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ARCHAEAN PLATE TECTONICS REVISITED
2. PALEO-SEA LEVEL CHANGES, CONTINENTAL AREA, OCEANIC HEAT LOSS AND THE AREA-AGE DISTRIBUTION OF THE OCEAN BASINS

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Abstract. In a previous paper, we derived plate tectonic models for continental accretion from the early Archaean (3800 m.y. B.P.) until the present. The models are dependent upon the number of continental masses, the seafloor creation rate and the continental surface area. The models can be tested by examining their predictions for three key geological indicators: sea level changes, stable isotopic evolution (e.g., continental surface area), and oceanic heat loss. Models of paleo-sea level changes produced by the accretion of the continents reproduce the following features of earth history: (1) greater continental emergence (lower sea level) during the Archaean than the Proterozoic; (2) maximum continental emergence about 3000 m.y. B.P.; and (3) maximum continental submergence (high sea level) from 30 to 125 m.y. B.P. The high sea level stand between 380-525 m.y. B.P. is only weakly reproduced, probably due to the simplified nature of the model. Changes in the number of continental masses can result in tectonic erosion or accretion of the continents, with resulting changes in sea level. The two major transgressions in the Phanerozoic, although still requiring some increase in the total terrestrial heat loss, can be sucessfully explained by a combination of increases in continental surface area and in seafloor creation rate. Changes in the total heat loss of the ocean basins predicted by our plate tectonic models closely parallel the changes in terrestrial heat production predicted by Wasserburg et al. (1964). This result is consistent with thermal history models which assume whole mantle convection. The history of changes in continental surface area predicted by our best continental accretion models lies within the ranges of estimated continental surface area derived from independent geochemical models of isotope evolution.

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INTRODUCTION

In a previous publication, we presented a quantitative plate tectonic model for continental accretion from 3800 m.y. B.P. until the present [Abbott and Hoffman, 1984]. In this paper, we develop geological tests of the model using our present knowledge of changes in paleo-sea level, total terrestrial heat production, and isotope fractionation during the portion of earth history preserved in the rock record. In our plate tectonic models of continental accretion, the decreasing heat loss from the earth with increasing age results in decreasing seafloor creation rates with time. Decreasing seafloor creation rates in turn increase the average depth of the ocean floor [Parsons, 1982]. The average water depth of mid-ocean ridges (and by implication sea level) is dependent upon both the area-age distribution of the ocean floor and the total continental surface area [Wise, 1974]. Therefore, any model of continental accretion which includes seafloor creation rates can be inverted for implied paleo-sea level and seafloor heat loss. Because fractionation of Rb, Sr, Nd, Sm, U, and Th among geochemical reservoirs occurs through the same processes which create continents, isotopic estimates of continental surface area are a test of our models.

The mechanisms proposed to account for pre-Pleistocene sea level changes include fluctuations in the volume of the earth [Egyed, 1956], the total volume of seawater [Armstrong, 1968], the seafloor creation rate [Hays and Pitman, 1973; Flemming and Roberts, 1973; Pitman, 1978], the continental erosion rate [Valentine and Moores, 1970; Harrison et al., 1981], terrestrial heat loss [Turcotte and Burke, 1978; Harrison, 1980], continental hypsometry [Hay and Southam, 1977; Bond, 1978], and the continental surface area [Wise, 1974]. Individually, all of these mechanisms (except an expanding earth) have influenced sea level change at some time during the past 3800 million years. However, changes in the total volume of seawater and Precambrian continental hypsometry are too poorly constrained to include in our present models. Therefore, the models are simplified, and seafloor creation rate, continental erosion rate, terrestrial heat loss, and continental surface area are the only variables included in our estimates of paleo-sea level.

Our knowledge of Proterozoic and Archaean sea level is limited. Hunter [1974a, b] found that the continents were more emergent (sea level was lower) during the Archaean than the Proterozoic and that peak continental emergence occurred between 3350 and 3000 million years ago. During the Phanerozoic, there have been two periods of maximum continental submergence (high sea level) roughly 30-125 m.y. ago and 380-525 m.y. ago [Hallam, 1977; Vail et al., 1977; Harrison et al., 1983]. In order for a quantitative model to be valid, it should reproduce these periods of sea level change.

The thermal history of the earth is a controversial subject. All of the thermal history models produced by fluid dynamicists predict a time lag between heat production and heat loss and a consequent ratio of external heat loss to internal heat production between 1.2 and 3 [Hanks and Anderson, 1969; McKenzie and Weiss, 1975; Sharpe and Peltier, 1979; Schubert et al., 1980; McKenzie and Richter, 1981]. The major points of contention have been the presence or absence of whole mantle convection, the radioactive element content of the mantle, and the oceanic contribution to total terrestrial heat loss.

