UC Irvine

UC Irvine Previously Published Works

Title

Sea level variations, global sedimentation rates and the hypsographic curve

Permalink

<https://escholarship.org/uc/item/7kh877kw>

Journal

Earth and Planetary Science Letters, 54(1)

ISSN

0012-821X

Authors

Harrison, CGA
Brass, GW
Saltzman, E
et al.

Publication Date

1981

DOI

10.1016/0012-821X(81)90064-9

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

[6]

Sea level variations, global sedimentation rates and the hypsographic curve

C.G.A. Harrison, G.W. Brass, E. Saltzman, J. Sloan, II, J. Southam
and J.M. Whitman

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149 (U.S.A.)

Received October 20, 1980

Revised version received March 5, 1981

Sea level changes during the Neozoic have been estimated by two different methods. The first involves measuring the amount of present-day land area which was flooded during the past, and using the present-day hypsographic curve to estimate the amount of sea level rise necessary to produce this flooding. The second involves the estimation of the changing volume of mid-oceanic ridges through time, and estimating sea level changes after having allowed for isostatic adjustment. A difference in sea level of 170 m is obtained from the two methods for the Cretaceous (80–100 m.y. B.P.). This is equivalent to a difference in continental flooding of 24 Mm², using the present-day hypsographic curve.

We attempt to explain this difference firstly by allowing for the fact that the present-day ocean basins have more sediment in them than did the Cretaceous ocean basins. This produces a sea level change in the opposite direction to that produced by the reduction in mid-ocean ridge volume since the Cretaceous. Secondly, we suggest another large factor in producing the difference is that the present-day hypsographic curve is not the correct one to use when studying sea level stands in the Cretaceous. Present-day average continental heights are closely related to continental areas. Accepting this principle, if continents are joined together in the past, their average height must be greater, and so their hypsographic curve must be steeper. A given sea level rise would produce less continental flooding during times of continental aggregation than it would today.

1. Introduction

The shape of the hypsographic curve plays an important role in determining sea level changes inferred from the percentage of continental flooding. If the shape of the hypsographic curve is accurately known, then a measurement of the area of continental flooding at any time will allow us to calculate the change of sea level which has produced this flooding. This has formed the basis of several different estimates of sea level change [1,2] during the Phanerozoic. However, these estimates are usually based on the shape of the present-day hypsographic curve, as determined by Kossinna [3]. Kossinna estimated that the amount of land between 0 and 200 m was 37 Mm² (or 24.8% of the land area) and that the amount of land between 200 and 500 m was 39.9 Mm² (or 26.8% of the

land area). If these values remain fixed through time, then it would be quite appropriate to say that the 36.5 Mm² of land flooded during the Cretaceous [1] represented a sea level rise of almost 200 m, or that the sea level rise of 344 m calculated by Pitman [4] should result in a flooding of about 56 Mm². However, as we shall show, there are serious reasons to doubt the constancy of the hypsographic curve through time. The sea level and flooded area values both refer to the same time interval, and it can be seen that there is a discrepancy between them. We shall attempt to account for this discrepancy in part by changes in the hypsographic curve through time.

We first revise the measurement of sea level change using ridge crest volume by allowing for sedimentation in the world ocean. Then we derive a method for calculating a hypsographic curve for

various times in the past. Finally, we apply these calculations to data on continental flooding in order to compare sea level calculated from continental flooding with sea level calculated from ridge crest volume.

2. Ridge crest volume

It has been suggested [2,5–7] that changes in the volume of ridge crest material might be a contributing factor to global changes in sea level. Hays and Pitman [2] suggested that spreading rates between the time period of 110 and 85 m.y. B.P. were significantly greater than at earlier or later times. On the assumption that the ridge segment lengths remained constant, they were able to calculate a change in volume between 10 and 85 m.y. B.P. of 0.189 Mm^3 . In order to measure sea level stands relative to today it is necessary to add about 0.016 Mm^3 onto this figure, making the total change in volume from today about 0.205 Mm^3 . Using the present-day hypsographic curve, and allowing for the isostatic response of the ocean floor to the extra loading of the water, this volume change translates into a sea level change of about 376 m.

In a later and more detailed analysis, Pitman [4] attempted to estimate the lengths of the various ridge crest segments through time, and coupled this with the better known spreading rates in order to obtain an estimate of sea level change. His more accurate estimate of ridge volume change from 85 m.y. B.P. to the present is 0.187 Mm^3 , giving a sea level change of 344 m (in which he allowed for melting of ice locked up in present-day continental ice sheets).

