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THE GLOBAL WATER CYCLE AND CONTINENTAL EROSION DURING PHANEROZOIC TIME (570 my)

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ABSTRACT. A sensitivity study is conducted to determine what effect two specific mechanisms, namely continental size and latitudinal location might have on the global water cycle. The global water cycle over Phanerozoic time (570 my) is established first by analyzing the distribution of rainfall (P), evaporation (E), and runoff (D), by bands of 10° of latitude, on the Present-day Earth and then applying these values to the ancient Phanerozoic world. In this backward projection, the global cosmic, climatic, and orographic conditions prevailing today, are supposed constant through time, while the only variable parameter controlling the system are the latitudinal positions of the continents and the relative area of continents and oceans.

The calculated Phanerozoic global runoff clearly shows that the humid periods are the Cretaceous (100 my), the Devonian-Silurian (400 my), and the Cambrian (500 my), while the dry periods are close to the Present-day (0 my), and the Permo-Triassic (200 my). The continental global runoff together with the survival rate of the volcanics are used to predict the fluctuations of the isotopic ratio $^{87}Sr/^{86}Sr$ in marine sediments. Predicted and measured values appear to be in good agreement (except for the Present) which somewhat validate the calculations. The continental runoff is also related to the sedimentation rate and is used to estimate the specific erosion rate of the continents through the Phanerozoic. Thus the sedimentation rate variations are understood as a consequence of the continental runoff fluctuations through time.

INTRODUCTION:
THE GLOBAL WATER CYCLE AT THE PRESENT DAY

Size of the reservoirs.—Most of the water in the hydrosphere is contained in the oceans and seas (13,700 10^{20}g or 1370 10^6 km^3, according to Garrels and Mackenzie, 1971; or Berner and Berner, 1987; 13,480 10^{20}g, according to Baumgartner and Reichel, 1975). Estimates for ground water and lakes differ between authors (see the evolution from Kossina, 1933; Meinardus, 1934; Hutchinson, 1957; Nace, 1967; Peixoto and Kettani, 1973; Garrels, McKenzie, and Hunt, 1975; Turekian, 1976; Ambroggi, 1977; to Berner and Berner, 1987) (table 1).

The present day water fluxes between reservoirs.—For the past several years, the global water fluxes estimates have varied between authors (Albrecht, 1960; Budyko, 1963; Mira Atlas, 1964; Budyko, 1970; L'Vovitch, 1970, 1973; Garrels and Mackenzie, 1971a; Unesco, 1978; Drever, 1982; Berner and Berner, 1987). The data selected here are those of Baumgartner and Reichel (1975). They are precise and are given in detail, latitude by latitude.

TABLE 1

Size of reservoirs in the present-day hydrosphere (10^{20}g)

Reservoirs	(1)	(2)	(3)	(4)
Oceans	13,700	13,480	13,380	13,700
Ground waters	3,300	81	234	95
Ice	200	278	240	290
Rivers and lakes	0.3	2.25	1.89	1.27
Atmosphere	0.13	0.13	0.13	0.13
Total	17,200	13,841	13,856	14,087

Garrels and Mackenzie (1971), (2) Baumgartner and Reichel (1975), (3) Unesco (1978), (4) Berner and Berner (1987)

Six terms describe the major fluxes between the Earth's surface reservoirs: (1) evaporation over the oceans (4.247 10^{20}g yr^{-1}), (2) precipitation onto the oceans (3.850 10^{20}g yr^{-1}), (3) the difference between marine evaporation and precipitation (0.397 10^{20}g yr^{-1}), (4) evaporation on land (0.714 10^{20}g yr^{-1}), (5) precipitation on land (1.11 10^{20}g yr^{-1}), (6) continental runoff (0.397 10^{20}g/yr^{-1}) (Baumgartner and Reichel, 1975). To conserve total water on a global scale, the excess of evaporation over the ocean (0.40 10^{20}g yr^{-1}) is equal to the excess of rainfall over land and is also equal to the global continental runoff (0.40 10^{20}g yr^{-1}) (table 2).

Holospheric distribution of evaporation and precipitations over the oceans.—The word holospheric means latitude by latitude. The Present-day distribution of precipitation (P), evaporation (E), and precipitation excess (D = P − E), over the oceans, for different degrees of latitude, are given in table 3 and in figure 1.

The world averages for rainfall, evaporation, and precipitation exess over the oceans are approximately equal to those for latitude 42° (N and S), while the weighted average position in latitude of the ocean is 8°S.

Over the oceans, precipitation is higher than evaporation except between 10° and 40° of latitude N and S. Around the sub-tropical

TABLE 2

Global water fluxes between reservoirs (10^{20}g yr^{-1})

	(1)	(2)	(3)
Evaporation over oceans	3.830	4.247	4.230
Precipitation over oceans	3.470	3.850	3.860
Excess evaporation	0.360	0.397	0.370
Evaporation over continents	0.630	0.714	0.730
Precipitation over continents	0.990	1.111	1.100
Excess precipitation	0.360	0.397	0.370
Global continental runoff	0.36	0.40	0.37

(1) Garrels and Mackenzie (1971), (2) Baumgartner and Reichel (1975), Berner and Berner (1987)

TABLE 3

Holospheric distribution of oceanic area (10^3 km^2), mean precipitation (P, mm/yr), mean evaporation (E, mm/yr), and mean precipitation excess (D = P − E, mm/yr) over oceans from Baumgartner and Reichel (1975). Mean sea surface temperatures (T, °C) are adapted from Lamb (1977)

Latitudes °N-S	Area (10^3 km^2)	Temperature T (C°)	Precipitation P (mm)	Evaporation E (mm)	Precipitation excess D (mm)
0-10°	67,658	26.8	1,606	1,367	239
10-20°	64,913	25.6	1,157	1,607	−450
20-30°	56,021	22.5	784	1,557	−773
30-40°	53,082	17.1	915	1,319	−404
40-50°	45,569	10.2	1,164	899	265
50-60°	36,632	4.3	1,066	578	486
60-70°	22,669	0.2	615	308	307
70-80°	11,356	−0.9	260	141	119
80-90°	3,518	−1.7	52	39	13
Total	361,110	17.3	1,066	1,176	−110

latitudes (23°27′) evaporation is much more important than precipitation (P < E), so that the global excess over the oceans is negative (D = P − E < 0).

The global total excess of evaporation over the oceans is calculated as follows:

$$361{,}110\ (10^3\ km^2) \times 110\ mm/yr = 0.397\ 10^{20} g/yr.$$

The oceanic sub-tropical latitudes provide most of the excess of evaporation and most of the water precipitation over the continents.

Holospheric distribution of evaporation, precipitation, and runoff over the continents.—The distribution of precipitation (P), evaporation (E), and precipitation excess (D = P − E) over the continents, for different degrees of latitude are given in table 4 and in figure 1. The relationship between precipitations and evaporations is given in figure 2.

Over the continents, precipitation is higher than evaporation. The difference is equal to the continental runoff. The continental runoff increases from the sub-tropical latitudes (124 mm, at 30°–40°) toward the equator (713 mm, at 0°–10°) and toward the temperate regions (269 mm, at 50°–60°). Farther north, it decreases from 50° to 60° to the polar regions. The smallest runoff is observed above the polar regions (64 mm) and around the sub-tropical latitudes (124 mm) as well (table 4). In desert areas, evaporation tends to equalize the rainfall, and as a consequence the continental runoff tends to zero. In the humid zones, the runoff increases with precipitation. For a given amount of rainfall, the evaporation is greater at higher temperature and smaller for lower temperature, so that the runoff is more important in temperate regions than in tropical zones (fig. 3). However, in figure 3, the regions for which rainfall greatly exceeds evaporation correspond to peculiar situations such as the horns of Africa and South America. They

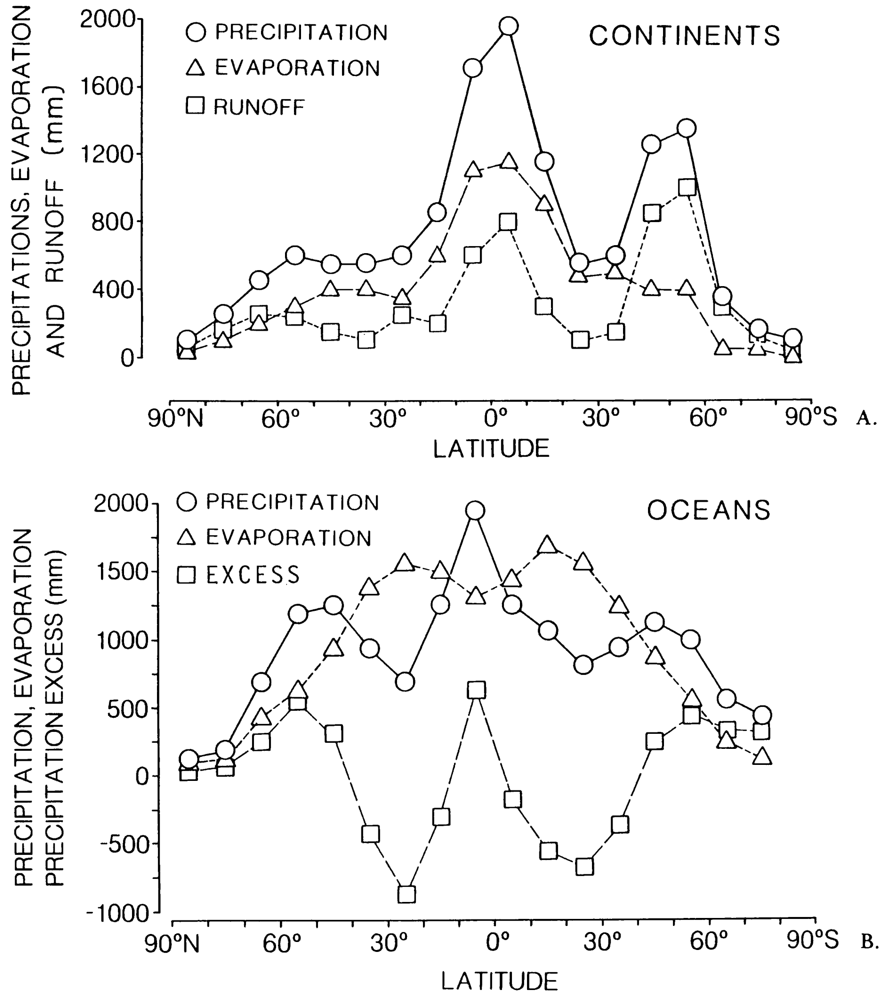


Fig. 1. Holospheric distribution of precipitation (P, mm/yr), evaporation (E, mm/yr) and excess or runoff (D, mm/yr) over the oceans and the continents after Baumgartner and Reichel (1975). Runoff (or excess over the oceans) is the difference between precipitation and evaporation (D = P-E).

will not be taken into consideration in our calculations. As an average, the total global difference between precipitation and evaporation, over the continents, that is; the global runoff is calculated as follows:

$$148{,}904\ (10^3 km^2) \times 267\ (mm/yr) = 0.397\ 10^{20} g/yr.$$

The global runoff flux is set equal to the flux of excess of evaporation over the oceans and to the flux of excess rainfall over the continents.

