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CONTINENTAL HYSOGRAPHY

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Abstract. We have used average continental elevations for 1-degree-square areas to construct detailed continental hypsographic curves. The curves available up to the present have been those prepared by Kossinna, but they suffer from some drawbacks, the most important being that the elevation interval is for the most part 1 km, which does not allow for very detailed work. Consequently, we have given data for each 0.1 km interval of elevation. The availability of the data on tapes allowed us also to make calculations of the average elevation of each continent, an important normalizing parameter when comparing continental hypsographic curves, and to add on the effects of the continental shelves. It has also allowed us to recalculate the amount of continent antipodal to continent and to produce a map of the world showing these areas. We have also used the detailed curves and the amounts of continental flooding during the Neozoic to derive records of sea level variation necessary to explain the amount of flooding for each continent through time.

INTRODUCTION

It has been over 60 years since data have been presented on continental hypsographic curves. Kossinna [1921, 1933] has given the most recent information about continental hypsography. Oceanic hypsography has been updated since Kossinna's papers by Menard and Smith [1966], and we felt that it was time for a new look at continental hypsography. Kossinna's analysis presented data at 0.2, 0.5, or 1.0 km intervals (mainly the last of these) which gives only a fairly generalized picture of the shape of the hypsographic curve. So one of our objectives was to present data at much more closely spaced intervals of elevation. By having more closely spaced contours it is possible to study anomalies in the hypsographic curve, such as that produced by the Tibetan plateau, which will be discussed below. We can also improve the values for the average elevations of the continents, which are good normalizing factors when comparing continental hypsographic curves [Harrison et al, 1981].

Since the earth has not had a stable configuration of continents through time, it is of potential value to be able to look at the hypsography of areas smaller than those listed by Kossinna. For instance, we know that India must have existed as a separate continental block for much of the Mesozoic and Paleogene,

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and so it would be interesting to look at the hypsography of India separated from Asia. Greenland was considered to be part of North America by Kossinna, but its elevation is very high because of the large continental ice sheet which covers most of it. The combination of it with North America will give a biased picture of the latter continent.

The availability of the data in an easily used form has also allowed us to recalculate the percentage of continent antipodal to continent. This was last done by Vening Meinesz [1952] and the result has been used in various speculations concerning the randomness of continental placement on the sphere [Evison and Whittle, 1961; Harrison, 1966].

THE DATA

Elevation data for this study were obtained on a magnetic tape from the Defense Mapping Agency-Aerospace Center, St. Louis, Missouri. The tape contained worldwide $1^\circ \times 1^\circ$ mean elevation values. Where topography was sufficiently rugged, a mean elevation was given for each of four $30' \times 30'$ quadrants per square degree. A character associated with each mean elevation denoted one of seven area types, as follows: (1) all positive land (land above sea level), (2) all ocean, (3) some negative land (land below sea level), (4) both land and ocean, (5) contains ice and mean elevation is for ice surface, (6) contains ice and mean elevation is in terms of land and ocean, and (7) significant lake area.

The defense department data were chosen after comparison with a similar global elevation tape prepared by the Rand Corporation. The Rand tape also reported mean elevations on a $1^\circ \times 1^\circ$ grid but did not use $30' \times 30'$ quadrants in rough areas. A character associated with each elevation also described the type of area but choices were narrowed to lake, land or ocean. As a check on accuracy the area higher than 2000 m and 3000 m on the African continent was measured by hand in the Times Atlas of the World and compared with the results of a hypsographic study of Africa from both tapes. The results are given in Table 1. It is apparent that breaking down degree squares into quadrants permits greater accuracy in determining the area of higher elevations. Appendix B presents a study of the

TABLE 1. Comparison of Data for Africa

Atlas	Rand Tape	DMA Tape
301 (>2 km)	271 (>1.95 km)	352 (>1.95 km)
30 (>3 km)	0 (>2.95 km)	18 (>2.95 km)

Areas are shown in units of 10^{-3} Mm^2 .

errors involved in determining hypsographic curves from the data on the DMA tape.

THE AREAS CONSIDERED

We have divided the continents up into several smaller areas. North America is considered separate from Greenland because Greenland is covered by large thicknesses of ice and because it was a separate plate from North America prior to 35.6 m.y. The boundary between North and South America is drawn at the Panama/Columbia border. Africa is considered as a separate plate from Madagascar, although Kossinna considered them together. The boundary between Africa and Arabia runs up the Red Sea and then along the Suez Canal to the -200 m contour of the Mediterranean.

Arabia is considered as a separate plate from the rest of Asia, as there has been relative motion between the two, and the line separating them has been drawn from the NE corner of the Mediterranean northeastward through the mountains of eastern Turkey and then southeastward along the Zagros Mountains of Iran, ending in the Straits of Hormuz. India has also been considered separately from Asia, as it has been moving relative to Asia for all of its recent history. The boundary between Asia and Europe has been drawn through the Black Sea, along the Caucasus to the Caspian Sea and then northward along the eastern boundary of the Urals into Obiskaya Bay, which empties into the Kara Sea. From there it goes almost due N to the intersection of the -200 m contour in the Barents Sea. (Novaya Zemlya and Zemlya Frantsa-Josifa are on the European side.) The lines separating these continental fragments are shown on Figure 1.

Australia has been treated separately from New Zealand. We have not produced separate curves for other oceanic islands, such as Iceland, Kerguelen, or Seychelles, but they have been included in the data for the whole earth.

We have included within each continent

the area of shelf out to a depth of 0.2 km. This is roughly the position of the shelf edge break and thus serves as a convenient boundary for the continental areas. It should be noted that other depth contours could be used. For instance, in matching up continental edges on either side of the Atlantic Ocean, Bullard et al. [1965] used deeper contours, at about 1.0 or 2.0 km.

THE MAJOR CONTINENTS

Table 2 gives information about the areas and average elevations of all the continental fragments studied. Also given in this table are the various central measurements of heights calculated from Kossinna's data by Harrison et al. [1981]. The median and modal elevations were calculated by fitting a smooth curve through Kossinna's points and calculating these elevations from the curves. In the case of the data presented here, the median elevation is calculated by linear interpolation within the 100-m interval which contains the median elevation. The modal elevation is calculated by fitting a quadratic curve through the 100-m range with maximum elevation and the two on either side of it. The center points of each range are used as values of the independent variable, and the position of the maximum value of the dependent variable is calculated in the normal way. The differences between Kossinna's central values and ours are in general quite small. The differences between the modal values tend to be greater than the differences between the median or mean values.