3. Sedimentation

Our first correction is to allow for variable sedimentation rates in the world oceans. It has been noted by Davies et al. [8] and Whitman and Davies [9] that there have been wide fluctuations in the rate of sediment deposition in the deep ocean through time. In particular, there seems to exist a large increase in sedimentation rate begin-

ning in the middle Miocene, which is observed in all oceans, in both carbonate and non-carbonate fractions. Further data on deep-sea sedimentation rates presented by Southam and Hay [10] show that sedimentation rates for non-carbonate sediments have been higher since the beginning of the Pliocene than at any other time during the past 100 m.y. On the assumption that the average sedimentation rate between 5 and 100 m.y. is applicable to periods earlier than 100 m.y., the increase in sedimentation rate during the past 5 m.y. represents a net unloading of the continents and deposition onto the sea floor which will have the effect of raising sea level over that time interval. We have calculated the average deposition rate over the past 5 m.y. and compared it to the average deposition rate between 100 and 5 m.y. B.P. After allowing for variable density (the more recent sediments are less dense than the older sediments), and correcting to a density of 2.7 Mg m^{-3} we find that the increased sedimentation rate during the past 5 m.y. is equivalent to a sediment blanket of thickness 40 m. Isostatic adjustment of the ocean floor to this sediment load means that the actual rise in sea level against the continental freeboard is reduced by multiplication with the following factor:

$$\frac{\rho_m - \rho_s}{\rho_m}$$

where ρ_m is the mantle density and ρ_s is the sediment density. Taking the mantle density to be 3.3 Mg m^{-3} gives a sea level rise of $0.6 \times 40 / 3.3$ or 7.3 m.

A possibly more important effect of sedimentation is to be found in the history of carbonate sedimentation in the deep oceans. As has been pointed out, the formation of deep water carbonates may have been much slower prior to the Late Cretaceous. Planktonic foraminifera did not evolve to any great extent until the Late Cretaceous [11,12]. It is possible also that coccolithophoridae did not evolve significantly until this time either [12], but since coccoliths represent only about 20% of present-day, deep-sea, calcareous sediments, their presence or absence in the past is a second order effect, compared with the effect produced by the absence of foraminifera. The main point is that the present-day content of

CaCO_3 in the ocean sediments is likely to represent a new addition of sediment to the ocean compared with the situation 100 m.y. ago when there was probably very little carbonate sediment in the deep ocean environment.

The presence of deep-water carbonates today, compared with the absence of these sediments 100 m.y. ago would have the effect of raising sea level today compared with sea level 100 m.y. ago. By summing up the world average carbonate sedimentation rates given by Southam and Hay [10] for the past 100 m.y., and by correcting to a zero porosity density of 2.7 Mg m^{-3} (that of calcite), we arrive at an average thickness throughout the ocean basins of 300 m. This again has to be corrected for isostatic adjustment of the ocean basins. This figure will be an overestimate if coccolith ooze was volumetrically important prior to 100 m.y. ago.

The net result of the excess non-carbonate deposition during the past 5 m.y. and the carbonate deposition during the past 100 m.y. is that sea level would be higher today than 100 m.y. ago by 62 m, all other things being equal. Because the effects of ridge crest volume and sedimentation work in opposite directions, the net lowering in sea level seen on the continents from 100 m.y. ago to today should be $344 - 62$ or 282 m.

There is another possible effect of deep-sea sedimentation on sea level which we consider. During the time of rapid sea-floor spreading, the average age of the oceanic crust was probably considerably less than the average age today. For constant sedimentation rates, there will be proportionately more sediment in the world ocean basins today than during the time of rapid sea-floor spreading during the Cretaceous. In order to estimate the magnitude of this effect we need to know the average ages of the ocean basins today and during the Cretaceous. The best compilation of oceanic area as a function of age for the present-day situation is given by Sclater et al. [13], and the average age turns out to be 60.4 m.y. For the 85-m.y. case, we take the published values of area given by Pitman [4] which give an average age of 26.4 m.y. for the crust younger than 70 m.y., which comprises 79.78% of the oceanic area. The other 20.22% has to be apportioned out to ages greater than 70 m.y. We have done this by pos-

tulating a uniform decrease of surface area with time for crust older than 70 m.y., such that the oldest crust is 140 m.y. old. This rate of decrease is similar to the rate of decrease shown by the older oceanic crust today. The resulting average age for crust 85 m.y. ago is 40.0 m.y., giving a difference in the average ages of 20.4 m.y. The average carbonate-free sedimentation rate since 100 m.y. ago is 4.0 m.y. (omitting the very high sedimentation rates seen over the past few million years). Thus the total effect on sea level today of the extra sediment is about 15 m. Because this is caused by an extra volume of sediment in the world ocean today compared with the amount during the Cretaceous, it also works in the opposite direction to the change in ridge crest volume. The net lowering of sea level, corrected for these two sedimentary effects, is 267 m.