TABLE 4

Holospheric distribution of continental area (10^3 km^2), mean precipitation (P, mm/yr), mean evaporation (E, mm/yr), and runoff (D, mm/yr) from Baumgartner and Reichel (1975), mean elevations (m) are from NCAR (Boulder, USA). Mean temperatures (T, °C) are calculated from Spangler and Jenne (1984)

Latitudes °N-S	Area (10^3 km^2)	Temperature T (C°)	Elevation (m)	Precipitation P (mm)	Evaporation E (mm)	Runoff D (mm)
0-10°	20,502	24.9	499	1,836	1,123	713
10-20°	20,660	24.2	620	984	733	251
20-30°	24,398	21.7	689	594	408	186
30-40°	19,736	14.6	1,182	551	427	124
40-50°	17,440	6.5	715	574	381	193
50-60°	14,894	0.8	427	589	320	269
60-70°	15,140	−8.9	556	422	183	239
70-80°	11,824	−31.2	1,176	189	50	139
80-90°	4,310	−41.1	2,299	80	16	64
Total	148,904	8.5	815	746	480	266

Relationship between continental runoff and rainfall.—From the data of figure 3, one can derive a simple polynomial equation that permits evaluation of continental runoff (D, mm/yr) as a function of rainfall (P, mm/yr) over the continents:

$$D = -6.022\ 10^{-11}\ P^4 + 3.83\ 10^{-7}\ P^3 - 5.90\ 10^{-3}\ P^2 + 5.41\ 10^{-1}\ P \quad (1)$$

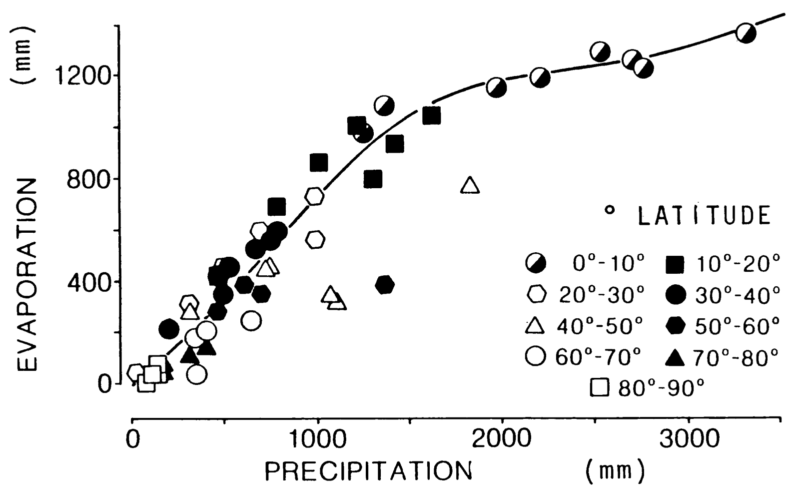


Fig. 2. Relationship in different bands of latitude between holospheric evaporation (E, mm/yr) and precipitation (P, mm/yr) over the continents, after Baumgartner and Reichel (1975). Evaporation over land increases when precipitation increases.

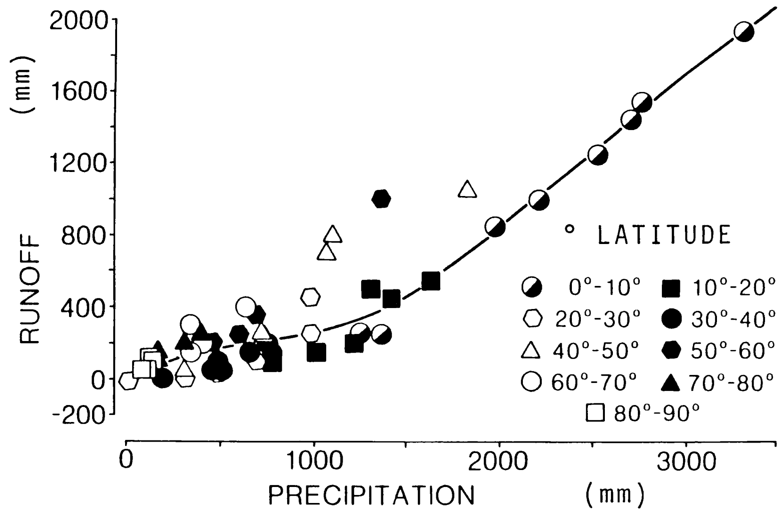


Fig. 3. Relationship between the holospheric continental runoff (D, mm/yr) and precipitation (P, mm/yr) over the continents, calculated from Baumgartner and Reichel (1975). Runoff over land also increases with precipitation.

with a correlation coefficient: R = 0.986 for 46 observations considered.

Continental rainfall as a function of continental area.—The holospheric distribution of the Present-day continental and oceanic areas as a function of latitude is given in figure 4. The number of continents and the average continental area are variable from the poles to the equator. It is clear that at the mid-latitudes of the northern hemisphere the continental area is large, and the number of continents is relatively low. For that reason, among others, the climate is relatively arid (for example, Central Asia), and the amount of rain received at these latitudes is rather small.

At a given latitude, the rainfall tends to decrease when the continental area tends to increase (fig. 5). Furthermore the slopes of the regression lines expressing the relationship between rainfall and continental area depend on latitude. At low latitudes (0°-10°) the slope of the linear function is negative and high (−0.28); the decrease is steep. On the contrary, the slopes of the regression straight lines are very small and negative at high latitudes (−0.01) or even positive near the tropics as well (0.02) (table 5). This simply says that the decrease in precipitation with the distance from the continental coasts is more effective in the regions of high rainfall than it is in regions of small rainfall. The influence of the distance from the coast is smaller in the arid regions of low rainfall (poles and sub-tropics). Furthermore, the ordinate at the origin may be regarded as the rate of precipitation over the continents

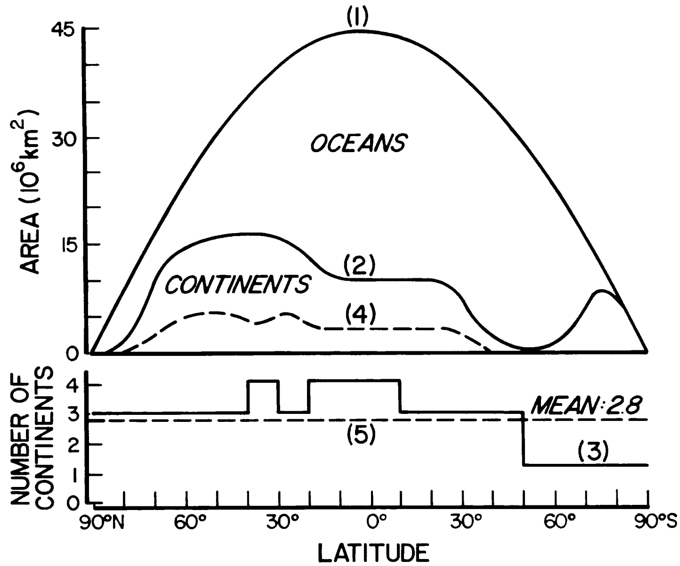


Fig. 4. Present-day holospheric distribution of continental and oceanic areas (1)—Earth area, (2)—continental area, (3)—number of continents, (4)—average area of continents [ratio between (2) and (3)], (5)—average number of continents.

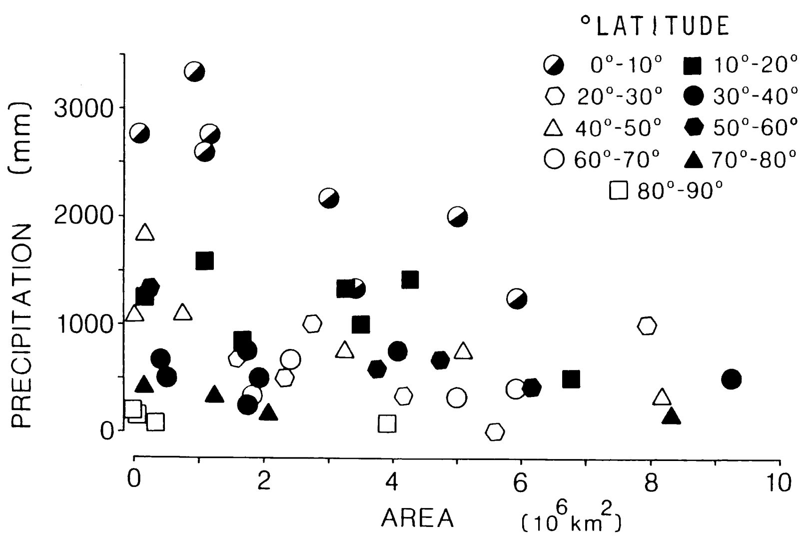


Fig. 5. Relationship between rainfall (P, mm/yr) and continental area ($10^6 km^2$) as a function of latitude. At a given latitude, rainfall decreases when continental area (average distance from seashore) increases; in each portion of latitude the decrease is linear (see table 5). Data are from Baumgartner and Reichel (1975).