If the thermal history model assumes whole mantle convection, the ratio of external heat loss to internal heat production is constant from 3700 m.y. ago until the present [Schubert et al., 1980] (Figure 1). Two lines of observational evidence strongly support the assumption of whole mantle thermal convection: (1) the viscosity contrast between the upper and lower mantle is less than an order of magnitude [Sharpe and Peltier, 1979; Yuen et al., 1982], rather than the 2 to 4 orders of magnitude increase in lower mantle viscosity required for separate upper and lower mantle convection cells [Davies, 1977; Kenyon and Turcotte, 1983]; and (2) acoustic tomography has shown that subducting slabs penetrate into the lower mantle to depths of 900-1000 km [Creager and Jordan, 1984]. Because of the strong indications that whole mantle convection occurs, our test of continental accretion models assumes that internal heat production and external heat loss have maintained a constant ratio over the time period from 3800 m.y. B.P. until the present.

The model of internal heat production which we use is that of Wasserburg et al. [1964], which is generally accepted as giving the best prediction of the radioactive element content of the mantle [Hanks and Anderson, 1969; O'Nions et al., 1979; McKenzie et al., 1980; Schubert et al., 1980]. This test compares the heat lost from the earth's interior via the ocean basins as predicted by any single accretion model to the estimate of internal heat production due to the decay of radiogenic K, U, and Th [Wasserburg et al., 1964]. These predictions are normalized to

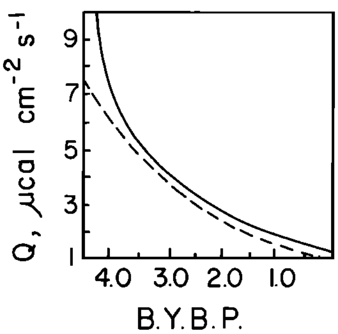

Fig. 1. Illustration of the predicted internal heat production (dashed line) and external heat loss (solid line) from a whole mantle convection model of Schubert et al. [1980]. Note that the two lines are parallel from 3700-3800 m.y. ago until the present.

present-day values. Over the earth's history, between 73% (present day) [Sclater et al., 1981] and 100% of total terrestrial heat loss (no continents) has occurred via the ocean basins. Therefore, the best prediction of normalized oceanic heat loss derived from any one accretion model will lie slightly above or directly on the line defining the normalized heat production model of Wasserburg et al. [1964] (Figure 1).

The last test of continental accretion models compares our estimates of changing continental surface area to estimates of continental surface area derived from geochemical models of isotopic evolution. This is presently the most dubious test of any continental accretion model, because predictions of past continental surface area based upon stable isotopic data have a broad range and are highly "model dependent" [Jahn and Nyquist, 1976; Windley, 1977a; Veizer, 1978; Armstrong, 1981; McLennan and Taylor, 1982; Veizer and Compston, 1982; Allegre and Rousseau, 1984]. Nevertheless, geochemical models do provide probable ranges of past continental surface area [Windley, 1977a]. They predict much slower continental formation at the present day than in the Archaean (3800-2500 m.y. ago) [McLennan and Taylor, 1982; Allegre and Rousseau, 1984]. As geochemical estimates of past continental surface area become increasingly refined with more isotopic data and more realistic models, the geochemical tests of future continental accretion models will produce more definitive results.

In this paper, we examine the implications for paleo-sea level, ocean basin heat loss, and continental surface area of two sets of continental accretion models: three models where the number of continents is changed consonant with paleomagnetic and geologic data [Briden et al., 1981; Smith et al., 1981; Burchfiel, 1983] and three models where the number of continental masses is held constant. Our previous models of continental accretion were very simplified in assuming that the number of continental masses had remained constant since the Archaean. Because the total erosion rate is proportional both to the square root of the continental surface area [Holland, 1978] and to the number of continental masses [Abbott and Hoffman, 1984], changing the number of continental masses can produce slow tectonic accretion or erosion of the continents.

TECTONIC EROSION AND ACCRETION OF THE CONTINENTS

Changes in the relative size and number of continental masses have occurred rapidly in earth history compared to those in total continental

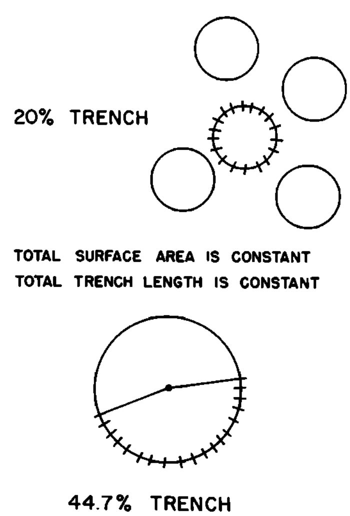

Fig. 2. Graphical illustration of the decrease in the size of the erosional area per unit length of trench when the number of round continental masses changes from one to five while the total continental surface area remains constant.