Appendix A gives further details concerning the hypsographic curves for each continent by showing the areas of each continent within each given height interval. It has been found useful to plot continental hypsographic curves as fully normalized curves, for purposes of comparison [Harrison et al., 1981]. The normalization is carried out in the following way. Area is plotted cumulatively as a percentage of the area of the whole continent. The height is plotted from the starting height of -200 m, normalized to the mean height from this datum. It would be possible to normalize by using the median elevation rather than the mean elevation. This would have the effect of fixing all the curves so that the 50% area position is crossed when each curve is at a normalized height of one.

The normalized hypsographic curves are plotted in Figures 2a-2c, in pairs of continents of similar area. Figure 2a compares the Asian curve (minus India and Arabia) and the African curve (minus Madagascar). Africa has relatively little land at high altitudes but has a very pronounced drop off from the level of maximum area. This level is marked by the position of the inflection point on a cumulative curve such as those shown in this paper. The modal elevation for Africa is much higher than for the other unglaciated continents (Table 2). This indicates that the total range of elevations within Africa is more limited than for other continents similar in size. From the hypsographic data which we have gathered it seems possible that we could demonstrate a relationship between local relief and erosion as described by Ruxton and McDougall [1967] and Ahnert [1970]. These authors show that there is a direct relationship between the speed of denudation and the local relief as measured by the difference between maximum and minimum elevation within a limited area. For instance, Ahnert [1970] calculated the local relief for a river basin as the average of the total relief seen in each 20 x 20 km square covering the drainage basin. Hay and Southam [1977] used the hypsographic curves of Kossinna to study this problem. We have calculated the difference between the mean and modal elevations for the six unglaciated large continental masses, and plotted these against the logarithm of the areas of the continents. This is shown in Figure 3, where it can be seen that the African point falls well below the line connecting the points from the other five continents. It turns out that Africa has a very much lower mechanical denudation rate from water flow than do the other continents [Hay and Southam, 1977]. This is probably in part due to the fact that the local topography, as measured by the difference between mean and modal elevation, is relatively so small. When rivers get to the level of the modal elevation on a continent, they must be flowing so slowly that mechanical erosion does not occur very fast. Therefore the difference between mean and modal elevation, shown in Figure 3, is a measure of erosion potential.

One feature of the Asian hypsographic curve, which does not show up in Figure 2a is that there are two modes in the differ-

Fig. 1. Areas of continent antipodal to continent. The polar areas are shown on Lambert equal area projections, and the lower latitudes are presented on a Mercator projection. Each $1^\circ \times 1^\circ$ continental tessera which is antipodal to continent on the opposite side of the earth is indicated by shading. These maps also show the divisions between the continents and continental fragments discussed in the text.

Fig. 1 (continued)

Fig. 1. (continued)

TABLE 2. New Data on Continental Hypsographic Curves

Continent or Subcontinent	Area, km^2	Mean Elevation, m	Median Elevation, m	Modal Elevation, m	Mean Elevation, m (1)	Median Elevation, m (1)	Modal Elevation, m (1)	Mean-Mode, m	Normalized Median Elevation	Normalized Modal Elevation	Fractional Area at Mean Elevation
1 Asia	42,641	756	341	24				732	0.565	0.235	0.320
2 India	4,466	713	299	150					0.547	0.383	0.168
3 Arabia	4,569	633	521	82					0.866	0.339	0.449
4 1+2+3	51,676	741	351	25	785	384	20		0.586	0.239	
5 Africa	30,250	623	513	326				297	0.866	0.639	0.397
6 Madagascar	0,653	415	349	25					0.893	0.366	0.475
7 5+6	30,903	619	510	313	717	530	358	476	0.867	0.626	
8 North America	26,735	499	304	23					0.721	0.319	0.333
9 Greenland	2,563	1,506	1,652	(see note 2)					1.086	...	0.530
10 8+9	27,298	587	327	23	554	260	46		0.670	0.283	
11 South America	20,098	523	248	132	514	259	65	391	0.620	0.459	0.260
12 Europe	12,817	202	129	108	249	118	10	96	0.818	0.766	0.307
13 Australia	11,124	243	175	99	248	168	27	140	0.847	0.675	0.397
14 Antarctica	13,676	1,964	2,182	(see note 3)	2,200				1.101	...	0.551
15 4+7+8+11+12+13	153,353	565	318	87					0.677	0.375	
16 9+14	16,239	1,892									
17 15+16	169,592	692									

(1) Data from Kossinna [1933] or calculated from Kossinna's data by Harrison et al. [1981].

(2) The differential hypsographic curve for Greenland shows several peaks. The major ones are at 0 m, 300 m, 700 m.

(3) The differential hypsographic curve for Antarctica shows several peaks. The major ones are at 100 m, 2600 m, and 3650 m.

ential curve, an uncommon situation. The other cases, to be discussed later, involve the curves from Arabia, India and South America, but they are much less pronounced. Figure 4 shows a portion of the differential curve for Asia, in which points have been plotted for each 100-m elevation range. The remarkable fact is that the areas between elevations of 3.5 km and 5.5 km appear to be anomalous. Below 3.5 km the area decreases fairly smoothly with increasing height. Above 5.5 km the same is true. But between these two elevations, there is an increase in area as a function of height up to a height of about 5.0 km, followed by a very rapid fall in area until an elevation of 5.5 km is reached. The area between these two elevations is 1.95 Mm^2 , and most of the area is located on the Tibetan plateau. The Tibetan plateau is probably the result of a double thickness of continental crust produced by the shallow underthrusting of the Indian sub-continent after its collision with Asia.