TABLE 5

Regression straight lines showing the dependence of precipitation (P, mm/yr) as a function of continental area (A, 10^6 km^2) for all the latitudinal zones, calculated from the data of Baumgartner and Reichel (1975). Generally precipitation (P) decreases when continental area (A) increases

Latitude	Equation of the Linear Regression
0-10°	$P = -0.28\ 10^{-3} A + 3009$
10-20°	$P = -0.09\ 10^{-3} A + 1413$
20-30°	$P = 0.002\ 10^{-3} A + 582$
30-40°	$P = 0.0019\ 10^{-3} A + 562$
40-50°	$P = -0.12\ 10^{-3} A + 1344$
50-60°	$P = -0.15\ 10^{-3} A + 1353$
60-70°	$P = -0.20\ 10^{-3} A + 522$
70-80°	$P = -0.02\ 10^{-3} A + 325$
80-90°	$P = -0.01\ 10^{-3} A + 139$

in the coastal areas (which can be different from the amounts of precipitation over the oceans, at the same latitude (see tables 3 and 5).

Continental rainfall as a function of elevation.—Elevation may also be taken into consideration. Nevertheless any clear relationship between rainfall and elevation could not be shown (fig. 6). Furthermore, when

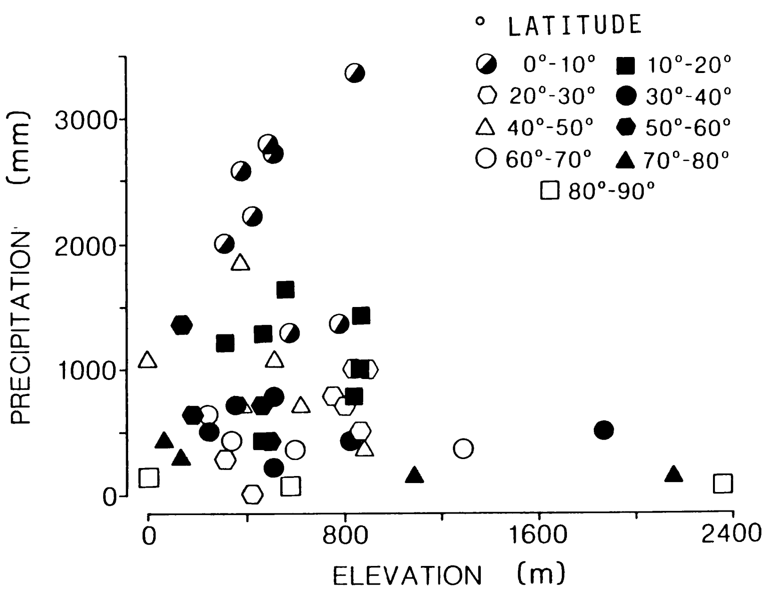


Fig. 6. Relationship between rainfall and elevation as a function of latitude. From Baumgartner and Reichel (1975) and NCAR (Boulder, USA). At a global scale, there is no relationship between land elevation and rainfall.

introducing elevation (H) in the linear relationships correlating rainfall (P, mm/yr) with continental area (A, 10^6 km^2), such as those given in table 5:

$$P\,(mm/yr) = a\,A\,(10^6\,km^2) + bH\,(m) + C \qquad (2)$$

the coefficient b appears as insignificantly small, compared to the coefficient a. Thus introduction of elevation does not improve the correlation coefficient of the regression.

Furthermore as already pointed out by many authors (see Garrels and Mackenzie, 1971) there is a direct relationship, at a continental scale, between mean continental elevation and continental area. Thus, elevation is implicitly taken into consideration when one wishes to explain the amount of rain as a function of continental area. Consequently at a global scale, the influence of elevation on rainfall will be considered for our purpose as not significant.

THE GLOBAL WATER CYCLE DURING THE PHANEROZOIC

During Phanerozoic time, continents moved over the surface of the Earth. Sometimes, they were separated (Cambrian), sometimes agglomerated to form Pangea (Permian, Triassic), and sometimes sepa-

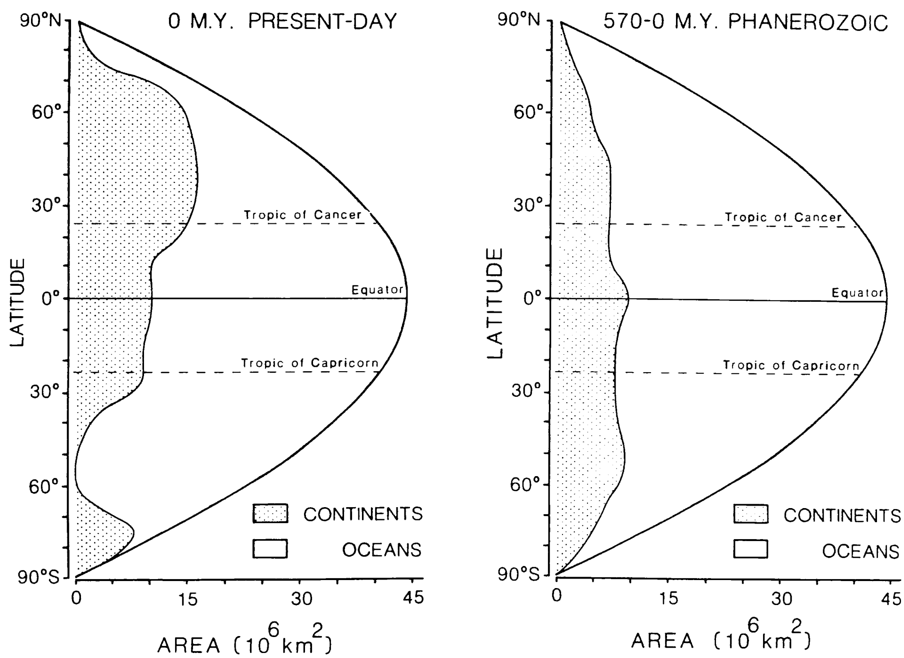
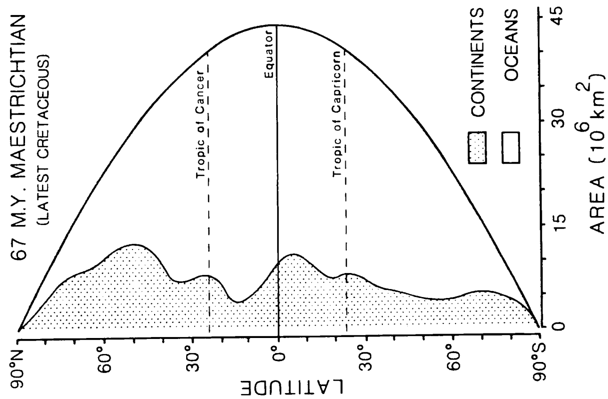
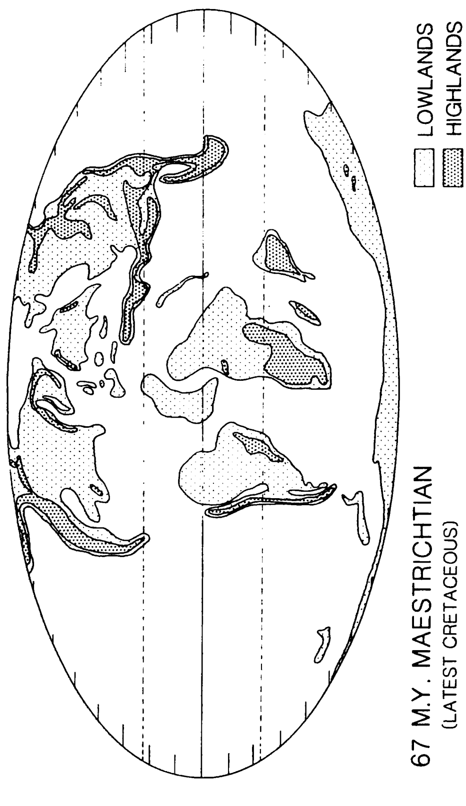


Fig. 7. Holospheric distribution of continental and oceanic areas for the Present-day and the average for the whole Phanerozoic.