4. Orogeny

Another phenomenon which can cause substantial changes in sea level is orogeny, whereby continental areas become smaller. The most important orogenic event causing substantial reduction in continental area during the Mesozoic and Cenozoic has undoubtedly been the collision of India with Asia which has caused substantial thickening of continental crust. We assume that the amount of continental crustal reduction is due to the presence of a double thickness of continental crust under the Tibetan plateau [14]. The Tibetan plateau is marked in almost all places by the 4-km contour. The amount of present-day Asia above 4 km is 2.3 Mm^2 . If we assume that this area is replaced by oceanic area of average depth equal to the average depth of the present-day ocean below 0.2 km, which is 4.1 km, we find an increase in oceanic volume of $9.43 \times 10^6 \text{ km}^3$. This will decrease the depth of the oceans by 26 m. The change in continental freeboard, after allowing for isostatic adjustment, will be 18 m. This area of thickening is in fact somewhat greater than that calculated from the size of greater India postulated by Klootwijk and Bingham [15]. This effect, being one of increase in ocean basin volume since collision commenced, is added on to that produced by

the slowing down of spreading, and results in a total sea level change of 285 m.

The effect of palinspastic reconstruction of the Alpine chain (from the Alpes Maritimes to the Hindu Kush) is an order of magnitude smaller. This can be seen by a simple calculation in which the chain is represented as a 5500-km-long mountain belt with triangular cross section of height 3.5 km and width 100 km. The belt must be matched by continental crustal thickening, for which we use values of 2.9 Mg m^{-3} for continental crustal density and 3.3 Mg m^{-3} for mantle density. The net decrease in continental area represented by this thickened continental crust, assuming a normal continental crustal thickness of 35 km, is 0.23 Mm^2 . It thus represents a negligible change in sea level.

5. Continental flooding

A completely independent estimate of sea level changes can be obtained by measuring the amount of continental flooding which has occurred through time. This is done by studying paleogeographic maps, which show areas of present-day continent covered by epicontinental seas. These areas are deduced from the presence of shallow-water marine sediments of the correct age. Egyed [1] determined from paleogeographic maps that the total amount of present-day continent which was flooded 100 m.y. ago was 36.5 Mm^2 . Barron et al. [16] have produced a series of paleogeographic maps at 20-m.y. intervals back to 180 m.y. B.P. in which the continental areas covered by shallow seas are indicated. Use of these maps plotted on equal area projections (some of which are shown in Barron et al. [21]) has allowed us to check the results of Egyed [1]. The way in which the maps are constructed is described by Barron et al. [16]. Our results of planimetering the equal area projections are shown in Fig. 1 (top curve). It can be seen that the maximum amount of present-day land covered by water occurs at 100 m.y. ago, at which time 31.5 Mm^2 was under water. This agrees very well with Egyed's figure when all things are considered. We prefer our value because it is based on more up-to-date information on paleogeography. Using

Fig. 1. Top curve: Amount of present-day land flooded by shallow seas as a function of time. Bottom curve: Change in the total amount of continental area flooded by shallow seas as a function of time, measured from today.

the present-day hypsographic curve, 31.5 Mm^2 flooding is produced by a sea level rise of 172 m, whereas Egyed's number gives a sea level rise of 202 m. The postulated sea level rise of 285 m determined by ocean basin and sediment volumes, would conversely produce a flooding of 49.1 Mm^2 of the present land area. There is thus a discrepancy of more than 100 m in the sea level rise, or about 18 Mm^2 in the amount of land flooded.

We believe that this discrepancy may arise from the possibility that the present-day hypsographic curve is not the appropriate one to use for the Cretaceous. It is probable that the Cretaceous hypsographic curve was steeper than the present-day one, and that a given sea level rise then would produce less continental flooding than the same sea level rise today. We therefore believe that the sea level rise was close to that given by Pitman's analysis of ridge crest volume, but that it produced less flooding than we would expect.

6. The hypsographic curve

Details of continental hypsographic curves are to be found in Fairbridge [17]. It has been known for some time that the average elevation of continents is related to the area of the continents. For instance, Hay and Southam [18] plotted the average height of the continents against the logarithm of their area. Most continents fall on a straight line. Antarctica is much too high for its area, after offloading the ice and allowing for rebound. Hay

TABLE 1

Relationships between average elevation, h^* , and continental area, A^*

Relationship	Equation	Correlation coefficient
Dependent on $\sqrt{A}$	$h = 0.1441 \sqrt{A} - 0.009$	0.9333
Power Law	$h = 0.1175 A^{0.5577}$	0.9509
Logarithm	$h = -0.4623 + 0.3731 \log_e A$	0.9604

* h is in km and A is in Mm^2 ; h is measured above -0.2 km.

and Southam suggest that this is because its erosion rate has been very low during the time that it has been covered by ice. Because of its excessive elevation, and because we do not know the details of its hypsographic curve as well as those of the other continents, we have not considered Antarctica to any extent.