Figure 2b shows the fully normalized hypsographic curves of North and South America. The North American curve is much less sinuous than that for South America, which is dominated by an extensive low lying portion, mainly consisting of the Amazon drainage basin, and an extensive area of relatively high mountains, representing the Andes. In contrast, North America has relatively few highly mountainous areas. The continuing subduction of the Pacific and Nazca plates under South America has kept the Andes very high. Although there has been extensive subduction of the Pacific plate under North America, there are today large areas in the west where subduction has ceased, these being basically the regions where the San Andreas fault is active and at the latitudes of the Gulf of California. Also, during much of the Cenozoic history of subduction along the western coast of North America, the subduction has been at an angle to the coast [Whitman, 1981] which means that the mountain building has not been as extensive as in South America, where subduction has been predominately perpendicular to the coast. In addition, the rate of subduction under South America has been much faster.

The greater slope of the North American curve at its inflection point is probably caused by three factors. Firstly, a fairly significant portion of North America was depressed below sea level due

Fig. 2. Normalized cumulative hypsographic curves of the major continental areas. The area (represented as a percentage of the whole area of the continent under consideration) lying above the height is plotted. The height is normalized by taking the height above the -200 m contour and dividing by the average height above the -200 m contour. (a) Curves for Asia (minus Arabia and India) and Africa (minus Madagascar). Circles are data for Asia from Kossinna and squares are for Africa from Kossinna. (b) Curves are for North America (minus Greenland) and South America. Circles are for North America and squares are for South America from Kossinna. (c) Curves for Australia (minus New Zealand) and Europe. The curves are almost exactly the same above a normalized elevation of 3.1. Circles are for Australia and squares are for Europe from Kossinna.

to ice loading during the last glacial period and isostatic uplift is not completely finished. Secondly, the Appalachian system is still elevated from the effect of the Hercynian orogeny, when the Iapetus Ocean closed. The third effect is that of the Colorado plateau uplift, which has produced extensive areas of the western United States which were uplifted about 20 m. y. ago. This uplift has removed land from close to a modal elevation (the area was one frequently flooded during the Cretaceous and Oligocene transgressions) to elevations in general much higher than this.

The South American differential hypsographic curve has two subsidiary peaks at elevations of 1.6 and 2.6 km (Figure 5). These areas are entirely within the Andes and do not represent very much of the total area of South America. Since the maxima are defined by only a small number of points, it is possible that they are due to random errors in determining the average elevation of the 1-degree-square areas (see Appendix B). The error of picking an average elevation for the

Andean region is, according to the DMA tape, over 100 m.

The comparison in Figure 2c is between Australia and Europe. It is again obvious on this plot that the Australian curve is somewhat less sinuous than the European

Fig. 3. Difference between mean and modal elevation in meters plotted against area of each continent (on a logarithmic scale).

Fig. 4. Portion of the differential hypsographic curve for Asia. The elevation interval is 0.1 km. For example, the point plotted at an elevation of 3.0 km, showing an area of $10.1 \times 10^{-2} \text{ Mm}^2$, shows the area lying between 2.95 and 3.05 km. The five straight dashed lines are drawn by eye through the points.

curve. One reason for this may be that the fluvial runoff rate for Australia is much less than the other continents when measured in runoff per unit area [Hay and Southam, 1977]. The other continents have runoff rates between 20 and $50 \text{ g cm}^{-2} \text{ yr}^{-1}$, whereas that for Australia is only $4 \text{ g cm}^{-2} \text{ yr}^{-1}$. The load of dissolved material carried away by Australian rivers is consequently low as well, being about a factor of 10 lower per unit area per unit time than for the other continents. Thus the absence of sharp modal elevation for Australia may be caused by the relatively slow rate of removal of material by erosion.

LAND AS A FUNCTION OF LATITUDE BANDS

We have recalculated the percentage of land and ocean within 5° latitude bands. The oceanic percentages are shown in Table 3. There are some significant differences between these figures and those presented by Kossinna [1933] (see Table 4 for comparisons). The major differences occur at high latitudes. The present data show greater amounts of land at high northern latitudes and smaller amounts of land at high southern latitudes than do the data presented by Kossinna. The information from high southern latitudes shows that Kossinna had no oceanic areas within 10°

of the south pole, whereas the Ross Ice Shelf stretches to slightly further south than 85°S. The major discrepancy occurs south of 75°S, with some minor discrepancy within the band between 70° and 75°S. Further north in the southern hemisphere the agreement between the two sets of data is good. Presumably, Kossinna did not know what was under the ice sheets and thought that some of them covered land areas, whereas we now know that the ice sheets sometimes cover areas of water.

The discrepancy in the northern hemisphere is less easy to explain. Both data sets give 100% ocean for the highest latitude band. But in every other band from 85° to 55°N Kossinna overestimates the amount of land compared with our data by more than 2%. We are unable to explain why Kossinna had a relatively poor knowledge about the geography of the high northern latitudes. A table presenting the comparison between our data and those of Kossinna is shown (Table 4).

THE ICE COVERED FRAGMENTS

In Figure 6 we compare the fully normalized hypsographic curves for Antarctica

Fig. 5. Portion of the differential hypsographic curve for South America. This is a curve generated from data which have been smoothed by taking weighted means using the two points immediately above and below the observation point (1/4, 1/2, 1/4).

TABLE 3 Percent Ocean in 5° Latitude Bounds

Latitude Band	Northern Hemisphere	Southern Hemisphere
90-85	100.0	0.0
85-80	84.0	21.1
80-75	70.0	26.9
75-70	53.6	43.1
70-65	23.3	79.7
65-60	26.1	99.5
60-55	42.1	99.8
55-50	39.2	96.2
50-45	44.7	97.2
45-40	52.0	96.2
40-35	57.1	93.1
35-30	56.9	83.3
30-25	59.3	78.2
25-20	64.6	75.4
20-15	70.8	76.1
15-10	75.7	79.4
10-5	75.4	77.1
5-0	78.7	75.4

and Greenland, both of which are covered with large thicknesses of ice. In looking at the DMA tape for Antarctica, we found that the average elevation was only 785 m, which appeared to be far too low. Kossinna's average elevation was 2200 m, and an examination of Antarctica in the Times Atlas revealed that most spot elevations are considerably higher than either figure. It therefore seems probable that the Antarctic data on the DMA tape are incorrect. However, the data on the Rand tape showed a mean elevation of 1964 m, which appears to be more correct. We have therefore used these data to generate a hypsographic curve for Antarctica. It is obvious that the curves in Figure 6 are very different from the curves presented in Figure 2, in that there is a much more even distribution of area as a function of elevation. This shape is presumably produced by the way in which ice flows in response to a constant load being added per unit area of the surface per unit time. Assuming that the continent is circular, of radius R and of maximum height H , we can derive an expression for the height h at radius r , which is

$$h = H [1 - (r/R)^2],$$

for which the average elevation is $H/2$.