67 M.Y. MAESTRICHTIAN
(LATEST CRETACEOUS)
Tropic of Cancer
Equator
Tropic of Capricorn
CONTINENTS
OCEANS
90°N
60°
30°
0°
30°
60°
90°S
LATITUDE
0
15
30
45
AREA (10^6 km^2)


LOWLANDS
HIGHLANDS
67 M.Y. MAESTRICHTIAN
(LATEST CRETACEOUS)

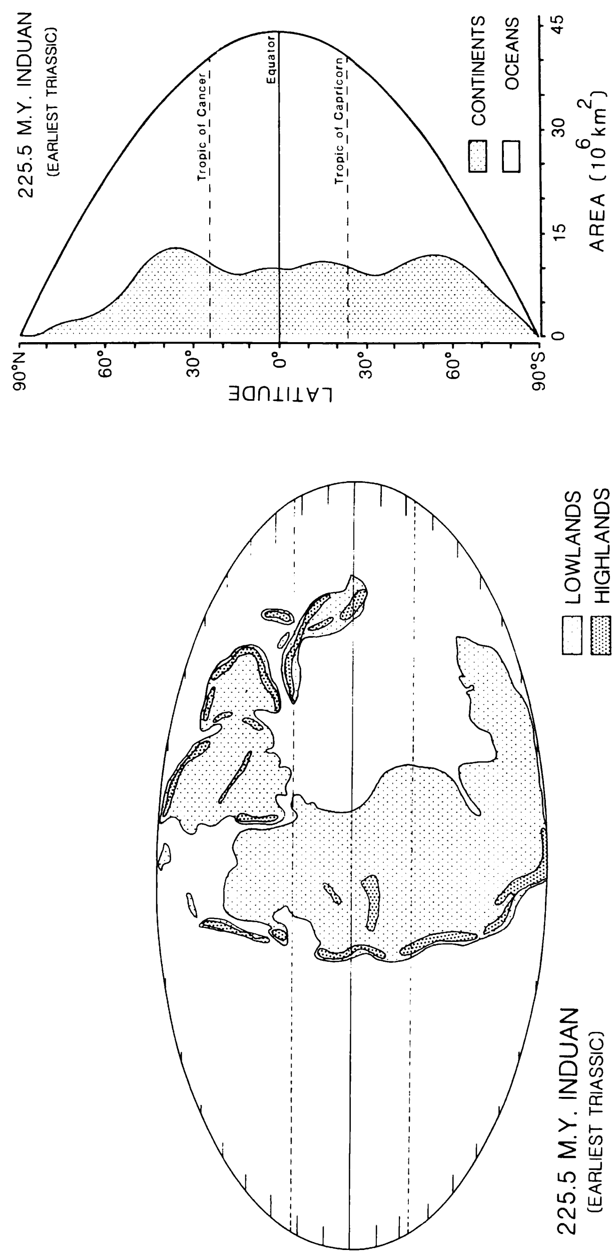


Fig. 8. Position of the continents and holospheric distribution of the continental areas at different geologic times. Redrawn and calculated from Scotese and others (1979) and Parrish, Ziegler, and Scotese (1982). (continued, p. 466)

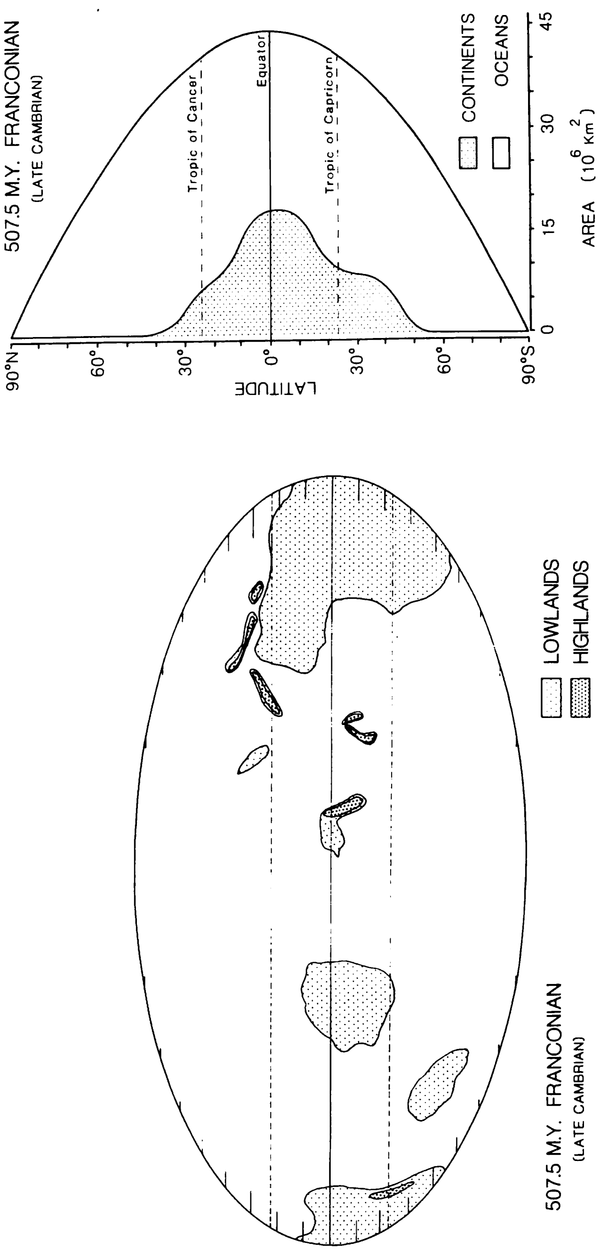


Fig. 8. (continued)

rated again (Cretaceous). Also they shifted in latitude so that they were located close to the South pole (Ordovician), to the North pole (Quaternary), to the equator (Cambrian), to both the equator and the temperate latitudes (Cretaceous), or to the sub-tropical latitudes (Triassic) (Scotese and others, 1979; Bambach, Scotese, and Ziégler, 1980; Mackenzie and Pigott, 1981; Barron and others, 1981; Parrish, 1982; Parrish, Ziegler, and Scotese, 1982). As a result, the number of continents, the continental area, and the relative latitudinal distribution of continents and oceans have been modified through time (figs. 7 and 8). As a result, the global climate has been changing too.

On the basis of the holospheric water balance for the oceans and the continents, characterizing the present day world, one may determine the rainfall, latitude by latitude (fig. 9) for the different continental situations observed during the last 600 my. Thus, holospheric rainfall data (mm/yr) available for the present-day are first corrected to take into consideration the changes of holospheric continentality through time, that is, the change of the continental area 10° of latitude by 10° of latitude through the Phanerozoic. Furthermore, the values obtained for the holospheric paleorainfall were used in order to calculate the continental runoff (mm/yr) from eq (1).

It is clear that, in our first order approximation model, we assume constancy of latitudinal distribution of climate, constancy of total CO_2 content in the atmosphere, et cetera. Only two specific mechanisms, namely continental size and latitudinal location are considered here.

Corrections for land surface area, through the Phanerozoic.—Land surface areas were measured on the paleomaps published by Scotese and

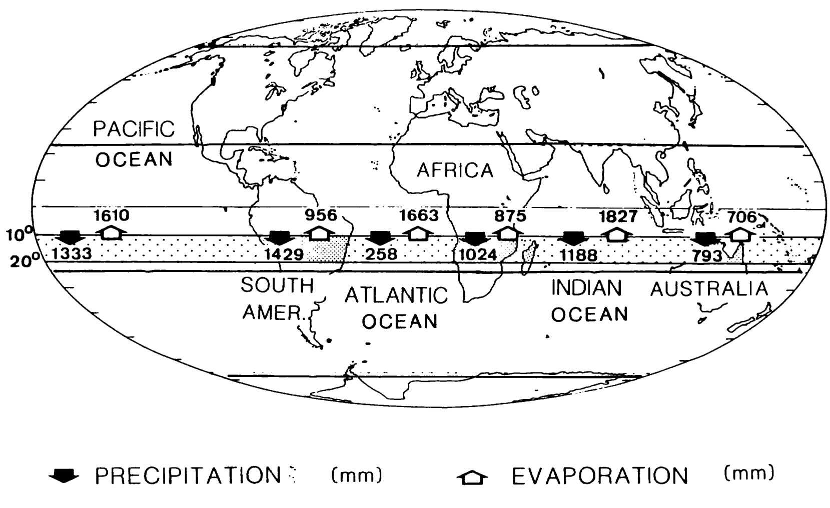


Fig. 9. An example of calculation of the global water balance at a given latitude (here 10°–20° S). From N'Kounkou (1989) and Probst (1989).

others (1979), Parrish, Ziegler, and Scotese (1982) and compared to those of Ronov and others (1980), Ronov (1982a, b) and Budyko, Ronov, and Yanshin (1985). The observed total paleoland area (A, $10^3 km^2$) has been found to decrease exponentially as a function of time (t, my):

$$A(t) = \exp(-0.00122 \times t + 11.941)$$
$$= 1.534 \times 10^5 \exp(-122\ 10^{-5} t) \quad (3)$$

probably for the same reasons as the one invoked by Garrels and Mackenzie (1971a) for the evolution of the sedimentary mass of sediments. In other words, as one progresses toward ancient times, information and continental contours are progressively lost, and consequently one can assume a constant average but fluctuating land area. Thus, for each age, the observed land area above sealevel is corrected by the same factor as the one used to transform the exponential regression line into an horizontal line (fig. 10). The recalculated land area fluctuates through time, and one distinguishes clearly two periods of rifting and high sealevel (450 and 100 my) separated by three periods of continental agglomeration and low sealevel (600 my, 200 my, and the Present-time) (Mackenzie and Pigott, 1981).