We have tried several functional forms to express the relationship between area and elevation. One way in which a continent could have a greater average height if it were larger in area is if all continents were of the form of a cone. In this case, if the conic angles were the same for each continent, then the average elevation, being one-third the highest elevation, would be directly proportional to the square root of the area. In fact, a plot of the square root of the continental areas against the average continental elevations produces points lying very close to a straight line. In these calculations, we have added the areas of the continental shelves to the various continents, and have also adjusted the average elevation on the assumption that the continental shelves (down to the -200 -m contour) have an average elevation of -40 m. Various expressions for the relationship are given in Table 1 and are plotted in Fig. 2 along with the observed points. It can be seen that, knowing the area, the simple logarithmic law is the best predictor of average elevation as the respective correlation coefficient is largest. However, it is interesting to note that the power law and the square root relationships give correlation coefficients almost as large, and the power relationship is close to a square root. Since the idea of a simple cone representing continents is obviously a gross simplifi-

Fig. 2. Relationships between average elevation and area for six continents. Antarctica is not plotted. Also shown are the best fitting logarithmic, power and square root curves.

cation of the real situation, we have decided to use the logarithmic relationship in order to estimate average elevations for different arrangements of continents.

It is customary in studying and comparing the geomorphology of drainage basins to measure the hypsographic of these basins. In order to compare one basin with another, the hypsographic curves are normalized by plotting fractional area against fractional height, this being measured from the lowest elevation of each basin up to the highest elevation of each basin. In the case of continents, the maximum height of each continent is not a good normalizing value, but the discussion above suggests that the average height of each continent might be a good normalizing factor. Consequently, we have plotted the hypsographic data from each continent in Fig. 3, normalizing to fractional area and to average height. It can be seen that the data from the continents are in moderately good agreement with each other. The task now is to determine an analytical expression for the individual continental data, and for the average curve through the points given in Fig. 3.

An expression which is commonly used to fit observed hypsographic data from individual

Fig. 3. Normalized hypsographic data from each continent. The continental heights are normalized by dividing observed height by average height. The average height of each continent would therefore be plotted as unity on the ordinate scale. Area is normalized so that total area for each continent is plotted as unity on the abscissa scale. The best fitting hypsographic curve through these points is also shown.

drainage basins is the following, modified from Strahler [19]:

$$y' = \left(\frac{1-x}{a+x} \cdot a \right)^z \quad (1)$$

where x is the fractional area of fractional height greater than y' , and a and z are constants. The range of y when x goes from 0 to 1 is from 1 to 0. So in order to apply this curve to the continental values, it must be further modified to the following:

$$y = \frac{1}{r} \left(\frac{1-x}{a+x} \cdot a \right)^z \quad (2)$$

where r is given by:

$$r = \int_0^1 y' dx \quad (3)$$

and is the average height represented by the normalized hypsographic curve. The shape of the curve varies depending on the values of a and z . If z is greater than unity the curve is entirely concave upwards and has no inflexion point. If:

$$a > \frac{1+z}{1-z},$$

then the curve is convex upward, and again has no inflexion point. For other values of a and z , there is an inflexion point, which marks the height at which there is maximum area. All the continents have hypsographic curves of this nature. In order to find out which values of a and z give the best fit to each of the continental hypsographic data points it is necessary to search through pairs of values a and z . For each pair of values the integral of y' is calculated numerically, and then the root mean square (r.m.s.) deviation between the theoretical curve and the observed data points is calculated. The pair of values of a and z which gives minimum r.m.s. deviation is then used. The deviation is done on values of x , the fractional area. If x_i and y_i are the pairs of observed values, then x'_i is calculated by putting y_i into equation (2), and the value of:

$$\left[\frac{\sum_{i=1}^n (x'_i - x_i)^2}{n} \right]^{1/2}$$

is calculated.

Fig. 4 shows the six continental hypsographic curves calculated in this way, along with the observed points. The curves in Figs. 3, 4, and 5 are plotted using equation (2). The observed points are plotted by dividing the observed elevations by the average elevations, and by representing the area as

a fractional area for the continent under consideration. Table 2 shows the values of some of the constants involved. We have also calculated the best fitting curve through all the normalized continental points shown in Fig. 3, and this curve is also shown in Fig. 3. In this case there is no

Fig. 4. Individual continental hypsographic values with their best fitting curves: (a) Asia, (b) Africa. Height and area are normalized as in Fig. 3.

Fig. 4 (continued). (c) North America, (d) South America.

number which can be given to the average elevation, and so the height at which the inflexion point occurs can only be given relative to the normalized height. We have also calculated the best fitting curve through the world hypsographic curve (excluding Antarctica), which is shown in the last line of Table 2, and in Fig. 5.