Patterson [1980] gives a generalized

TABLE 4 Comparison Between Kossinna and Present Data

Latitude Band	Northern Percent Ocean		Southern Percent Ocean	
	Kossinna	Present	Kossinna	Present
90°-60°	50.2%	43.5%	58.8%	63.8%
60°-30°	50.0%	49.6%	94.3%	93.7%
30°-0°	71.3%	71.1%	77.1%	76.9%
Hemisphere	60.66%	59.53%	80.92%	81.28%
Sphere	70.80%	70.45%		

equation for the surface elevation of an ice sheet. He recommends an equation of the general form

$$h = H \sqrt{1 - \frac{r}{R}}$$

This is the equation for a parabola with a horizontal axis and contains three interesting features. First, because the axis of such a parabola is horizontal, the ice front at $r/R = 1$ is vertical. Second, because the curve never becomes horizontal at $r/R = 0$, a circular ice sheet with such a profile is not flat at $r/R = 0$, but rises to a conical point. Third, the hypsography of such a circular ice sheet reflects this non-horizontal center region by rising rather steeply at small fractional areas.

The curve we have selected is a parabola with a vertical axis. The ice front is no longer vertical, but the center of the sheet is horizontal. The hypsographic curve of a circular ice sheet with this profile is a straight line. The profiles

and hypsographic curves of the two parabolas are shown in Figures 7a and 7b. Although the horizontal parabola is based on the rheology of ice, we suspect that the vertical parabola is a better representation of the ice surface given its flat summit and its similarity to the measured hypsography of Greenland and Antarctica.

In practice, the two models are not greatly different. The model preferred by us has a mean and median elevation at half the maximum elevation, and with no modal elevation. The second model has a modal elevation at 0.577, a mean at 0.533, and a median at 0.541 of the maximum elevation.

There must be some influence at work keeping the ice sheet in Greenland relatively higher than that in Antarctica, for although the areas differ by a factor of 5.3 (or radii by a factor of 2.31), the average elevations only differ by a factor of 1.3. Accumulation rates of snow on the two ice caps could have a significant effect. The accumulation rate of snow on the Antarctic ice cap is about $15 \text{ g cm}^{-2} \text{ yr}^{-1}$ [Denton et al, 1971]. The accumulation rate of snow during the past 100 years at the Camp Century site on Greenland has been $32 \text{ g cm}^{-2} \text{ yr}^{-1}$ [Dansgaard et al., 1971], which is a factor of 2.1 greater than the average accumulation in Antarctica.

CONTINENTAL FRAGMENTS

In Figure 8 we compare the hypsographic curves of Arabia and India. Both of these subcontinents are involved in collision with the rest of Asia. Consequently, they should both show fairly large areas at great elevations. This is obviously true of India, whose curve is displaced from the ordinate by a larger amount than any other continent at small fractional areas. One sign of this is that the mean elevation occurs at a smaller fractional

Fig. 6. Fully normalized hypsographic curves for Antarctica and Greenland. The points are the data for Antarctica from Kossinna. See caption to Figure 2 for further details.

area than for any other continental fragment or continent (Table 2). The curve for Arabia, however, is very different from that of India. Arabia is about the same size as India, and the collision zone length for Arabia is similar to that for India, so that we would expect the relative area at high elevations to be about the same as that for India. But in fact, it is considerably less. It turns out that the fully normalized curve which is most like the Arabian one is that from Australia. We suggest that the Arabian curve is the result of Arabia being further away from a steady state regime than the other continental masses which we have discussed. The buildup of high elevations has obviously not proceeded nearly as far as it has in the case of the collision of India with Asia. This is odd because it is believed that the collision rate between Arabia and Asia is greater than the collision rate between India and Asia [Minster and Jordan, 1978]. This results in strike slip motion along the Owen fracture zone to the NE of the Carlsberg Ridge, on which right lateral motion has been observed [Harrison and Ball, 1973]. However, this factor may be ameliorated by the fact that India has been colliding with Asia for a longer time than has Arabia.

Another reason why we believe that the

Fig. 7. (a) Profiles of ice covered continents according to the two models discussed in the text. (b) Hypsographic curves for the two models of ice-covered continents.

Fig. 8. Fully normalized hypsographic curves for Arabia and India. See caption to Figure 2 for further details.

Arabian curve represents a non steady state situation is that there is evidence of a reversal of slope in the differential curve. This can be seen in the cumulative curve by a change in slope at a normalized height of about 1.00. The differential curve for Arabia is shown in Figure 9 in which the reversal of slope is obvious. The excess area represented by the difference between the full and dashed line between elevations of 0.6 and 1.3 km is 0.73 Mm^2 , or 16.0% of the total area of Arabia. Most of the land in Arabia which falls between the elevations of 600-1300 m lies within a band about 700 km wide running parallel to the Red Sea. It therefore appears that this anomalous area between 0.6 and 1.3 km may be related to

Fig. 9. Portion of the differential hypsographic curve for Arabia (solid line). The elevation interval is 0.1 km. The point plotted at an elevation of 0.0 km, showing an area of $4.3 \times 10^{-1} \text{ Mm}^2$ shows the area lying between -0.05 and 0.05 km. The dashed line shows what the curve would look like if there were only one major mode in the data. The difference in area between the dashed line and the full line is 0.73 Mm^2 . A portion of the differential hypsographic curve for Africa is also plotted (circled dots) by using an area scale 10 times smaller (right ordinate). The excess area for the African curve is shown by the difference between the circled dots and the plain dots.

the fact that Arabia was once part of Africa, which as we have seen is an anomalous continent in that its modal elevation is very high compared to the other continents. The fact that the portion of Arabia which contains the anomalous area is one of the driest on earth suggests that erosional patterns may be in part responsible for these anomalous areas. The separation between Arabia and Africa occurred about 25 m.y. ago [Cochran, 1981]. Sometimes continental separation is accompanied by uplift of the areas around the rift, but this does not seem to have been a dominant process for the areas of land surrounding the Gulf of Aden [Cochran, 1981].