The global water cycle during the Phanerozoic.—For each of the geological periods we calculated the holospheric distribution of land

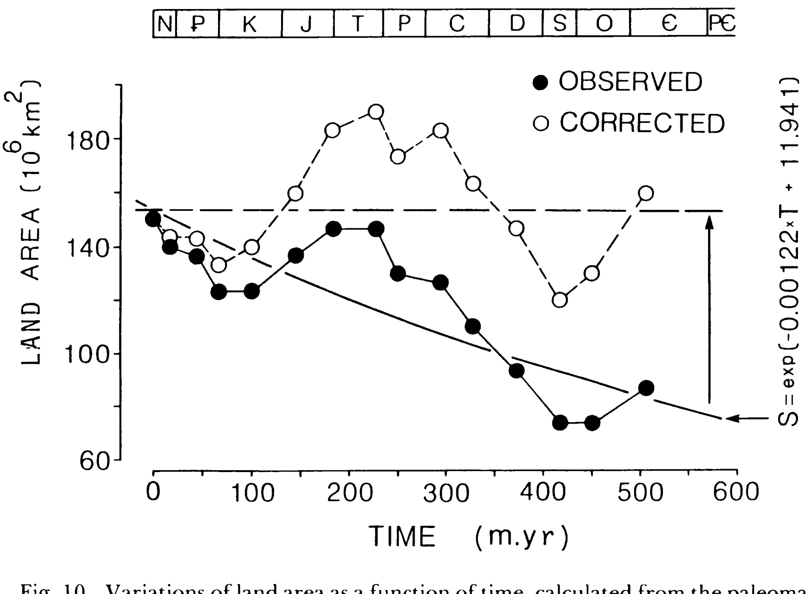


Fig. 10. Variations of land area as a function of time, calculated from the paleomaps of Scotese and others (1979) and Parrish, Ziegler, and Scotese (1982).

area by 10° latitude zones. The global runoff ($D^{\circ}_{c,t}$, 10^{20}g/yr) for each period t was obtained by summing the individual runoff ($D_{i,t}$, mm/yr) for each latitude zone (i) multiplied by the corresponding area ($A_{i,t}$) of the continent in this zone and at that time (table 6):

$$D^{\circ}_{c,t} = \sum_{i} D_{i,t} \times A_{i,t}. \tag{4}$$

Then the value of $D_{c,t}$ is recalculated to take into consideration the correction for area, that is, the ratio between the measured (A_t°) and the corrected continental area (A_t) (eq 3):

$$D_{c,t} = D^{\circ}_{c,t} \times A_t/A_t^{\circ}. \tag{5}$$

Finally the values of $D_{c,t}$ (10^{20}g/yr) are interpolated linearly between the ages selected by Scotese and others (1979) and Parrish, Ziegler, and Scotese (1982), in order to characterize the mean age of each of the geological periods (table 6; fig. 11).

$D_{c,t}$ (10^{20}g/yr) is the continental runoff calculated from the data available for continents only. However, at a global scale the continental runoff (D_c) should be equal to D_o, the excess of evaporation over rainfall for the oceans ($D_c = D_o$). The oceanic evaporation excess D_o, calculated by using the same procedure as that followed for D_c, is given in table 7 and compared to D_c in fig. 11. $D_m = (D_c + D_o)/2$ is the average, also given in figure 11. It appears clearly that D_c and D_o (which are equal for the Present-day) are close to each other for the latest 300 my but progressively separate for the earliest 300 my during which the relative position of continents and oceans largely differs from the one presently observed. However, the process we have followed for evaluating D_c permits some general comments and shows some trends in which one can have some trust.

Note that the geological periods characterized by a high runoff value are the Cretaceous (100 my), the Silurian, and the Devonian (400 my). On the contrary, the lowest values are those of the Present-day (0 my) and the Triassic (200 my). For the Cambrian (550 my) results are uncertain and do not permit us to tell if at that time the global runoff was greater or smaller than during the Devonian or Carboniferous.

The examination of table 6 shows that during the Cambrian both rainfall (P_c = 1124 mm/yr) and evaporation (E_c = 725 mm/yr) should have been the highest of the Phanerozoic. This is because the continents were located close to the Equator. For this reason we think that probably D_o is underestimated and D_c is probably closer to the reality. This is also what is suggested by examination of the fluctuations of $^{87}Sr/^{86}Sr$ isotopic ratio in Phanerozoic marine carbonates.

FLUCTUATIONS OF THE ISOTOPIC RATIO $^{87}Sr/^{86}Sr$ IN MARINE CARBONATES

The $^{87}Sr/^{86}Sr$ ratio in marine carbonates of a given age is considered as equal to the isotopic ratio of seawater at the same time. The

TABLE 6

The global water cycle through Phanerozoic time. The continental global the continental global runoff (D_C, $10^{20}g/yr$) are calculated by using the at a global scale, should be equal to the continental runoff by using the

	Time Mid Duration		Area Continental		Area Oceanic	
	Age (my) (1)	(my) (2)	Measured (10^3km^2) (3)	Corrected (4)	Measured (10^3km^2) (5)	Corrected (6)
Present	0.0	0.0	148,904	148,904	361,110	361,110
Cenozoïc	34.0	68.0	137,682	143,132	372,332	366,882
Cretaceous	99.0	62.0	124,881	140,450	385,133	369,564
Jurassic	153.5	47.0	140,938	170,337	369,076	339,677
Triassic	201.0	48.0	145,903	187,121	384,111	322,893
Permian	252.5	55.0	129,024	175,077	380,990	334,937
Carboniferous	311.0	62.0	122,827	177,697	387,187	332,317
Devonian	371.0	58.0	98,220	152,426	411,794	357,588
Silurian	420.0	40.0	76,338	124,993	433,676	385,021
Ordovician	470.0	60.0	76,024	131,600	433,990	378,414
Cambrian	550.0	100.0	86,740	159,321	423,274	350,693

(1) and (2) are respectively mid-age and duration from Afanasseyev and Zykov (1975). (3) and (5) land area and oceanic area (10^3km^2) measured from Scotese and others (1979), and Parrish, Ziegler and Scotese (1982). (4) Continental area (10^3km^2) corrected by eq (3). (6) oceanic area (10^3km^2) calculated from the difference 510014-(5).

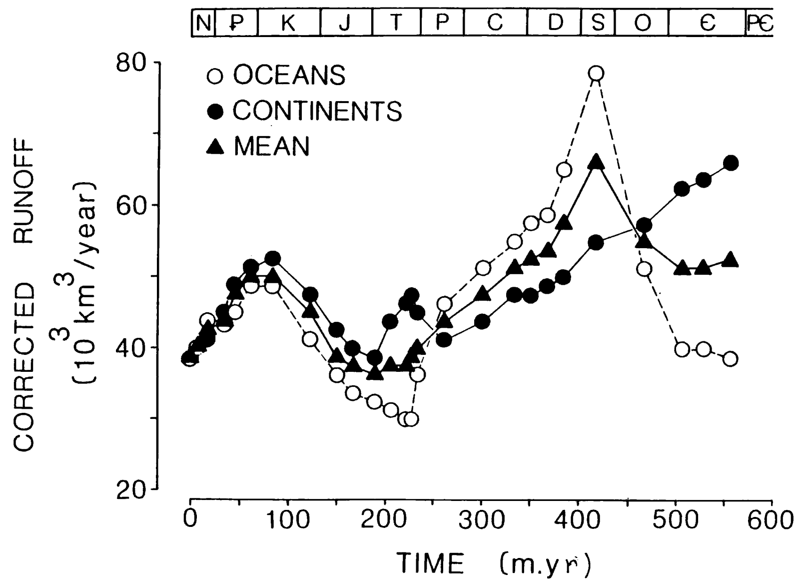


Fig. 11. The global continental runoff (D_c) during Phanerozoic time (last 600 my). D_c, D_o, D_m are respectively continental runoff, oceanic evaporation excess, and the average calculated runoff (D_m = (D_c + D_o)/2).

TABLE 6 *(Continued)*

rainfall (P_C, $10^{20}g/yr$), the continental global evaporation (E_C, $10^{20}g/yr$) and corrected continental area. The oceanic excess of evaporation (D_O, $10^{20}g/yr$), corrected area.

Continental rainfall		Continental evaporation		Continental runoff		Oceanic evaporation excess	Average runoff
Pc (mm/yr) (7)	Pc (10^{20}g/yr) (8)	Ec (mm/yr) (9)	Ec (10^{20}g/yr) (10)	Dc (mm/yr) (11)	Dc (10^{20}g/yr) (12)	Do (10^{20}g/yr) (13)	Dm (10^{20}g/yr) (14)
746	1.11	480	0.71	266	0.40	0.40	0.40
843	1.21	523	0.75	320	0.46	0.44	0.45
870	1.22	509	0.71	361	0.51	0.47	0.48
625	1.06	386	0.66	239	0.41	0.35	0.37
601	1.12	370	0.69	231	0.43	0.31	0.37
592	1.04	359	0.63	233	0.41	0.45	0.43
570	1.01	320	0.57	250	0.44	0.51	0.48
683	1.04	360	0.55	323	0.49	0.57	0.53
811	1.01	373	0.47	438	0.55	0.76	0.66
1,066	1.40	627	0.83	439	0.58	0.55	0.56
1,124	1.79	725	1.15	399	0.64	0.39	0.51

(7), (9), and (11) rainfall (P_c) evaporation (E_c) and drainage (D_c). (12) the fluxes (10^{20}g/yr) of rainfall (P_c) evaporation (E_c) and drainage (D_c), the global runoff over the continents. (13) Oceanic excess evaporation flux (D_o) (10^{20}g/yr), and (14) the average runoff flux ($Dm = (D_c + D_0)/2$, 10^{20}g/yr)

curve of figure 12 shows that this isotopic ratio has varied through time between 0.7070 and 0.7090 (Faure, 1982). These fluctuations are in fact due to variations among the relative contributions of strontium coming to the ocean from (1) the reactions between basalt and seawater on the ocean floor and (2) from weathering on the continents (Peterman, Hedge, and Tourtelot, 1970; Clauer and Tardy, 1971; Brevart and Allegre, 1978; Veizer and Compston, 1974; Clauer, 1976; Brass, 1976; Tremba and others, 1975; Faure, Asserto, and Tremba (1978); Kovach, 1980; Albarède and others, 1981; Burke and others, 1982; Faure, 1982; Veizer and others, 1983; Albarède and Michard, 1987; Tardy, 1986).