Several observations may be made about these theoretical curves. The positions of the inflexion points are almost all very close to sea level, those from Asia and North America being just below sea level, whereas those from Australia, South America and Europe being just above sea level. The only exception to this is the inflexion point for Africa,

Fig. 4 (continued). (e) Europe, (f) Australia.

which occurs 358 m above sea level. There seems to be no explanation for this phenomenon other than to postulate that Africa has been tectonically uplifted in the recent past. This may be due to its apparent lack of motion with respect to hot spots over the past 25 m.y., as postulated by Burke and Wilson [20]. The r.m.s. deviations are mostly in the

neighborhood of 2%, except for Asia and the World. These two curves, being based on larger total areas than the rest, would be expected to be smoother, which is indeed the case. The curve for all the individual continents (Fig. 3) is obviously less capable of fitting all the data points, but its r.m.s. error is only 5% of the continental area,

Fig. 5. World (excluding Antarctica) continental hypsographic data points with the best fitting curve. Height and area are normalized as in Fig. 3.

which emphasizes the basic similarity between all the continental curves.

Since the average curve through all the continental points shown in Fig. 3 is used later to

derive hypsographic curves for different continental groupings it is perhaps worth looking at the fit between observed points and calculated curve in more detail. At the lowest relative elevations (between 0 and 0.5 of the normalized elevation) the curve is at a greater fractional area than the points by an average of 0.014. In the next elevation range (between 0.5 and 1.0 of normalized elevation) the curve is at a smaller fractional area than the points by an average of 0.021, whereas at the next elevation range (1.0 to 1.5), the curve and the points agree to within 0.002. These deviations are very small and would not have a great effect on the discussions of the shape of the hypsographic curve below. We may thus assume that the curve shown in Fig. 3 is an accurate representation of an average normalized hypsographic curve for any continent or continental grouping.

In order to bring out further relationships, the values of a and z have been plotted in Fig. 6. Also plotted are two sets of curves. The curves marked with x show the position of the point of inflexion as a and z are changed. It can be seen that in the place where the continents plot on this diagram, the inflexion point is almost entirely controlled by the value of z . And thus Africa, which has the lowest value of z , has an inflexion point at a smaller fractional continental area than do the other continents. The second set of curves show how the value of r varies with a and z . This figure shows that the curves for Africa, Europe and South America, with generally lower values of a and z , are different from the rest of the curves. The three continents mentioned have much lower values (by about an order of magnitude) of r than the other three continents. In this respect the theoretical curves are not very good, because they predict much greater maximum heights for these continents than actually occur.

7. Amount of flooding during the Cretaceous

Our task now is to estimate the amount of flooding which took place during the Cretaceous due to a sea level rise of 285 m. We first consider Australia. This continent separated from Antarctica about 55 m.y. ago. Thus during the

TABLE 2
Theoretical hypsographic curves

Continent	Area (Mm ²)	Average elevation above -0.2 km (km)	Height above sea level of inflexion point (km)	x value at inflexion point	r	a	z
Asia ($n=9$)	53.68	0.985	-0.020	0.846	0.136	0.0290	0.70
Africa ($n=7$)	31.08	0.917	0.358	0.680	0.0199	1×10^{-5}	0.36
North America ($n=7$)	30.84	0.754	-0.046	0.835	0.142	0.0290	0.68
South America ($n=8$)	20.23	0.714	0.065	0.750	0.0139	8×10^{-5}	0.50
Europe ($n=6$)	13.01	0.449	0.010	0.720	0.0121	2×10^{-5}	0.44
Australia ($n=5$)	11.60	0.448	0.027	0.740	0.294	0.0579	0.48
All continents ($n=42$)	-	-	0.376	0.760	0.112	0.00724	0.52
World ($n=9$)	160.44	0.806	0.027	0.797	0.122	0.0145	0.60

Fig. 6. Values of a and z plotted for the six continents, the combined individual continents and the world (excluding Antarctica). Also shown are contours of equal values of r (the average height of the normalized hypsographic curve) and x , which is the position of the inflexion point.

time of the Cretaceous transgression, Antarctica and Australia were joined together into a larger continent with a greater average height. The total area of Australia and Antarctica is 25.7 Mm². This gives an average elevation of 0.749 km (from the third expression in Table 1). The fraction of continent flooded by a sea level rise of 285 m (or 0.485 km above our datum) is then 0.474 or 5.5 Mm² for Australia. We do not have to worry about Antarctica because almost none of it is at present within 300 m of sea level and there is almost no paleogeographic information about the location of shallow seas which might have covered it in the past. A 285-m sea level rise would produce a flooding of 0.655 or 7.6 Mm² of Australia, using the present-day hypsographic curve.

We next consider South America and Africa. These continents split apart about 120 m.y. ago, slightly earlier than the time of the maximum amount of continental flooding. But drainage patterns which have caused South America's average elevation to become reduced during the past 120 m.y. had scarcely made an impact 100 m.y. ago. We are therefore justified in calculating the effect of joining Africa with South America, remembering that the correction produced at 100 m.y. may be a little large. The combined area of South America and Africa is 51.31 Mm², giving an aver-

age elevation of 1.007 km. A sea level rise of 285 m (to 0.485 km above our datum) would produce a flooding of 0.337 or 6.8 Mm² for South America. The same sea level rise will produce a flooding of 11.3 Mm² for present-day South America.