surface area and terrestrial heat loss (and, therefore, seafloor creation rate) [Schubert et al., 1980; McKenzie and Richter, 1981]. As a result, the most likely cause of short term (10-100 million year as opposed to 100-1000 million year) variations in continental surface area is a tectonic process controlled by the relative size and number of continent masses. These changes are controlled by at least four mechanisms: (1) addition of island-arc/ophiolite complexes [Fyfe and McBirney, 1975; Burke et al., 1976]; (2) addition of hot-spot chains [Duncan, 1982]; (3) reduction by continent-continent collision [Valentine and Moores, 1970; Harrison et al., 1983]; and (4) tectonic accretion or erosion of sediments at trenches [Hussong and Wipperman, 1980; Ziegler et al., 1981; Coulbourn et al., 1981]. The first three processes are controlled by changes in the rate of seafloor creation and in the ratio of continental to oceanic surface area. The fourth process, tectonic erosion or accretion of sediments at trenches, depends primarily on the volume of sediment delivered to the trench [Ziegler et al., 1981].

As shown in Figure 2, the simple process of rifting a supercontinent into five equal-sized fragments with a continental divide in the center of each fragment decreases the total surface area supplying sediment to a trench. Erosion rate is proportional to the square root of the surface area [Holland, 1978] (Figure 3). If there is an increase in the number of continental masses from one to seven (Figure 3), then the net decrease in terrestrial sediment supply to the trench is about 40%. Along the west coast of South America, regions with an equatorial climate have high rainfall rates and high erosion rates. They have experienced Cenozoic tectonic accretion at the trench. Regions with a desert climate and low erosion rates have experienced Cenozoic tectonic erosion at the trench [Ziegler et al., 1981].

In our model of continental accretion, decreases in the total number of continental masses cause eventual increases in the surface area of the continents. As we have shown, supercontinent formation decreases the net erosion rate while increasing the likelihood of tectonic accretion to the continent at trenches. In the following

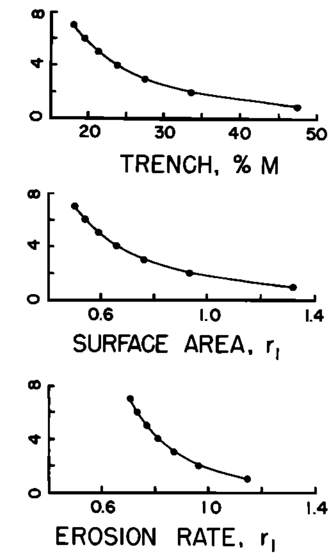

Fig. 3. (Top) Percentage of continental margin which is trench, %M, versus the number of round continental masses, N. Total continental surface area and trench length are constant. (middle) Surface area eroded per unit length of trench in units of radius, r_1, versus the number of continental masses, N. (bottom) Bulk erosion rate per unit length of trench in units of radius, r_1 versus the number of continental masses, N. Erosion rate is assumed to be proportional to the square root of total surface area [Holland, 1978].

models, we do not attempt to quantify the increase in surface area caused by tectonic accretion at an individual trench. Instead, we use a simple balance between erosion of the continents and magmatic addition to the continents.

MODEL FOR CONTINENTAL ACCRETION

In our previous work, we developed a model for igneous activity at continental margins as a function of the age distribution of oceanic lithosphere in subduction zones. We assumed that the maximum age of oceanic lithosphere at subduction, t_m, has increased linearly with time, from 38.5 m.y at 3800 m.y. to 50 m.y. at 3500 m.y. to 180 m.y. at the present [Abbott and Hoffman, 1984]. Petrologic evidence indicates that andesites cannot be generated at convergent margins if the descending plate subducts buoyantly. The transition from bouyant to nonbouyant subduction occurs when the subducting oceanic lithosphere is between 40 and 70 m.y. old, depending upon crustal thickness. The average transition age is approximately 50 m.y. old [Sacks, 1983]. Andesites first appeared in the geologic record roughly 3500 m.y. ago [Windley, 1977b; Condie, 1982]. Thus, we assumed that t_m was equal to 50 m.y. at 3500 m.y. ago.

As we will show, such a linear rate of change of the maximum age of the oceanic lithosphere at subduction, t_m, produces a roughly exponential decay in heat loss due to seafloor creation which is consistent with some thermal models of terrestrial heat production [Wasserburg et al., 1964; McKenzie and Weiss, 1975]. This does not imply that terrestrial heat loss equals terrestrial heat production in the mantle, but rather that the values of both heat production of the mantle and heat loss due to seafloor creation have decreased as the earth has aged [Schubert et al; 1980; McKenzie and Richter, 1981].