^{87}Sr is radiogenic strontium generated by the decay with time of ^{87}Rb or radioactive rubidium. Rubidium is abundant in granites and in potassium-rich rocks, while it is of much lesser abundance in basalts and potassium-poor rocks. Consequently, as an average, the $^{87}Sr/^{86}Sr$ isotopic ratio in basalts is low (0.7040) while it is high (0.7200) in granitic rocks, sandstones, shales, et cetera. Roughly the average $^{87}Sr/^{86}Sr$ isotopic ratio characterizing seawater of the Phanerozoic (0.7080) is in part (75 percent) due to basalt seawater interaction and in part due to weathering (25 percent):

$$0.708 = 0.75 \times 0.7040 + 0.25 \times 0.720. \qquad (6)$$

As a consequence of steady state, the $^{87}Sr/^{86}Sr$ isotopic ratio in seawater tends to decrease (1) when the seafloor spreading rate tends to increase and when the global tectonic activity rises, and/or (2) if the

TABLE 7

Corrected continental area ($10^3 km^2$), continental runoff ($10^{20} g/yr$), mass of (the present day abundance of rocks of a given age span, divided by the and erosion rate ($tons/km^2/yr$ of mg/l)

Systems	Duration (my)	Age (my)	Continental area ($10^3 km^2$)	Continental area ($10^3 km^2$)	Continental runoff ($10^{20} g/yr$)	Continental runoff ($10^{20} g/yr$)
References	(1)	(2)	(3)	(4)	(5)	(6)
Present	0	0	148,904	148,904	0.397	0.397
Cenozoic	66	33	136,826	143,132	0.440	0.457
Cretaceous	66	99	124,881	140,450	0.450	0.507
Jurassic	53	159	140,938	170,337	0.336	0.406
Triassic	50	210	145,903	187,121	0.336	0.432
Permian	45	258	129,024	175,077	0.301	0.409
Carboniferous	65	313	122,827	177,679	0.306	0.443
Devonian	55	373	98,220	152,426	0.317	0.492
Silurian	35	418	76,338	124,993	0.334	0.547
Ordovician	55	463	76,024	131,600	0.334	0.578
Cambrian	80	530	86,740	159,321	0.345	0.634

(1) Durations and (2) mean-age of the geological periods (my) from Afanasseyev and Zykov (1975). Continental area ($10^3 km^2$). (3) measured from Scotese and others (1979) and Parrish, Ziegler and Scotese (1982), and (4) corrected in this paper. Continental runoff (DG_t, 10^{20} g/yr) (5) calculated from the measured continental area given in column 3 or (6) calculated from the corrected continental area given in column 4.

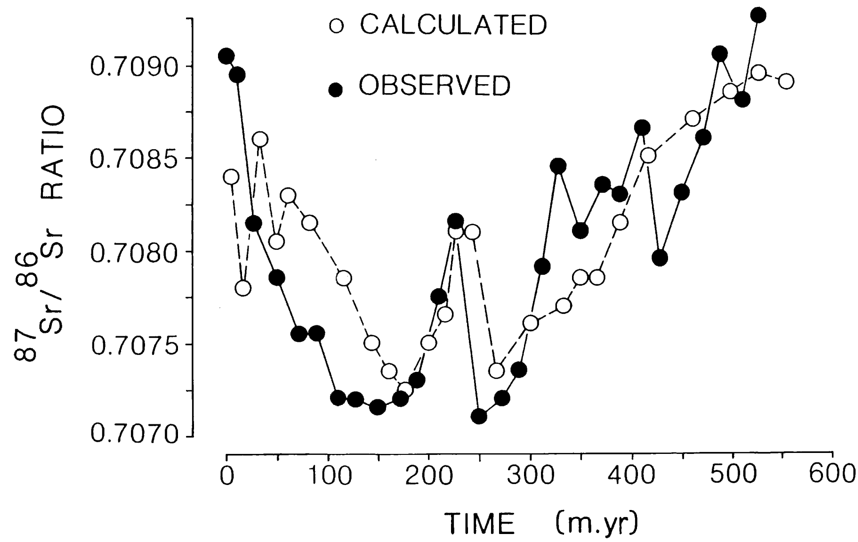


Fig. 12. Fluctuations of the isotopic ratio $^{87}Sr/^{86}Sr$ of seawater during the Phanerozoic, measured (from Faure, 1982) and calculated in this study.

TABLE 7

(Continued)

sediments of a certain age, surviving to-day (10^{20}g), survival rate of sediments duration of the span) (10^{20}g/my), sedimentation rate (10^{20}g/my)

Sediments Surviving (10^{20}g)	Survival Rate (10^{20}g/my)	Sedimentation Rate (10^{20}g/my)	Sediments Recycled (10 g/myr)	Erosion Rate (tons/km^2/yr)	Dissolved and Suspended Materials (mg/l)
(7)	(8)	(9)	(10)	(11)	(12)
—	—	161.0	0.0	107.7	404.1
5,769	87.4	96.3	8.9	67.3	210.5
4,300	65.1	87.2	22.1	62.1	172.1
2,282	43.1	68.9	25.8	40.5	169.6
1,408	28.2	52.4	24.2	28.0	121.4
1,088	24.2	51.8	27.6	29.6	126.7
1,377	21.2	53.4	32.2	30.9	120.5
1,816	33.0	99.3	66.3	65.2	201.7
678	19.4	66.7	47.3	53.4	121.9
978	17.8	69.9	52.1	53.1	120.9
1,574	19.7	94.3	74.6	59.2	148.7

(7) Amounts of sediments surviving (10^{20} g), and (8) survival rates (10^{20}g/my) from Gregor (1985). (9) Sedimentation or erosion rates (10^{20}g/my) corrected from the data of column 8 in this paper. (10) Rates of sediments recycled or of sediments re-eroded, calculated by the difference between columns 9 and 8. (11) Specific erosion rates (tons/km^2/yr), calculated from columns 9 and 4. (12) Dissolved and suspended matter contentration (mg/l) in the continental runoff calculated in column 6.

continental runoff and the weathering rate decrease. On the contrary, the $^{87}Sr/^{86}Sr$ isotopic ratio increases if the submarine volcanic activity decreases and/or if the continental runoff increases (figs. 13 and 14; table 8).

In general, when global tectonic activity increases, the amount of CO_2 produced increases, the concentration of CO_2 in the atmosphere rises, the global temperature and the global continental runoff together increase (Mackenzie and Pigott, 1981; Berner, Lasaga, and Garrels, 1983; Probst and Tardy, 1989). Because volcanic activity and continental runoff together increase, the fluctuations of $^{87}Sr/^{86}Sr$ isotopic ratio in the ocean are finally very small. Therefore, they can be recalculated on the base of a multiple regression including the rate of submarine volcanism Vsm (10^6 km^3/my from Ronov and others, 1980) and the global continental runoff (D_c, 10^9km^3/my) (table 8).

The multiple regression can be written as follows:

$$^{87}Sr/^{86}Sr = 2.535\ 10^{-8}\ D_{c,t}(10^9 km^3/my) + 2.167\ 10^{-5} \times 1/Vsm\ (10^6 km^3/my) + 0.7062 \quad (7)$$

(correlation coefficient R = 0.68, for 26 observations considered) in which $D_{c,t}$(10^9km^3/my) is the global continental runoff, and Vsm (10^6km^3/my) is the survival rate of the submarine volcanism: the present day abundance of rocks of a given age span, divided by the duration of the span.

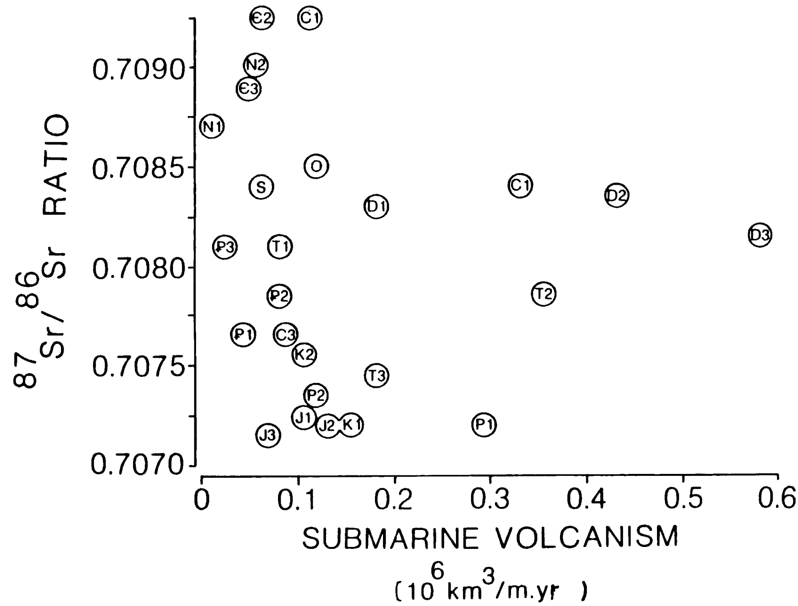


Fig. 13. Relationship between the $^{87}Sr/^{86}Sr$ isotopic ratio in marine carbonates (from Faure, 1982) and the surviving rate of submarine volcanism, calculated from Ronov and others (1980), for the major geological periods.

For many years, Ronov and his coworkers have demonstrated the close relationship between the amounts of carbonates deposited and those of volcanic rocks produced (see Budyko, Ronov, and Yanshin, 1985). This is simply because carbonates take their CO_2 from the volcanic emissions. Furthermore because the erosion of marine carbonates exposed on lands also contributes to the $^{87}Sr/^{86}Sr$ isotopic ratio of the ocean, it appears interesting to introduce, in the regression, the survival rate of carbonates ($10^6 km^3/my$, from Ronov and others, 1980):

$$^{87}Sr/^{86}Sr = 2.7754\ 10^{-8}\ D_{c,t}(10^9 km^3/Myr) + 6.233\ 10^{-5} \times 1/\text{carbonates}\,(10^6 km^3/Myr) + 0.7060 \quad (8)$$

(correlation coefficient R = 0.69 for 26 observations).