If we do the same calculation for Africa, we find a flooding of 10.5 Mm² compared with a present-day flooding of 7.7 Mm². This change is in the opposite direction to the changes for Australia and South America, the reason being that Africa is very high today compared with its area (see Fig. 2) and also has a steeper hypsographic curve at low elevations than do the other continents. The net change in area flooded for the three continents Australia, South America and Africa is thus 3.8 Mm².

Another area in which discrepancies may arise is at high northern latitudes. These land areas were loaded by ice during the last glacial period, and have not yet completely isostatically rebounded from the effect of the offloading of the continental glaciers. They are therefore lower than they would be for an ice-free environment such as was in existence during the Cretaceous. The present-day hypsographic curve is therefore less steep than it would be for ice-free conditions. A rough estimate of this effect can be found in Barron et al. [21]. In their fig. 9, the amount of land area at latitudes greater than 60°N is shown as a function of time. The land area today in this region is 3.9 Mm² less than the land area 20 m.y. ago. This difference is not due to continental drift, which has produced a negligible increase in land area at high latitudes during the past 20 m.y., and is also not due to sea level changes. We may take this as a rough measure of the amount of land which is at present within 200 m of sea level, but which, after final isostatic readjustment, would be greater than 200 m above sea level. A total of 7.7 Mm² is, therefore, accounted for out of the discrepancy of about 18.0 Mm². Thus about 43% of the discrepancy has been satisfactorily explained.

8. Discussion

If we compare the Cretaceous (100 m.y.) paleogeographic map of Barron et al. [16] with

present-day continental topography, several things are obvious. Much of present-day South America is within 200 m of sea level. These areas are predominantly within the Amazon and Parana drainage basins, where the continental shield areas have been eroded to an elevation of less than 200 m. Other parts of the shield area are above 200 m, and we suppose that prior to the development of these drainage basins, most of the shield areas were above 200 m. Thus, in the early stages of the development of the Amazon and Parana rivers we would suspect that most of the land in South America was above 200 m, and therefore not greatly flooded by sea level rises of between 200 and 300 m. Since these drainage basins could only develop subsequent to the opening of the South Atlantic at 120 m.y. B.P. it seems likely that South America would not be very affected by a sea level rise of the amount postulated to explain the Cretaceous transgression. This is indeed the case. The paleogeographic map shows that very little of the present-day land area of South America was affected by the Cretaceous transgression.

In Australia, there was a significant transgression during the Cretaceous which covered the Lake Eyre basin and part of the Nullarbor plain, both of which areas are mostly within 200 m of sea level. However, the Darling river drainage basin, much of which is within 200 m of sea level today, was apparently not covered by a Cretaceous shallow sea. Presumably drainage from the Lake Eyre basin was established to the north during the Mesozoic, whereas no adequate drainage was established from the present-day Darling river basin, because it is more closely surrounded by the mountains of the Great Dividing Range.

The situation in Africa is somewhat different. As we have already pointed out (and has been pointed out by Hay and Southam [18] and Bond [22]) Africa is several hundred meters higher today than the other continents (see Table 2). This uplift probably occurred mainly during the Tertiary, as the erosion from Africa is not less than half of what would be normal for a continent of its size [18]. Bond [22] also came to the conclusion that the uplift of Africa occurred during the late Tertiary.

That the shape of the continental hypsographic

curve can change radically is borne out by another observation we have made, and which was briefly discussed by Southam and Hay [10]. The bottom curve in Fig. 1 shows the change in the total amount of shallow seas as a function of time. This curve was obtained by planimetering on equal area maps the total amount of exposed continent as a function of time and subtracting this from the total continental area. The two curves in this figure are not the same because it is possible for present-day continental shelves to be above sea level in the past. What the curves show is that, for instance, at 180 m.y. B.P. about 19.5 Mm² of present-day shelf was above sea level. This amount becomes greater the further back in time we go from the present day, because of the gradual effect of the joining together of individual continents into Pangaea, with the consequent emergence of significant quantities of present-day shelf areas.

The fairly uniform increase in the deviation between the two curves shown in Fig. 1 suggests that the calculations done in the last section to estimate the continental flooding 80–100 m.y. ago may have underestimated the changes in the hypsographic curve between the present day and the Cretaceous. Southam and Hay [10] have pointed out that the length of passive (rifted) margins has grown continuously since 180 m.y. ago, when the rifting of North America from Africa started the breakup of Pangaea. Fig. 7 shows the increase in

Fig. 7. Increase in length of rifted margins since the split up of Pangaea.

the length of rifted margins with time since the breakup of Pangaea, and to a first approximation the increase has been linear with time, when averaged over time intervals of a few tens of millions of years. The total increase has been 87.5 Mm. The average width of the rifted continental shelves today is about 220 km, established from total discrepancy between the two curves in Fig. 1 and the total length of rifted margins.