Oceanic lithosphere younger than 50 m.y. old subducts buoyantly and with less magmatic activity than older oceanic lithosphere [Sacks, 1983; Abbott and Hoffman, 1984]. The ratio of magmatic activity between old and young lithosphere, R_v, was estimated to lie between 6 and 10, based on petrologic criteria. The rate at which continent-building igneous activity, C_c, occurs is thus [Abbott and Hoffman, 1984]

$$C_c = \frac{[C_o]\ P_m}{G} \left[F + R_v\ (1-F) \right] \qquad (1)$$

where C_o is the seafloor creation rate (and hence subduction rate), G is a coefficient which is arbitrarily adjusted to cause the results to converge upon the present continental area, F is the fraction of ocean floor surface which is less than 50 m.y. old and P_m is the fraction of partial melt generated at zones of subduction of young (< 50 m.y. old) lithosphere.

In order to estimate the actual rate of continental accretion, the effects of erosion must be considered. For this model, the only important erosion is that which transports continental debris to the ocean. Therefore, the erosion rate of continents is assumed to be proportional to the square root of the surface area of each continent (for circular continents). The total material added to the ocean basins by erosion is then proportional to both the total area and the total number of continental masses. Assuming that, at the present time, erosion approximately balances the addition of new material [Holland, 1978], and that all of the continents are of equal size, past continental erosion rates, C_{ss}, are [Abbott and Hoffman, 1984]:

$$C_{ss} = E_r \left[\frac{A_c(T)\ \ N(T)}{A_c(T_o)\ N(T_o)} \right]^{1/2} \qquad (2)$$

where $A_c(T)$ is the area of continents at any time T in earth history, $A_c(T_o)$ is the present day area of the continents, N(T) is the number of continental masses in the past, $N(T_o)$ is the number of present continental masses, and E_r is the present day cumulative erosion rate. In order to avoid discontinuous steps in the rate of continental accretion, N(T) is linearly interpolated between times in earth history for which the number of separate continental masses is known.

At any time in earth history, T, the change in total surface area $\partial A_c(T)/\partial T$ of the continents is

$$\partial A_c(T)/\partial T = C_c(T) - C_{ss}(T) \qquad (3)$$

where C_c is the rate of continental magmatic activity, C_{ss} is the continental erosion rate, and ∂T is the time increment. For each model, equation (3) was solved iteratively to cause the continental area to converge upon the present continental area.

MATHEMATICS OF PALEO-SEA LEVEL

In order to apply our continental accretion model to the problem of paleo-sea level, we make several assumptions: (1) the total volume of water in the oceans has not changed appreciably since continental accretion began roughly 3800 m.y. ago; (2) the errors in estimates of paleo-sea level arising from ignoring continental hypsometry are a maximum of about 15% [Parsons, 1982]; (3) total ridge length and trench length are directly controlled by the seafloor creation rate; (4) Archaean oceanic crust was not thicker than at present [Abbott and Hoffman, 1984]; and (5) changes in sea level caused by Himalayan-type collisions can be ignored. The first assumption may be invalid for the Archaean, although there is good evidence that much of the present ocean volume had degassed from the mantle by 2500 m.y. ago [Armstrong, 1968]. Nevertheless, relative changes in sea level over 10-500 m.y. intervals are predicted quite accurately by the model. The last assumption, that Himalayan type collisions can be ignored is certainly justified for the Cretaceous sea level change, as the amplitude of this change is about 20% of the total sea level change [Harrison et al., 1983]. Furthermore, the driving force for continental collision may increase with increasing age of the plate, much as maximum convergence rates increase with increasing age of the plate [Carlson et al., 1983]. If this is true, then Himalayan-type collisions and the corresponding sea level changes may have been much less intense in the Archaean.

Using the triangular distribution of oceanic area versus age [Parsons, 1982] and holding C_o constant, the total volume of water in the oceans, V(t,T), is [Parsons, 1982]

$$V(t_m,T) = \int_0^{t_m} d(t)\,\frac{dA}{dt}\,dt$$

$$= C_o \int_0^{t_m} d(t)\left[1 - t/t_m\right] dt \quad (4)$$

where d(t) is a function describing the deviation of the water depth from a reference depth d_o as a function of the age of the oceanic lithosphere t. To correctly describe the change in depth of the midocean ridge with increasing lithospheric age requires two functions. The first function is valid for lithospheric ages, t, between 0 and 35 m.y. [Parsons, 1982]:

$$d_1(t) = d_o + at^{1/2} \quad (5)$$

where d_o = 2500 m and a = 350 m/m.y.$^{1/2}$ The second function is valid for lithospheric ages, t, between 35 m.y. and t_m [Parsons, 1982]:

$$d_2(t) = d_r - be^{-t/\tau} \quad (6)$$

where d_r = 6400 m, b = 3200 m, τ = 62.8 m.y. Note that the reference depths (d_r and d_o) are different for the two functions. Equation (7) describes the relationship between the total volume of water in the ocean, V, at any time in earth history, T, and the depth of the ocean floor:

$$V(t_m,T) = C_o \int_0^{t=35} d_1(t)\left[1 - t/t_m\right] dt$$

$$+ C_o \int_{t=35}^{t=t_m} d_2(t)\left[1 - t/t_m\right] dt \quad (7)$$

Because the total volume of the ocean is assumed to be constant, the results of this integration can be solved for the reference depth of the midocean ridge d_o:

$$V(t_m,T) =$$

$$C_o\left[d_o t + 2/3\ at^{3/2} - \frac{d_o t^2}{2t_m} - \frac{2at^{5/2}}{5t_m}\right]_{t=0}^{t=t_1} +$$

$$C_o\left[d_r t - \frac{d_r t^2}{2t_m} + b\tau e^{-t/\tau}\left[1-t/t_m - \tau/t_m\right]\right]_{t=t_1}^{t=t_m} \quad (8)$$

MODELS OF CONTINENTAL ACCRETION RATES

There are two sets of continental accretion models. The first set [Abbott and Hoffman, 1984] show rates of continental accretion for a constant number of continental masses and for R_v equal to 6, 8 and 10 (Figure 4). The second set shows estimated rates of continental accretion when the number of continental masses is allowed to vary over time (Figure 5). For both sets of models, values of R_v equal to 8 and 10

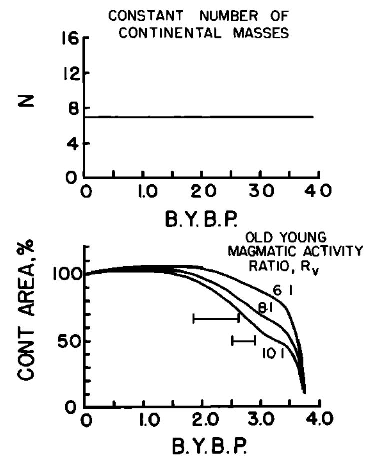

Fig. 4. (Top) Number of continents versus time in earth history used in the continental accretion model. (bottom) Continental surface area as a percentage of present continental surface area versus time in earth history. The three models are for R_v equal to 6, 8 and 10, where R_v equals the ratio of subduction zone magmatism resulting from the subduction of nonbuoyant old (> 50 m.y. in age) oceanic lithosphere and versus that resulting from the subduction of buoyant young oceanic lithosphere. The two error bars on the graph are estimates of the surface area of continents which had accreted by a given time range in earth history as derived from Rb-Sr data [Windley, 1977a].

allow us to reproduce the three phases of continental accretion believed to be observed in the Archaean. Isotopic evidence indicates that rapid continental accretion occurred between 3800-3500 and 3100-2600 m.y. [Hurley and Rand, 1969]. In the intervening period, 3500-3100 m.y., continental accretion was believed to have been slower [Moorbath, 1975a, b; Windley, 1977a; 1975; McCulloch and Wasserburg, 1978; McLennan and Taylor, 1982]. Continental areas estimated from isotopic data at various times in earth history are also plotted in Figures 4 and 5 [Jahn and Nyquist, 1976; Windley, 1977a; Veizer, 1978; McLennan and Taylor, 1982; 1983]. The models which incorporate a change in the total number of continental masses from ~15 at 3800 m.y. B.P. to ~7 at the Cambrian-Proterozoic boundary are clearly much more consistent with the isotopic data (Figure 5).

The results of our numerical models of continental accretion provide three important parameters for our paleo-sea level model: C_o, the rate of continental creation; A_e-A_c (the surface area covered by oceans); and t_m, the maximum age of the oceanic lithosphere at subduction. Once these parameters are established for any time in earth history, T, equation (8) can be solved for the reference depth of the mid-ocean ridge. The change in reference depth of the mid-ocean ridge with time in earth history is approximately two thirds of the actual change in sea level because subtraction or addition of a layer of water causes the lithosphere to rise or sink isostatically. Therefore, the true change in mid-ocean ridge depth (sea level) is [Parsons, 1982]