Returning to the African hypsographic curve, it can be seen that this too ex-

hibits a slight slope change at about a normalized elevation of 1.0 (Figure 2a). A portion of the differential hypsographic curve for Africa is also plotted on Figure 9, using a different scale (10 times smaller) for the area. The points plotted at elevations of 1.0, 1.1, and 1.2 km indicate areas which are considerably larger than a smooth curve would predict. The excess area from the dotted line in Figure 9 is 0.95 Mm^2 . The recent uplift of Africa is discussed in greater detail below.

ANTIPODALITY OF CONTINENT AND OCEAN

The availability of data on tape allowed us to make calculations concerning the antipodal arrangement of continent and

ocean. This has been used in the past to argue about the randomness of continental areas on the surface of the earth [Evison and Whittle, 1961; Harrison, 1966]. We have calculated the area of continent which is antipodal to ocean, using the 200-m depth contour (the edge of the continental shelf) as the boundary between the two types of crust. The areas of continent antipodal to continent are shown in Figure 1, where it can be seen that most of these areas are located within Antarctica, and at corresponding high-latitude areas around the Arctic Ocean, and within South America and corresponding areas in China, South East Asia, Siberia, and Mongolia. There are minor amounts in Kerguelen (North America) and the Iberian Peninsula (New Zealand).

Data on percentages and areas are given in Table 5. The total continental area measured was 170.895 Mm² or 1.316 Mm² greater than the total amount for the continents listed in Table 2. Most of this comes from areas not listed in Table 2, such as New Zealand, Kerguelen, Iceland, and Spitzbergen. The total continental area was somewhat less than that used by Harrison [1966], whose figure was 34.4% of the earth. The percentage of continent opposite ocean used by Harrison [1966] was greater than that formed here, 82.6 compared with 79.85%. Harrison was trying to find out whether the observed percentage of continent opposite ocean was too large to have been caused by a random arrangement of continents on the surface of the earth. He did this by a series of Monte Carlo simulations using continents of different sizes and shapes. The conclusion, that there was less than one chance in fourteen that the arrangement could be due to chance, has to be changed, because the percentage is changed. Examination of the data used by Harrison [1966] revealed that for the case of triangular continents the percentage of tries in which the observed percentage of continent opposite ocean was exceeded was about 14%, representing one chance in seven. From the revised antipodality of continent and ocean it is now no longer necessary to postulate any nonrandom placement of continents on the surface of the earth.

SEA LEVEL CHANGES AND CONTINENTAL ELEVATION CHANGES

We have also used the refined hypsographic curves of the six major ice-free continents (Asia-including Arabia and

TABLE 5 Antipodal Arrangements

	Area, Mm ²	Percent of Total Area
Total continental area	170.895	33.51
Total oceanic area	339.113	66.49
Total earth	510.008	100.00
Continent opposite ocean	134.923*	

*78.95% of continental area

India, Africa, North America-excluding Greenland, South America, Europe, and Australia) to study sea level changes. Data on the extent of present day continent flooded by shallow seas were planimeted from equal area paleogeographic maps similar to those shown by Barron et al. [1981] for each of these six continents. The amount of flooded present day land was measured on each of the maps, which were produced at 20-million-year time spacings. On the assumption that the hypsography of each continent does not change, the amount of flooding can be related to sea level changes by using the hypsographic curves. The results are shown in Figure 10. There are several things apparent about the curves shown in this figure. Firstly, the data from individual continents do not agree. Therefore either the data are wrong, or the individual continental hypsographic curves have changed. Much discussion has taken place concerning this method of estimating sea level change. Some papers look at overall trends which might have taken place in all the continents through time [Harrison et al., 1981], and others look at possible individual changes from continent to continent [Bond, 1978].

We believe that the scatter of data points in Figure 10 is not just due to poor information concerning the amount of continental area flooded at each time slice. There is a consistency about the data which argues against this. The information contained in these curves is a combination of sea level variations, changes in the elevation of some continents relative to the others, and changes in the hypsographic curves of the continents themselves.

It is possible to produce an average elevation of the ocean surface by averaging the individual points for each of the continents. When this is done, it turns out that the African curve is always

Fig. 10. Sea level changes measured from the area of individual continental land areas flooded and the individual hypsographic curves of the continents. Data from six continents are shown. In addition, the asterisks show the average elevations of sea level for each time interval.

higher than the mean curve, as is the European curve. In contrast, the Australian and South American curves are always below the mean. Only the North American and Asian curves cross the mean.

A second point is that most of the curves have maxima and minima at about the same ages. For instance, there is a maximum in all the curves at 40 m.y. B.P., except for the North American curve, where the maximum is at 20 m.y. B.P. All the curves have minima at 60 m.y. B.P. There are maxima in the North American and Asian curves at 80 m.y. B.P., in the African, European, and South American curves at 100 m.y. B.P. and in the Australian curve at 120 m.y. B.P. Three of the curves have maxima at 140 m.y. B.P. These general patterns suggest strongly that there is a coherent pattern in the individual curves governed at least partly by a world wide phenomenon, which we think is eustatic sea level change.

Bond [1978] used data from five continents (Africa, Australia, North America, South America, and Europe) to determine sea level change during the Cretaceous and Tertiary. He used four time slices (Miocene, Eocene, Late Campanian-Early Maastrichtian, and Albian) in order to determine the elevation above present sea level from percentage flooding and individual hypsographic curves. He found that there were certain groupings of elevations determined from individual continents, with other data points lying