Eq (7) is used to calculate $^{87}Sr/^{86}Sr$ in the ocean from the values of continental runoff and submarine volcanism survival rate given in table 8. Comparison between measured and calculated values are shown in figure 12. The agreement is rather good except for quite large deviations between observed and calculated values for the Present-day, the late Tertiary, and the Cambrian. These deviations may be due, among other reasons, to the fact that on the continents the proportions of

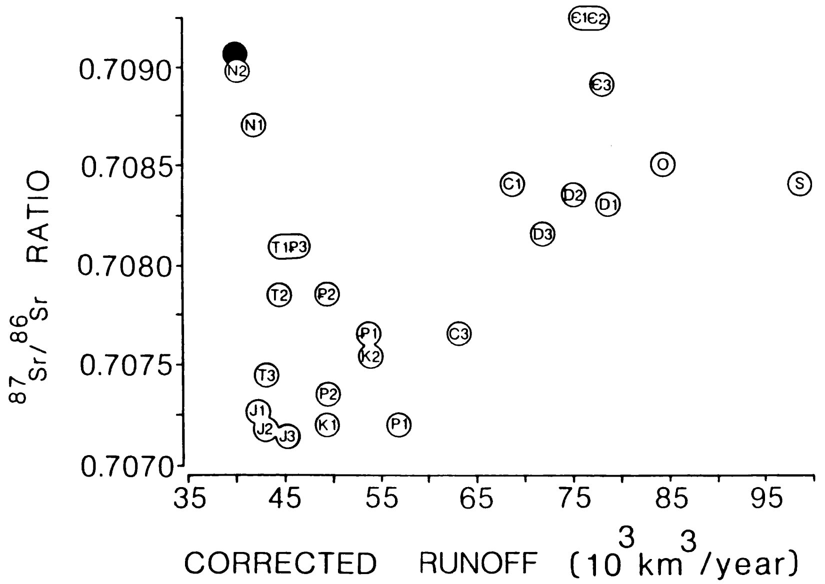


Fig. 14. Relationship between the $^{87}Sr/^{86}Sr$ isotopic ratio in marine carbonates (from Faure, 1982) and the global continental runoff estimated in this study for the major geological periods.

granitic rocks and evaporites ($CaSO_4$) or carbonates ($CaCO_3$) exposed to weathering have been fluctuating through time and have been inducing changes in the $^{87}Sr/^{86}Sr$ isotopic ratio in the continental global runoff (Albarède and Michard, 1987). The good agreement of the two curves of figure 12 may finally suggest that our evaluation of the global land runoff estimation is reasonable.

GLOBAL EROSION AND SEDIMENTATION RATES

The survival rate of the sediments (surviving mass or surviving volume of sediments per unit time of deposition) during the Phanerozoic has been studied by Gregor (1970), Garrels and Mackenzie (1971a, b), Veizer and Jansen (1979), and Walker (1981). Refined data and interpretations were recently proposed by Gregor (1985).

The survival rate of sediments.—The following calculations use Gregor's (1985) data for sedimentary mass fluctuations. The sedimentary mass (S(t), 10^{15}tons/my decreases exponentially as a function of time (t, millions of years). The regression function is the following:

$$\text{Ln } S(t) = -2.95\ 10^{-3}\ t + 1.977. \qquad (4)$$

At t = 470 my (Ordovician) for example, one calculates S = 1.805 × 10^{15} tons/my which is close to the 1.78 10^{15} tons/my, the survival rate given by Gregor (1985).

TABLE 8

Submarine volcanism survival rate (present-day abundance of rocks of a given time span divided by the duration of the span); carbonate survival rate ($10^6 km^3 / my$, from Ronov and others, 1980); global continental runoff ($10^6 km^3 / my$, this study); $^{87}Sr/^{86}Sr$ isotopic ratio (from Faure, 1982) through Phanerozoic time

		Mean Age (my)	Duration (my)	Submarine Volcanism ($10^6 km^3/my$)	Marine Carbonates ($10^6 km^3/my$)	Gobal Runoff ($10^9 km^3/my$)	$^{87}Sr/^{86}Sr$ Isotopic Ratio —
Present-day		0	0	—	—	39.70	0.7090
Neogene	Pliocene	4.0	4.0	0.052	0.043	40.08	0.7090
	Miocene	15.5	19.0	0.015	0.102	41.45	0.7087
Paleogene	Oligocene	31.0	12.0	0.024	0.051	45.27	0.7081
	Eocene	47.5	21.0	0.094	0.239	49.44	0.7078
	Paleocene	62.0	8.0	0.032	0.126	51.88	0.7076
Cretaceous	Upper	83.0	34.0	0.102	0.284	51.96	0.7075
	Lower	116.0	32.0	0.114	0.199	47.46	0.7072
Jurassic	Upper	142.5	21.0	0.075	0.337	42.53	0.7071
	Mid	160.5	15.0	0.124	0.273	40.48	0.7071
	Lower	176.5	17.0	0.076	0.180	38.51	0.7072
Trias	Upper	197.5	25.0	0.297	0.312	40.90	0.7074
	Mid	215.0	10.0	0.355	0.243	44.14	0.7078
	Lower	277.5	15.0	0.242	0.323	46.53	0.7080
Permian	Upper	245.0	20.0	0.233	0.182	45.02	0.7073
	Lower	267.0	25.0	0.183	0.277	41.41	0.7072
Carboniferous	Upper	300.0	40.0	0.079	0.198	43.07	0.7076
	Lower	332.5	25.0	0.416	0.699	47.03	0.7084
Devonian	Upper	352.5	15.0	0.583	0.514	48.68	0.7081
	Mid	368.0	16.0	0.586	0.771	49.12	0.7083
	Lower	388.0	24.0	0.171	0.147	49.80	0.7083
Silurian		417.5	35.0	0.055	0.136	54.66	0.7083
Ordovician		462.5	55.0	0.097	0.139	57.77	0.7084
Cambrian	Upper	502.5	25.0	0.081	0.476	62.25	0.7089
	Mid	530.2	30.0	0.077	0.326	63.46	0.7092
	Lower	557.5	25.0	0.094	0.295	63.46	0.7092
Average				0.152	0.248	47.92	0.7080

The original sedimentation rate can be evaluated by assuming that, on the average during the Phanerozoic, the rate was constant and by transforming the decreasing exponential function into an horizontal straight line crossing the ordinates at S_0 for $t = 0$ ($Ln\ S_0 = 1.977$). (See fig. 15).

One finds: $S_0 = 7.221 \times 10^{15}$tons/my, which is smaller than from the 8.7×10^{15} tons/my reported by Gregor (1985) for the Tertiary. At each geological period, the factor (f(t)) used to transform the mass of sediments surviving into the mass of sediments supposed to have been originally deposited is equal to the one required to transform the decreasing exponential function into the horizontal straight line at the ordinates $S_0 = 7.221 \times 10^{15}$tons/my. Thus, the supposed original deposition or sedimentation rate can be evaluated. It fluctuates significantly around a constant average value of 7.2×10^{15}tons/my (fig. 15; table 7).

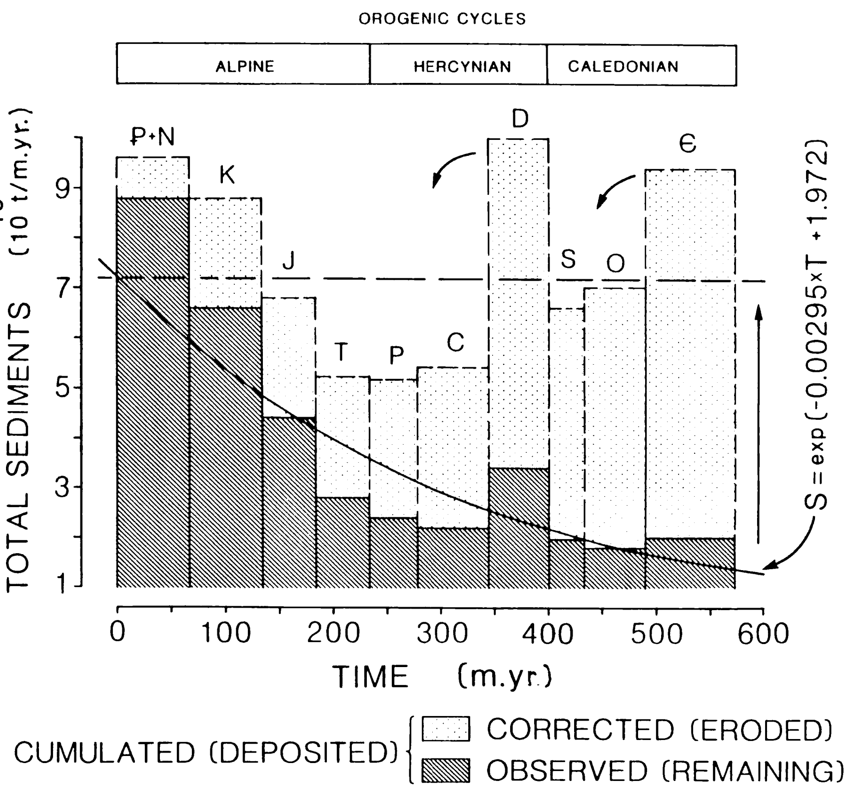


Fig. 15. Sediment survival rate (the Present-day abundance of rocks of a given age span, divided by the duration of the span, from Gregor, 1985) and sedimentation rate during the Phanerozoic (10^{15}tons/my).