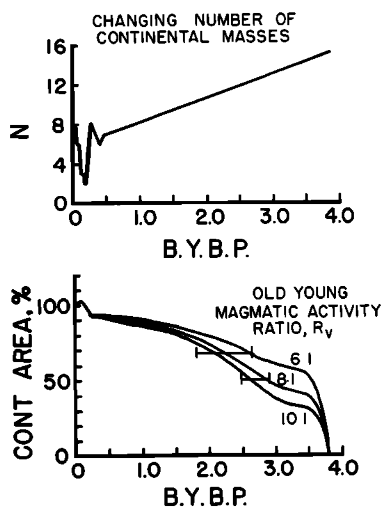

Fig. 5. (Top) Number of continents versus time in earth history as used in the continental accretion model shown below. Data sources for the number of continental masses are [Briden et al., 1981] for 0-180 m.y. B.P. [Smith et al., 1981] for 180-600 m.y. B.P., and [Burchfiel, 1983] for 3200-3800 m.y. B.P. We have linearly extrapolated from >15 continental masses at 3800 m.y. B.P. to 7 continental masses at 600 m.y. B.P. The actual history between 600-3800 m.y. B.P. is undoubtedly far more complex. (bottom) Continental surface area as a percentage of present continental surface area versus time in earth history. The three models are for R_v values of 6, 8 and 10. The two error bars are the same as in Figure 4.

$$\Delta d = \left[\frac{\rho_m - \rho_w}{\rho_m}\right] \Delta d_o \tag{9}$$

where ρ_m = 3.33 g/cm^3 and ρ_w = 1.0 g/cm^3.

MODELS OF PALEO-SEA LEVEL (MID-OCEAN RIDGE DEPTHS)

Using equation (8), the six accretion models were used to generate six paleo-sea level models, three for a constant number of continental masses (Figure 6) and three for a variable number of continental masses (Figure 7). Both groups of paleo-sea level predictions are consistent with the observation that the continents were more emergent in the Archaean than in the Proterozoic [Hunter, 1974a, b]. The paleo-sea level predictions for a changing number of continental masses (Figure 7) are remarkably consistent with Hunters' [1974a, b] estimate of peak continental emergence (lowest sea level) between 3000-3250 m.y. ago. This is different from our predicted period of maximum continental emergence (low sea level) which extends from 2750 to 3250 m.y. Considering the preliminary nature of the model and the limited data base, this does not appear to be a significant difference.

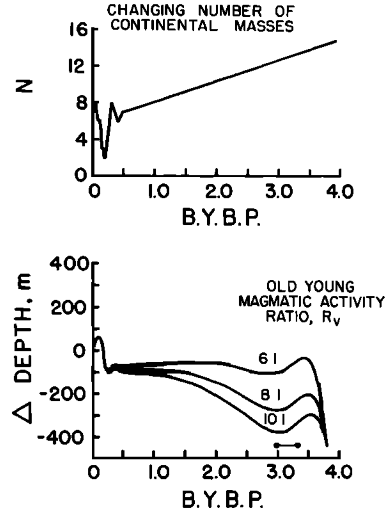

Fig. 7. (Top) Number of continents versus time in earth history as used in the sea level model shown below. (bottom) Change in sea level or mid-ocean ridge depth versus time in earth history for a changing number of continental masses. Dots connected by a line on the bottom of the graph are described in Figure 6.

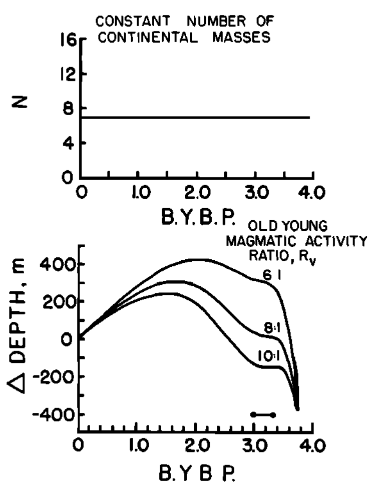

Fig. 6. (Top) Number of continents versus time in earth history as used in the sea level model shown below. (bottom) Change in sea level or mid-ocean ridge depth versus time in earth history calculated from the continental accretion models. Dots connected by a line on the bottom of the graph are estimates from Hunter [1974a, b] of the time of maximum continental emergence (lowest sea level) during Precambrian time.

DISCUSSION

To better test the validity of our model, the paleo-sea level predictions for the Phanerozoic can be compared to those of other workers (Figure 8). In the period where paleomagnetic reconstructions of the number of continents are available at 20 m.y. intervals (0-180 m.y. B.P.) [Briden et al., 1977; Harrison et al., 1981], the predictions of our model and the data of others agree quite well, because our amplitude of 75 m is within the error limits of present methods of estimating Cretaceous sea level [Kominz, 1984]. In the rest of the Phanerozoic, where continental reconstructions are only available at 60 m.y. intervals, the sign of the sea level signal agrees with other data but the amplitude is much too small.