Steckler and Watts [23] have shown that even today, after 195 m.y. (their estimate for the time of separation between North America and Africa) of subsidence, there is still significant sinking going on along the East coast of the United States. Of course today most of this sinking does not greatly alter the hypsographic curve, as sediments are deposited to keep the shelf close to sea level. But some lowering of present-day land areas occurs, because of the flexural rigidity of the lithosphere, or because the initial heating of the passive margin prior to breakup extended well landward of the present continental shelf edge. For instance, Pitman [4] used the concept of a hinge line, which is that line within the continent which suffers no subsidence. Subsidence seaward of the hinge line is supposed to be linearly related to the distance from the hinge line, and can be modified by sediment deposition or erosion. The fall line landward of the COST B-2 well is about 75 km landward of the strand line today [23].

A more important factor has been demonstrated by Royden and Keen [24]. They show that under certain circumstances, passive margins may be uplifted prior to rifting, and only regain their original elevation after several tens of millions of years. In order to explain the sedimentary history revealed in wells in the Labrador Sea they postulated that subcrustal stretching prior to rifting was considerably greater than crustal stretching. This results in uplift of up to several hundreds of meters which is only removed after up to 30 m.y. of subsidence. If the original continent in which rifting took place was at an elevation of several hundred meters, then major effects on the shape of the continental hypsographic curve could be seen for the total time it takes for the continent to subside by an amount equal to the sum of these elevations.

It therefore seems reasonable to calculate a hypsographic curve for Pangaea, and to use some curve intermediate between that and the present-day curve in order to find out what sort of sea level rise is equivalent to a flooding of 31.5 Mm^2 (at 100 m.y. B.P.) of present-day land area. There are two possibilities for calculating a Pangaeian hypsographic curve. The first is to calculate an average elevation if all the continents are joined into one super continent of area 174.54 Mm^2 (including Antarctica). This gives an average elevation of 1.464 km. This can then be used to derive a hypsographic curve using the values of a and z from line 7 in Table 2. This hypsographic curve is the top one shown in Fig. 8. This curve is likely to be too steep. The continents of Pangaea are not closely bunched, but are split by one very large re-entrant sea (Tethys). This suggests that the continents be joined into three separate groups, such as Gondwanaland, Asia, and North America-Europe. It should be noted that for the present-day correlation between area and average elevation, we separate Europe from Asia. Three separate hypsographic curves can be generated for each of these super-continents, and then added together to give a combined curve, which is the middle one shown in Fig. 8. A sea level rise of 0.285 km above present sea level (or 0.485 km from our datum)

would cause a flooding of 50.5 Mm^2 . Allowing for the present-day areas below sea level (28.3 Mm^2) means that 22.2 Mm^2 of present-day land area would be flooded. The equivalent amount using the present-day hypsographic curve is 48.2 Mm^2 . Thus, the observed flooding of 31.5 Mm^2 falls closer to the Pangaea value than it does to the present-day value. Since the hypsographic curve responds rather slowly to changes in amount of passive margin, because of the slowness in developing new drainage patterns, the slowness in denuding the continents using these new drainage patterns, and the long time constants associated with thermal subsidence of the continental lithosphere, it seems entirely reasonable that the hypsographic curve at about 90 m.y. ago was somewhat closer to the middle curve in Fig. 8 than to the present-day curve. Therefore, there seems to be no reason to suspect a discrepancy between the two methods of calculating sea level rise. A figure of 285 m for 90 m.y. ago is probably accurate to within 50 m.

9. Conclusions

The calculation of ridge crest volume done by Pitman suggests that sea level was about 340 m

Fig. 8. Present-day hypsographic curve (excluding Antarctica) and two postulated curves for Pangaea (including Antarctica). Left-hand ordinate is height (unnormalized) above datum. Right-hand ordinate is height (unnormalized) above present sea level.

higher during the Late Cretaceous than it is today. The presence of about 300 m of carbonate sediment and about 40 m of non-carbonate sediment in the ocean basins today which were not in the ocean basins 100 m.y. ago, plus extra sedimentation due to the greater average age of the ocean basins today, creates a sea level change in the opposite direction of about 80 m. The Himalayan orogeny produces a lowering of sea level of about 20 m. Thus the combined effect of ridge crest and sediment volumes should be a change in sea level of about 280 m. Using the present-day continental hypsographic curve and the percentage of land flooding during the Late Cretaceous, we arrive at a sea level increase of only 170 m. We have attempted to explain this discrepancy by changes in the shape of the hypsographic curve.