The Cambrian, Devonian, Cretaceous, and Tertiary geological periods show the largest sedimentation rates, whereas the Carboniferous, Permian, and Triassic show the lowest. It is interesting to remark that the general trend of sedimentation rate as a function of time follows rather nicely the one we have observed for the strontium isotope ratio $^{87}Sr/^{86}Sr$) (fig. 12)

The worldwide erosion rate should be equal to the sedimentation rate, so that the specific sediment yield of the rivers (10^6 tons km^{-2} my^{-1}) as well as the concentration of the dissolved and the suspended material (mg/l) can be easily calculated by taking into consideration for each geologic time period (1) the total global runoff intensity, (D_c); (2) the total amount of sedimentary rocks eroded or deposited; and (3) the land area through the Phanerozoic. It is clearly shown in figures 16 and 17 that the Devonian period was particularly wet and a period of strong erosion. It is also shown that the two values characterizing the present erosion rate (108 10^6 tons/km^2/my or 404 mg/l) according to Milliman and Meade (1983), Meybeck (1987), or Berner and Berner (1987) are

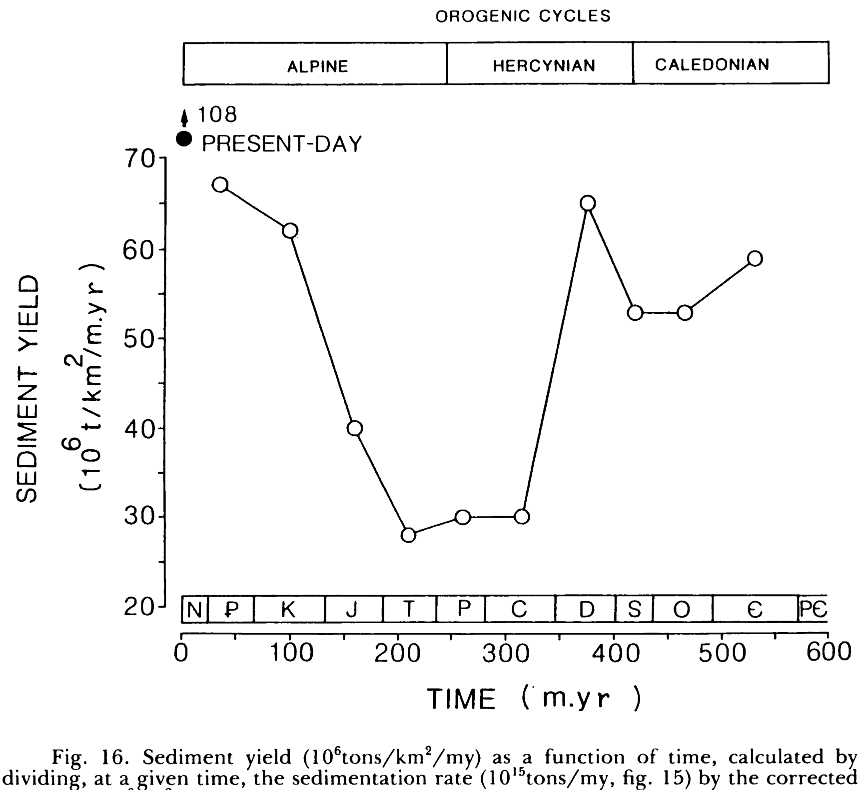


Fig. 16. Sediment yield (10^6tons/km^2/my) as a function of time, calculated by dividing, at a given time, the sedimentation rate (10^{15}tons/my, fig. 15) by the corrected land area ($10^6 km^2$, fig. 10).

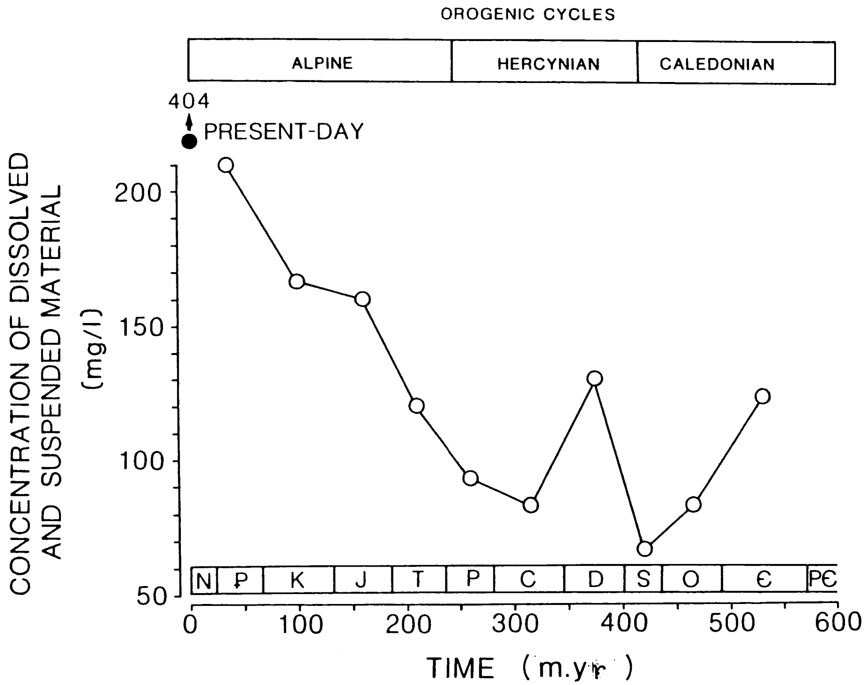


Fig. 17. Average concentration of suspended plus dissolved material in the rivers of the world (mg/l), during the Phanerozoic time, calculated by dividing, for each period, the mass of sediments effectively deposited (sedimentation rate) by the global runoff (table 7).

much higher than the average erosion rate for the Phanerozoic. This is generally attributed to the influence of human industrial activity, deforestation, et cetera. However, the erosion rate never ceased to rise from the end of the Jurassic to the present time, so that the high erosion rate observed today may be due also to an effect of increased tectonic activity. Furthermore, most of the erosion comes today from the Himalaya region, and such speculation should be concentrated on this region.

CONCLUDING REMARKS

We have used the present day global water cycle to reconstitute the fluctuations of rainfall (P), evaporation (E), and runoff (D) during the Phanerozoic. The method followed is based on the assumption that the conditions prevailing in the past were similar to those characterizing the present day world and that the global climatic factors were regulated only by the position of the continents in latitude and by the relative area of continents and oceans through time.

The present day global water cycle is the following (10^{20}g/yr):

Evaporation over oceans	4.25
Rainfall over oceans	3.85
Difference	0.40
Rainfall over continents	1.11
Evaporation over continents	0.71
Continental runoff	0.40

On a global scale, the rainfall deficit over the oceans is equal to continental runoff.

Our estimates show that continental runoff should have fluctuated considerably between 0.35 10^{20}g/yr (Triassic) and 0.65 10^{2}g/yr (Devonian). They also show clearly that the Cretaceous (0.50 10^{20}g/yr) was probably about 20 percent wetter than the present day (0.40 10^{20}g/yr). These differences can be explained by the continental motion at the Earth's surface. During the Cretaceous, continents were separated and dominantly located at humid latitudes whereas at the present-day continents are much more agglomerated and located closer to the polar regions. During Triassic time, Pangea had a large continental area located at dry latitudes, and consequently the global runoff at that time appears as the lowest observed for the Phanerozoic.

The estimation of the global runoff fluctuations was tested through its ability to explain, together with estimates of submarine volcanism and the amounts of carbonate deposited, the fluctuations of the isotopic ratio $^{87}Sr/^{86}Sr$ in marine carbonates. It appears clearly that submarine volcanism cannot be considered as the only factor responsible for the low or high values of $^{87}Sr/^{86}Sr$ in marine carbonates such as for example 0.707 during the Jurassic together with an intense volcanic activity or 0.709 at the Present-day or during the Cambrian together with a low volcanic rock production. For example, the Devonian, a time characterized by a very high production rate of volcanic rocks, should consequently show a low $^{87}Sr/^{86}Sr$ isotopic ratio. However, it exhibits a high value of 0.7085 which is mainly due to a large continental runoff flowing over land areas characterized by a high strontium isotope ratio. Furthermore, the increase of volcanism shown around 250 my is accompanied by a small value of $^{87}Sr/^{86}Sr$ in marine carbonates (0.707), also because at that time the continental runoff was very low (0.35 10^{20}g/yr). The high isotopic value at the beginning of the Phanerozoic reflects our interpretation, and one may think that, during the Cambrian, the continental runoff was high while the volcanic activity was probably low.

Finally, the evaluation of the continental runoff combined with an evaluation of the effective continental area as well as an estimation of the effective sedimentation rates allows estimation of erosion rates through the Phanerozoic. It appears that the low rate of sedimentation characterizing Permo-Triassic times is certainly due to a considerable decrease of the continental runoff, whereas the very high sedimentation rate characterizing the Devonian times appears to be the consequence of a considerable increase of the continental runoff due to an especially favorable position of continents under the humid latitudes.

Thus, without taking deliberate care of the influence of possible extraterrestrial or cosmic factors, as well as the influence of elevation and relief variations, we have emphasized here the consequences of the continental motions on climatic variation, fluctuation of the global water cycle, and global erosion and sedimentation rates through the last 600 my. The $^{87}Sr/^{86}Sr$ isotopic fluctuations and the amount of sediments deposited as functions of time show that as a first order approximation the global conditions controlling ancient climates may have been similar to those prevailing at the present time.

ACKNOWLEDGMENTS

Our nicknames have been determined to be alternately either those of the *Trois Mousquetaires*: Aramis, Athos, and Porthos because of differences in our respective size or those of the Three Wise Magi: Melchior, Balthazar, and Gaspar, because of differences in our respective skin color. The spontaneous and delicate choice of nicknames indicates a wide cultural background and a warm humanity. This article is dedicated to our friend and master Robert M. Garrels. We acknowledge his culture, his genial scientific and humoristic inspiration. Many ideas we have been conveying for years are from him and several of his jokes are *henceforth* taught all around the world. As a specimen we select the most famous: BLAG, formed with the initials of Berner, Lasaga, and Garrels. Correctly written, *blague* means in French, either hoax, flummery, all-bosh, or cock-and-bull story. Without him today we feel empty.

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