well outside of these groupings. He therefore made corrections by moving certain data points back into the groupings. In particular, he found that the African points for the Miocene and Eocene were much higher than for the other four continents, and supposed that Africa has at the present day a steeper hypsographic curve than it did during these times. Thus he supposed that Africa has risen since the Miocene and also rose between the Eocene and Miocene. These corrections were then applied to all the earlier African sea level points. We do not agree with the details of this method of analysis. We are not overly impressed with the groupings of data points shown in Figure 10 and feel that the data do not justify this treatment. If these corrections are applied to Africa, then the African point for 60 m.y. B.P. would lie very far below the points for the other continents. There are several additional pieces of evidence that there was a major regression of epeiric seas in Africa during the Paleocene. Rona [1973] has presented evidence from a variety of sources for a major regression occurring during this time. The regressive event did not last very long and so fell in between the Eocene and Late Campanian-Early Maastrichtian analyses of Bond [1978]. It is interesting to note that there is also another minor regression recorded in Africa [Rona, 1973] during the Early Miocene which should be at approximately the time of our 20 m.y. measurement. In order to record events of this short a time scale, it would be necessary to draw paleogeographic maps at less than 10 m.y. intervals. Bond's analysis ended up by moving most points downwards, with the result that his sea level rise for the Albian was less than 100 m. We prefer to believe that the hypsography of individual continents today gives a good snapshot of average continental elevations, with some continents lying high (e.g., Africa), whereas other continents are lying low (such as South America and Australia). There is a possibility that portions of the average curve shown in Figure 10 are too low. Since it is impossible to measure relative sea level below that of today, it is possible that points for individual continents which lie on the abscissa should in fact be below the abscissa, meaning that the average curve could be too high for these time periods.

Superimposed on this average curve is a

Fig. 11. Sea level deviations of individual continents measured from the mean sea level for each time interval. Curves which rise on going from older to younger ages indicate that the continent has undergone subsidence. Curves which fall on going from older to younger ages indicate that the continent has undergone elevation during that time interval. Except for the two end points, the curves have been smoothed by a weighted running mean of three points, the weights being 0.2, 0.6, 0.2.

tendency for the hypsographic curves to be "steeper" in the past, that is, to have less area close to sea level. The hypsographic curve of a large continent is steeper than that of a group of small continents of the same area. The hypsographic curve of the continents has become "shallower" since the breakup of Pangea as the new smaller continents have adjusted to their new configurations [Harrison et al., 1981]. Nevertheless, we believe, with Bond, that the data suggest relative motions of the individual continents in response to some asthenospheric forces about which we know very little at the moment.

With this concept in mind we can discuss the vertical motions shown by each continent, by comparing the deviations of sea level measured for that continent from the mean sea level. The results of this analysis are shown in Figure 11. The curves have been smoothed by taking a weighted mean of the point and the preceding and succeeding points, with a weighting of 60%, 20%, 20% in order to make the main trends more obvious. Smoothing has not been done for the first and last points. The scale on the left is the sea level deviation, and is thus not

necessarily an accurate indication of the amount of continental rise or fall. We start off with a discussion of the African curve, which shows the largest deviations from the mean curve. Africa has undergone three major periods of subsidence (180-160, 120-100, and 60-40 m.y.) followed by periods of emergence, of which the most recent has been the most rapid and of the largest amplitude. In general, it has stood much lower in the past than it is today. Africa today is a very high standing continent with the highest median and modal elevations of any large ice free fragment and a mean elevation almost as great as Asia, although it is a much smaller continent (see Table 2).

The curve for Europe shows very few large scale deviations from the mean, and can be characterized by an overall elevation at a fairly constant rate since 160 m.y. B.P. The North American curve shows that there was a very gradual subsidence from 180 to 80 m.y. B.P. followed by a significant elevation from 80 to 40 m.y. B.P. North America has been subsiding since 40 m.y. B.P. Confirmation of overall subsidence of North America from the time period 100 to 60 m.y. B.P. (Albian to Paleocene) has been suggested by Bond

[1976], who measured the thickness of shallow water marine sediments deposited on the continent during this time interval. He found that thicknesses in excess of what could be explained by his calculated sea level rise during the Cretaceous transgression (i.e., greater than 700 m, allowing for isostatic subsidence due to sediment load) covered large parts of the continent. He suggested that these parts had subsided relative to the rest of the continent in order to make room for the extra thickness of sediment.

South America also shows a fairly simple pattern of gradual subsidence since 160 m.y. B.P. Australia is in the sense the opposite of Africa, having been in general much higher in the past than it is today. Subsidence occurred between 160 and 120 and between 80 and 0 m.y. B.P. with a period of active elevation in between. The Asian curve oscillates around the zero level. There was a slow elevation between 180 and 100 m.y. B.P. and also since 60 m.y. B.P., with a period of subsidence in between.

One possible interpretation of the data shown in Figures 10 and 11 is that the "average" curve in Figure 10 is a true eustatic sea level curve and that the curves in Figure 11 represent the true average vertical motions of the continents. Certainly the shape of the "average" curve looks very much like previous reconstructions of sea level although its maximum at 100 m.y. is only about 175 m. Harrison et al [1981] calculated a value of 170 m by using the total area of continent flooded and a present day global hypsographic curve. The small difference between the maximum elevations is due to the different weightings used. Harrison et al [1981] essentially weighted the continents according to their area, whereas in this paper the eustatic sea level curve has been arrived at by giving each continent equal weighting. Harrison et al [1981] also suggested that the process of the breakup of Pangea had caused a change in the hypsographic curve such that today there is more area at low elevation than there was 100 m.y. ago. Allowing for the steeper hypsographic curve 100 m.y. ago added 110 m to the figure of 170 m, giving a total sea level rise of 280 m. Since the "average" curve appears to represent eustatic sea level changes, there is reason to believe that the deviations from the mean shown in Figure 11 represent true changes in the relative elevations of the continents.

In this discussion of relative changes in elevation of continental areas, we do not wish to suggest that each continent behaves as a rigid mass which moves vertically in a uniform manner. Rather, we believe that the curves shown in Figure 10 and 11 indicate that substantial fractions of continents are acting together in moving upward and downward, with the result that amounts of flooding for individual continents can be substantially more or less than those deduced from the average (eustatic) sea level changes which have been previously documented.

Smith [1982] has discussed the late Cenozoic uplift of various continental areas. He suggests that uplift may be caused by small amounts of excess heat producing phase changes within the continental mantle. Further work needs to be done to see whether such a mechanism could explain all of the relative motions shown in Figure 11.