We have shown that the hypsographic curves from individual continents can all be described approximately by the same equation, provided that the curves are normalized so that fractional area is plotted against height normalized to the average height of each continent. The important factor is that the average height of a continent is fairly closely related to its area. When continents are joined together, their average height is greater, and the hypsographic curve will be in general steeper than the sum of the individual present-day hypsographic curves. By correcting the hypsographic curves in this manner, we have been able to explain most of the discrepancy between the two methods of determining sea level change.

Acknowledgements

We appreciate discussions with Eric Barron and Bill Hay which have helped clarify our thinking on sea level changes. We thank Walter Pitman for an extensive review. Research supported by the National Science Foundation. Contribution from the Rosenstiel School of Marine and Atmospheric Science, University of Miami.

References

- 1 L. Egyed, Change of Earth dimension as determined from paleogeography data, *Geophys. Pura Appl.* 33 (1956) 42–48.

- 2 J.D. Hays and W.C. Pitman, III, Lithospheric plate motion, sea level changes and climatic and ecological consequences, *Nature* 246 (1973) 18–22.
- 3 E. Kossinna, Die Erdoberfläche, in: *Handbuch des Geophysik*, Band II, B. Gutenberg, ed. (1933) 869–954.
- 4 W.C. Pitman, III, Relationship between eustasy and stratigraphic sequences of passive margins, *Geol. Soc. Am. Bull.* 89 (1978) 1389–1403.
- 5 A. Hallam, Major epeirogenic and eustatic changes since the Cretaceous and their possible relationship to crustal structure, *Am. J. Sci.* 261 (1963) 397–423.
- 6 H.W. Menard, *Marine Geology of the Pacific* (McGraw-Hill, New York, N.Y., 1964) 271 pp.
- 7 J.W. Valentine and E. Moores, Plate-tectonic regulation of faunal diversity and sea level: a model, *Nature* 228 (1970) 657–659.
- 8 T.A. Davies, W.W. Hay, J.R. Southam and T.R. Worsley, Estimates of Cenozoic oceanic sedimentation rates, *Science* 197 (1977) 53–55.
- 9 J.M. Whitman and T.A. Davies, Cenozoic oceanic sedimentation rates: how good are the data?, *Mar. Geol.* 30 (1979) 269–284.
- 10 J.R. Southam and W.W. Hay, Global sedimentary mass balance and sea level changes, in: *The Sea*, Vol. 7, C. Emiliani, ed. (in press).
- 11 A. Boersma, Foraminifera, in: *Introduction to Marine Micropaleontology*, B.U. Haq and A. Boersma, eds. (Elsevier, Amsterdam, 1978) 19–77.
- 12 W.W. Hay and J.R. Southam, Calcareous plankton and loss of CaO from the continents, *Geol. Soc. Am. Abstr. Progr.* (1975) 1105.
- 13 J.G. Sclater, C. Jaupart and D. Galson, The heat flow through oceanic and continental crust and the heat loss of the Earth, *Rev. Geophys. Planet. Phys.* 18 (1980) 269–311.
- 14 P. Bird and N. Toksoz, Strong attenuation of Rayleigh waves in Tibet, *Nature* 266 (1977) 161.
- 15 C.T. Klootwijk and D.K. Bingham, The extent of Greater India, III. Palaeomagnetic data from the Tibetan sedimentary series, Thakkhola region, Nepal Himalaya, *Earth Planet. Sci. Lett.* 51 (1980) 381–405.
- 16 E.J. Barron, C.G.A. Harrison, J.L. Sloan, II and W.W. Hay, Paleogeography 180 million years ago to the present, *Eclogae Geol. Helv.* (in press).
- 17 R.W. Fairbridge, *Encyclopedia of Geomorphology* (Reinhold, New York, N.Y., 1968) 1295 pp.
- 18 W.W. Hay and J.R. Southam, Modulation of marine sedimentation by the continental shelves, in: *The Role of Fossil Fuel CO₂ in the Oceans*, N.R. Anderson and A. Malahoff, eds. (Plenum Press, New York, N.Y., 1977) 569–605.
- 19 A.N. Strahler, Hypsometric (area-altitude) analysis of erosional topography, *Geol. Soc. Am. Bull.* 63 (1952) 1117–1142.
- 20 K. Burke and J.T. Wilson, Is the African plate stationary?, *Nature* 239 (1972) 387–390.
- 21 E.J. Barron, J.L. Sloan, II and C.G.A. Harrison, Potential significance of land-sea distribution and surface albedo variations as a climatic forcing factor: 180 m.y. to the

- present, *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 30 (1980) 17–40.
- 22 G. Bond, Evidence for Late Tertiary uplift of Africa relative to North America, South America, Australia and Europe, *J. Geol.* 86 (1978) 47–65.
- 23 M.S. Steckler and A. Watts, Subsidence of the Atlantic-type continental margin off New York, *Earth Planet. Sci. Lett.* 41 (1978) 1–13.
- 24 L. Royden and C.E. Keen, Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence curves, *Earth Planet. Sci. Lett.* 51 (1980) 343–361.