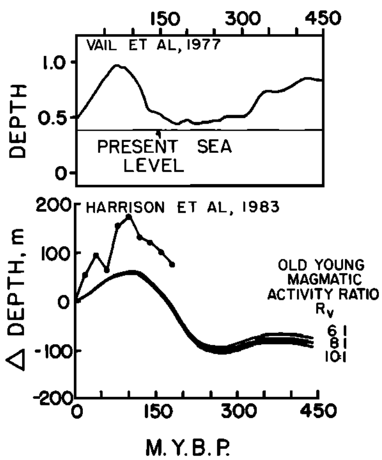

Fig. 8. (Top) Relative sea level changes from Vail [1977] versus time as estimated for the Phanerozoic (0-600 m.y. B.P.). The maximum amplitude of the sea level changes is estimated to be about 350 m [Kominz, 1984]. (bottom) Change in sea level or mid-ocean ridge depth versus time from continental accretion model shown in Figures 5 and 7. The dots connected by lines are estimated sea level changes from 0-180 m.y. ago from Harrison et al. [1983]. These sea level values use an improved continental hypsometric curve.

Nevertheless, it is encouraging that a relatively primitive model of the continental accretion history can reproduce so much of the known history of changes in sea level.

A further interesting result of our modeling is that changes in sea level on continents appear to lag behind reductions in the total number of continental masses (Figure 9). This is caused by the fact that there is an erosional "break-even" point in the number and size of continental masses which determines whether continental erosion or accretion will dominate. As long as the system continues to have a small enough number of large continental blocks, the continents will increase in surface area and sea level will rise. The different time lags between the point in time with the minimum number of continental masses and the maximum height of sea level are caused by the fact that different continental configurations take longer to reach the erosional "break-even" point. In the Phanerozoic, erosion predominates over accretion when the number of continents increases to 4 or 5. Therefore, the formation of a single supercontinent which requires 100 m.y. to break up into 4-5 continents will produce a longer, higher sealevel rise than the formation of 3-4 separate continental blocks which require 20-40 m.y. to break up into 4-5 continents.

Another test of these models is a direct comparison of the predicted continental accretion rates with those derived from geochemical data (Figure 10). In this case, we only include the continental accretion models in which the number of continents vary with time. The potassium/sodium ratios of Engel et al. [1974] and strontium isotopic ratios from Veizer and Compston [1974, 1976] show two aligned peaks at 400 m.y. and 1300 m.y. These peaks probably coincide with times of low amounts of continental erosion (e.g., supercontinent formation), and the 400 m.y. peak does indeed correspond to the period when there was a Permian supercontinent. With regard to strontium ratios, although average ratios over 50-200 m.y. intervals are a function of

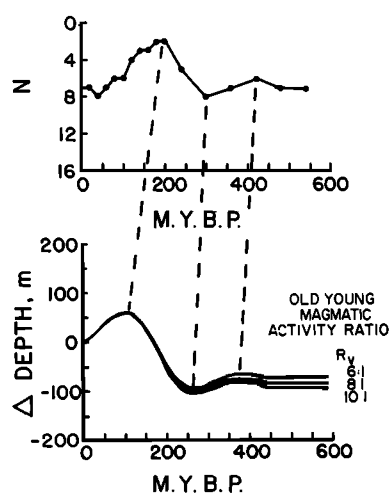

Fig. 9. (Top) Number of continents versus time in earth history used in sea level model shown below. (bottom) Change in sea level or mid-ocean ridge depth versus time in earth history calculated from our continental accretion model. The data for Phanerozoic time show a time lag between times of minimum numbers of continental masses (and consequent reduced continental erosion) and times of resulting high sea level.

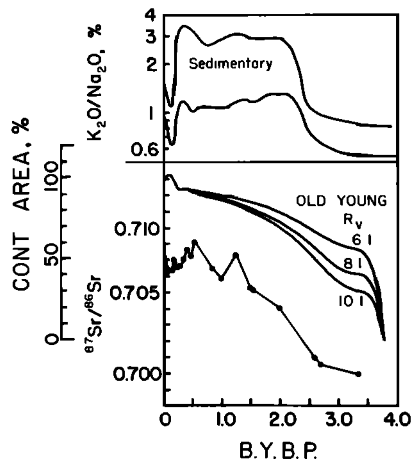

Fig. 10. (Top) Potassium/sodium ratios from Engel et al. [1974] versus time in earth history. (middle) Continental area as a percentage of present continental surface area versus time in earth history for the accretion model which incorporates a changing number of continental masses (Figure 5). (bottom) Strontium isotopic ratios versus time in earth history as compiled from Veizer and Compston [1974, 1976]. The strontium isotope data is averaged at 20 m.y. intervals from 0-180 m.y. and 60 m.y. intervals from 180-600 m.y., corresponding to the availability of data on the number of continental masses from paleomagnetic reconstructions [Harrison et al., 1983; Briden et al., 1981; Smith et al., 1981].

long-term continental surface area, there are shorter term peaks and troughs which probably correspond to short-term changes in the amount of continental erosion. These short-term changes in continental erosion may in turn result in sea level changes [Hart, 1973]. Therefore, strontium isotopic ratios and other geochemical data thought to reflect continental evolution must be reevaluated in terms of the time interval for which averages of several reliable measurements are available.