Although the depths of the ocean basins can be predicted to first order by knowing the age of the ocean floor [Sclater et al., 1980], there are significant anomalies in this relationship, which have been shown by Menard and Dorman [1977] for the Pacific Ocean. For instance they show a depth anomaly in the eastern equatorial Pacific in which an area greater than 12 Mm² is deeper than predicted by at least 200 m. By analogy with the vertical movements recorded in the geology of the atoll of Enewetak, Menard and Dorman suggest that epeirogenic movements of the ocean floor can occur, with uplifts or downwarps of several hundred meters, covering many square megameters of area, and with time spans of 1 or a few tens of millions of years. Similar epeirogenic continental movements could cause the relative sea level variations recorded in Figures 10 and 11. It may be significant that Asia, the largest continent, shows one of the closest relationships to the average sea level variation curve in Figure 10. This is to be expected if the areas of epeirogenic uplift and downwarp are considerably smaller in size than this continent, in that the average effect seen by Asia would be only some fraction of the total uplift or downwarp experienced by part of it.

We might expect, from a study of Figure 11, that Australia, which has been slowly subsiding for the past 80 m.y., and Europe, which has been gradually emerging during the same time, would have rather different hypsographic curves (Figure 2c),

especially as they are approximately the same size. Despite the greater sinuosity of the European curve, they are in fact remarkably similar. For instance, they both have 29% of their areas at elevations below 50 m, which is considerably greater than the corresponding amounts for the other continents (see Appendix A). The reason is probably that there are two conflicting processes going on. Although we would expect larger areas at low elevations for Australia due to its subsidence, this is offset to some extent by the much less rapid erosion for Australia, especially solution erosion, which is the only way of effectively eroding low-lying areas.

These patterns of uplift and subsidence shown in Figure 11 should manifest themselves in other geological phenomena. For instance, after a period of rapid uplift, the amount of erosion should in general be larger, because the local relief will be greater. Provided that the climate is suitable for fluvial erosion, it should be possible to detect this erosion by studying the pattern of continental shelf sedimentation. Thus shelf sedimentation should be very rapid for certain sections of the North American shelf after the rapid uplift between 80 and 60 m.y. The same might be true for Africa after the rapid uplift which ended at 60 m.y., except that the time available for rapid erosion is small, since Africa fairly quickly subsided by a large amount. The rapid uplift which Africa has undergone in the past 40 m.y. might be difficult to see in the sedimentary record, since fluvial erosion on Africa is today much less than expected due to the extremely dry climate [Hay and Southam, 1977].

Sleep [1976] and Hancock and Kauffman [1979] have attempted to measure eustatic sea level changes during the Cretaceous, and absolute sea level differences from the Cretaceous to the present day, by determining the present day elevations of locations where shallow water Cretaceous marine sediments abut onto unconformities or onto shield rocks. Hancock and Kauffman [1979] corrected for water depth where possible. The sea level curve that Hancock and Kauffman obtained showed a maximum rise in sea level of over 600 m, which occurred during the Campanian. This number seems impossibly large, and it is difficult to conceive of a reasonable cause for such an effect. However, it may be that the areas on which this sea level curve was based have themselves suffered

some amount of epeirogenic uplift since the formation of the sediments on which the measurements are based. There is in fact some evidence for this in the data for the Lower Turonian. This substage is thought to have lasted a very short time, only about 1 m.y. [Obradovich and Cobban, 1975], so that sediments of this age collected from around the world can be considered contemporaneous. Two sedimentary horizons from France gave a sea level rise of about 300 m, one horizon from Iowa gave a sea level rise of 450 m, whereas another horizon in Nigeria gave a rise of 630 m. This very large difference of over 300 m could be caused by different amounts of uplift happening in the three areas since the Lower Turonian.

CONCLUSIONS

Our study of continental hypsography based on the new data supplied by DMA and the Rand Corporation has shown that Africa is significantly higher than the other continents with a restricted range of elevations. Africa's erosion potential is lower than the other continents as shown by the difference between its mean and modal elevations. Asia has a region of anomalous altitude, the Tibetan plateau, which causes a reversal in its differential hypsographic curve and is probably due to a doubling of continental crust by underthrusting. North and South America differ primarily in the effects of subduction.

The hypsographic curves of Greenland and Antarctica are governed by the physics of flow in their ice caps and are entirely different from those of their unglaciated counterparts. Arabia and India show small areas of anomalously high elevation related to their tectonic setting.

The relative amounts of flooding of the continents can be used to determine in a general way the sense of vertical motion occurring to each continent during the time period considered. Eustatic sea level changes are removed from the individual continental records by assuming that the average continental flooding is caused by eustatic sea level change. Deviations of individual continental flooding curves from the eustatic curve represent individual continental epeirogenesis or subsidence. During the last 200 m.y., some continents have always been lower than today (Africa and Europe) while others have always been higher (South America and Australia).

