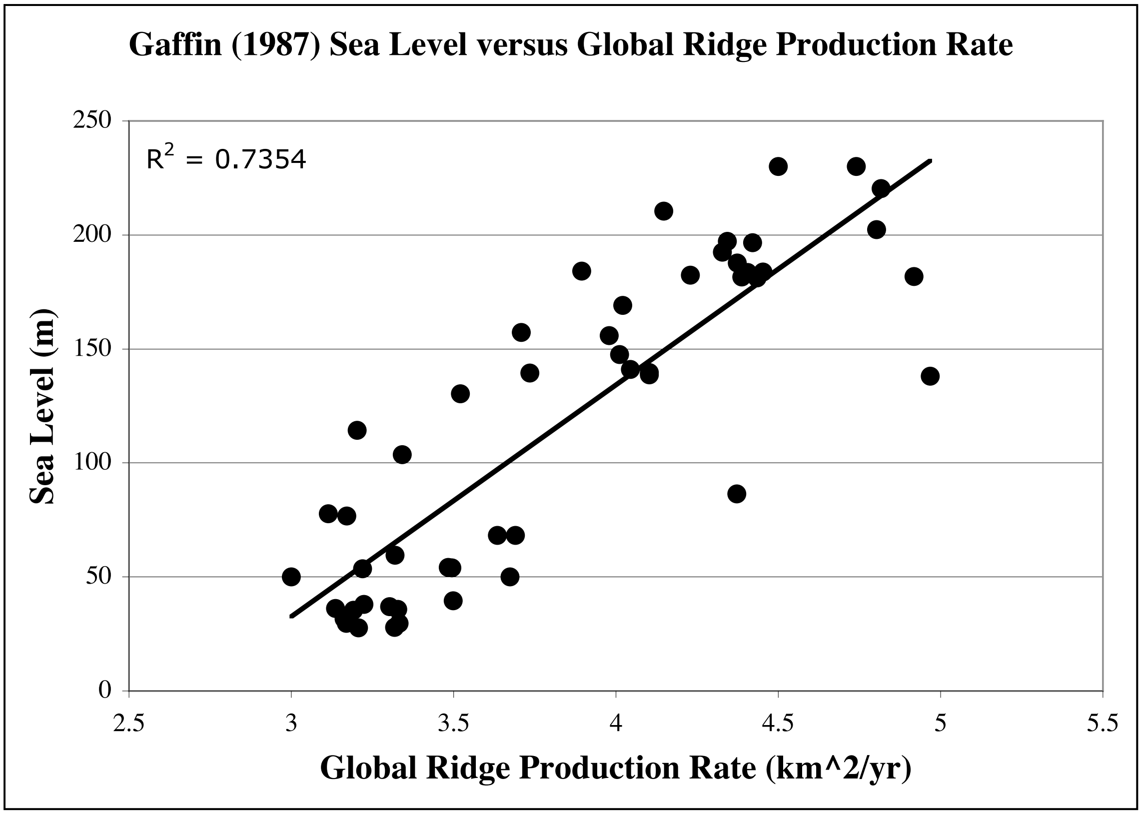
Gaffin (1987) Sea Level versus Global Ridge Production Rate
R² = 0.7354
250
200
150
100
50
0
Sea Level (m)
2.5
3
3.5
4
4.5
5
5.5
Global Ridge Production Rate (km^2/yr)

Figure 4