There is much controversy about the ratio of total surface heat loss to internal heat generation [Schubert et al., 1980; McKenzie and Richter, 1981]. If the whole mantle convected throughout earth history, estimated heat production and heat loss values for the past 3800 m.y. should show roughly the same pattern when both are normalized to the present. Therefore, the last test of the validity of the models presented here compares normalized heat loss due to seafloor creation to the normalized heat production models of Wasserburg et al. [1964] and McKenzie and Weiss [1975] for constant (Figure 11) and variable (Figure 12) numbers of continental masses. The continental accretion models which show the best fit to the heat production model of Wasserburg et al. [1964] are those with R_V values of 8 and 10 and a variable number of continental masses (Figure 12). These are the same accretion models which show the best fit to isotopic estimates of continental surface area and to geological estimates of paleo-sea level.

CONCLUSIONS

Our models of continental accretion, particularly those with an old:young ratio of magmatic activity, R_V, between 8:1 and 10:1 and a variable number of continental masses, are consistent with what is known about Archaean paleo-sea level, terrestrial heat loss, and continental surface area from isotopic and geologic data. In particular we can reproduce the following features of earth history: (1) High rates of continental accretion between 3800-3500 and 3100-2600

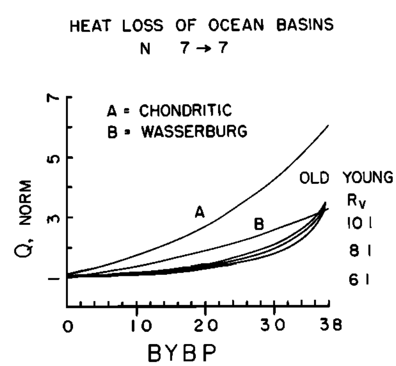

Fig. 11. (Top) Number of continents (N) versus time in earth history used to generate continental accretion models and consequent heat loss models shown below. (bottom) Normalized heat production models for the mantle from Wasserburg et al. [1964] and for a chondritic earth [McKenzie and Weiss, 1975]. Normalized heat loss due to sea floor creation for continental accretion models with R_V values of 6, 8 and 10.

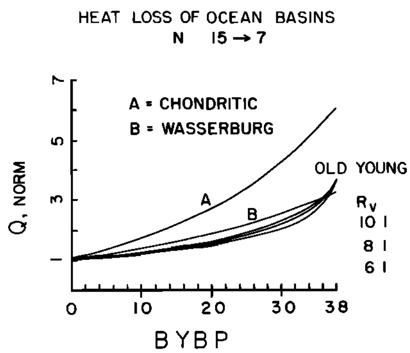

Fig. 12. (Top) Number of continents, N versus time in earth history used to generate continental accretion models and consequent heat loss models shown below. (bottom) Normalized heat production models for the mantle from Wasserburg et al. [1964] and from McKenzie and Weiss [1975]. Normalized heat loss due to seafloor creation for continental accretion models with R_v values of 6, 8 and 10.

m.y. ago, with a plateau in accretion between 3100-2600 m.y.; (2) greater continental emergence in the Archaean than in the Proterozoic, with maximum emergence occurring about 3000 m.y. ago; (3) higher sea level between 30-125 m.y. ago and (weakly) 380-525 m.y. ago than in the rest of the Phanerozoic; (4) a rate of terrestrial heat loss due to seafloor creation which parallels estimates of radiogenic heat production in the mantle [Wasserburg et al., 1964]; (5) estimates of continental surface area which fall within the range of estimates derived from independent geochemical models based upon fractionation of isotopes.

The implications of this modelling are as follows: (1) Most tectonic features of the Archaean, including variations in sea level (continental submergence) can be explained in a plate tectonic framework; (2) both the number and size of the continental masses in early earth history influenced the amount of continental detrital input to the oceans and continental isotopic recycling of strontium; therefore assuming a linear dependence between continental detrital input to the oceans and total continental surface area can lead to underestimates or overestimates of the paleocontinental surface area; (3) higher rates of terrestrial heat loss from seafloor creation, although still needed to explain the major Phanerozoic marine transgressions, need not be as great as suggested by previous workers [Turcotte and Burke, 1978; Harrison, 1980].

The two parameters which most strongly influence our models are the estimates of R_v, the ratio of the volume of magmatic activity between nonbouyant and buoyant subduction, and estimates of the number of continental masses, N, at various times in Earth history. What is required to improve the models is detailed computations of Phanerozoic magmatic volumes (for R_v) and comprehensive compilations of Proterozoic-Archaean paleomagnetic poles and age determinations (for N). Better definition of these parameters will allow us to revise our models accordingly.

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