APPENDIX A. Area as a Function of Elevation

Elevation Interval, m*	Asia	India	Arabia	Africa	Madagascar	North America	Greenland	South America	Europe	Australia	Antarctica	World
-200 to -150	4412	363	179	1982	118	5682	539	1961	2355	1741	1089	23106
-150 to -50	25227	1051	719	4855	0	18775	884	8687	11584	13679	2140	92101
-50 to 50	66390	5995	4241	10649	1290	35107	1020	22774	23319	16829	5550	197434
50 to 150	51300	6174	4815	14858	471	29217	889	35264	34264	19307	7058	203780
150 to 250	39760	6187	3605	24112	584	28217	742	32571	26178	16797	4070	183328
250 to 350	28590	5245	3585	40057	817	31183	1118	22869	8561	12878	2446	157855
350 to 450	22126	5320	3850	35008	232	23490	755	16022	5124	11343	2596	126730
450 to 550	21096	3624	2627	31717	803	13986	687	11863	4062	8537	1849	101512
550 to 650	16013	2544	1878	26402	233	9966	837	8660	2342	3818	2590	75779
650 to 750	14155	699	3815	15709	705	7733	919	6761	2273	1240	1974	56218
750 to 850	14242	960	2829	14079	582	6624	677	5474	2031	655	2051	50256
850 to 950	11021	110	2760	13027	232	4944	357	3772	1446	1033	1961	41146
950 to 1050	12410	327	3122	14072	116	5959	480	2320	1619	737	1877	43126
1050 to 1150	10652	357	1697	13281	233	4433	502	1202	805	222	2767	36348
1150 to 1250	11108	226	890	13530	0	4834	366	1238	144	491	2082	34909
1250 to 1350	7981	111	449	7864	0	5997	384	1428	540	246	2123	27123
1350 to 1450	8054	109	621	5776	117	4675	669	365	176	0	2704	23267
1450 to 1550	5789	136	203	5369	0	4199	394	613	198	123	3198	20223
1550 to 1650	4672	108	496	2187	0	3945	593	1017	153	123	3732	17026
1650 to 1750	3650	189	332	1394	0	2352	546	1266	326	0	2280	12335
1750 to 1850	2855	213	518	1683	0	3437	812	483	196	246	2447	12890
1850 to 1950	2829	53	793	1380	0	2697	801	931	46	123	2490	12142
1950 to 2150	5470	189	646	1586	0	5459	1496	1188	154	0	6284	22472
2150 to 2350	3067	265	720	1047	0	1901	2011	933	159	123	6713	16939
2350 to 2550	2987	158	218	304	0	1057	2201	800	91	123	8030	15969
2550 to 2750	2860	184	78	304	0	1093	2059	1628	0	123	10740	19068
2750 to 2950	1665	54	91	91	0	196	1519	783	23	369	9656	14355
2950 to 3150	2006	135	153	153	0	192	1228	674	0	123	8191	12702
3150 to 3350	1332	213	31	31	0	0	151	930	0	123	7291	10071
3350 to 3550	1277	79	161	0	0	0	0	809	0	0	6068	8233
3550 to 3750	1327	161	1327	0	0	0	0	830	0	0	8643	10961
3750 to 3950	1421	287	0	0	0	0	0	1037	0	123	3727	6595
3950 to 4350	3478	473	0	0	0	0	0	2910	0	0	350	7211
4350 to 4750	4253	396	0	0	0	0	0	810	0	0	0	5459
4750 to 5150	6250	762	0	0	0	0	0	114	0	0	0	7126
5150 to 5550	3488	940	0	0	0	0	0	0	0	0	0	4428
5550 to 5950	878	264	0	0	0	0	0	0	0	0	0	1142
5950 to 6350	102	0	0	0	0	0	0	0	0	0	0	102
6350 to 6750	25	0	0	0	0	0	0	0	0	0	0	25

*Areas are in units of 100 km².

*The world total continental area above -200 m is 171.349 Mm². This is slightly different from the value in Table 5 because these numbers were generated by using the half degree square average elevations where they were available, whereas the data in Table 5 were generated using the 1-degree-square average elevations everywhere.

Appendix B

This section contains a discussion of the errors involved in determining the hypsographic curves. On the DMA tape, there is a number for each 1° square, which is the estimate of the accuracy with which the average elevation can be determined for that square. This number depends partly on the availability of information for the elevation within that 1° square, and partly on the complexity of the contours in the 1° square. If the contours are very complex, or if there are large changes of elevation within the square, it is more difficult to estimate the average elevation from the information available. Since most of the information concerning the continental elevations is contained at the lower elevations, we have calculated average errors for each continent, for degree squares which were less than 1.15 km in elevation. These unweighted averages are shown in Table B1. It can be seen that the continents with the best known topography are North America and Europe. Of the other major land areas, Africa is surprisingly well known, whereas South America is the least well known.

There is a tendency for the information to be most accurate at low positive elevations above sea level. This is illustrated in Table B2. In this table, the error data from each fragment have been normalized to the average error for that continent, and average errors have been established for each elevation interval by using the information from all the fragments listed in Table B1. Table B2

Table B1 Mean Errors for Ice Free Continents*

Continent	Mean Error, m	Number of Squares
Asia	32	6778
India	26	412
Arabia	31	644
Africa	28	5612
Madagascar	252	55
North America	16	6583
South America	97	1606
Europe	21	2115
Australia	53	972

Calculated for all squares with average elevation less than 1.15 km.

TABLE B2 Mean Error as a Function of Elevation

Elevation, m	Mean Error	Number of Squares
-200 to -150	1.75	531
-150 to -50	1.48	1857
-50 to 50	1.38	3525
50 to 150	0.73	3307
150 to 250	0.76	3013
250 to 350	0.76	2926
350 to 450	0.74	2433
450 to 550	0.83	1997
550 to 650	0.88	1441
650 to 750	0.98	983
750 to 850	1.13	836
850 to 950	1.42	706
950 to 1050	1.41	694
1050 to 1150	1.39	528

Mean error is normalized by the average error for each continent.

shows that the elevations of areas below sea level are less well determined than those above sea level. The best determined elevations lie between 50 and 450 m. There is also a degradation of information at higher elevations.

It is obvious that of the major fragments, the hypsographic curve for South America is liable to be least accurate. Not only is the average error largest, but also the number of data points is relatively small. A simple set of Monte Carlo trials revealed that the standard deviation in the median value for a set of areas whose true heights were equally distributed at 2 per meter, but which were misplaced with a standard deviation of 100 m was 6.6 m. For North America, with about 5 areas per meter elevation and an error of only 16 m for the placement of each individual area, the error on the median elevation is only 0.7 m.

The mean elevations will be considerably more accurate, since they depend on errors of a few tens to several hundred meters in a large number of individual areas. Thus even for Madagascar, with an average individual error of 250 m, the error in determining the mean elevation of this fragment is only 34 m. For all other fragments it is much less, both because the individual errors are much smaller and also because the numbers of 1° squares are much greater.

Errors of any nature are likely to

reduce the peak of the modal elevation. This can be easily demonstrated, because if all the true elevations of the individual areas were within one elevation range, errors in placing them in their correct elevation range would cause some to fall outside the proper elevation range, whereas there would be none from neighboring elevation ranges to take their places. Alternatively, with a completely smooth differential hypsographic curve, errors will produce some variations in this.

The data from Greenland show a roughly constant error of about 50 m. But the Rand tape, from which we obtained information on Antarctica, had no estimates of error, so that we are somewhat in the dark concerning how accurate the hypsographic curve for Antarctica is.

It is obvious that much more information about continental elevations would be useful. For satellite gravity observations, it is necessary to have topography accurate to about 10 m over wavelengths appropriate for the satellite elevation. It is hoped that altimetric satellites can eventually be used to obtain this information.

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