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RECONSTRUCTING THE AGE AND LITHOLOGY OF ERODED SEDIMENT

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Abstract : The reconstruction of ancient sediment fluxes is based on the assumptions that young sediment is generally unconsolidated, has the greatest areal exposure and thus has the greatest probability of being eroded. Young sediment is therefore recycled more rapidly than old sediment which is more consolidated and has a smaller areal exposure. This assumption is the fundamental principle underlying the theory of sediment recycling.

We assume that on a global scale the sedimentary system is in steady state and has a mass that remains constant because most younger sediments are derived from cannibalization of older sediments through erosion. This implies that gains of sediment mass from weathering, erosion, and deposition of igneous and crystalline metamorphic rocks are exactly offset by losses to subduction and metamorphism.

The general decline of sediment mass with age is approximated by a simple exponential decay $y = A e^{-bt}$ where y is the remnant of the original sediment flux at time t, that would be observed today after t m.y. of recycling at a constant rate of erosion b ("average recycling proportionality parameter" of Veizer and Jansen, 1985), and a constant depositional rate, A (the rate at which sediment is being deposited at present).

The new total sediment mass for the Phanerozoic is 2082.6 × 10^{21} g. Based on a least squares fit of an exponential decay curve to the data, we have determined the average zero - age flux rate of Phanerozoic sediment to be 5.756 × 10^{21} g m.y.$^{-1}$ and the average rate of sediment recycling to be -2.062 × 10^{-3} m.y.$^{-1}$. New estimates of the mass of Proterozoic and Archaean sediments are also presented; these are 845.5 × 10^{21} g and 15.0 × 10^{21} g for the masses of Proterozoic and Archaean sediments respectively.

Because neither rocks of a particular lithology or age can be selectively protected from erosion, it is possible to reconstruct mass - age distributions for different lithologies. Detrital rocks dominate the sedimentary system in terms of mass, and can be regionally confined as a closed system. The recycling rate of detrital rocks can be used on both global and regional scales to reconstruct past sediment fluxes of both detrital and chemically or biologically precipitated materials.

Key words : Mass - age, Sediment - cycling, Phanerozoic, Fluxes

SEDIMENT RECYCLING AND SEDIMENT MASS - AGE DISTRIBUTIONS

Veizer and Jansen (1979) have reviewed the development of ideas regarding sediment cycling in the introduction to their paper on basement and sedimentary recycling and continental evolution. They noted that since the turn of the century it had been recognized that the existing mass of sedimentary rock per unit time approximates an exponential decay curve with increasing age of the deposit.

This was first discovered in terms of maximum preserved thickness of stratigraphic units (Barrell, 1917; Schuchert, 1931) and was interpreted as a reflection of increasing rate of tectonism through geologic time. It was Gilluly (1949), who recognized that the exponential relationship is an expression of the more complete preservation of younger deposits. Gregor (1968, 1970) used the compilations of Ronov (1968) and Holmes (1965) to calculate the rate of denudation of the continents which would produce the results observed. Garrels and Mackenzie (1971a) presented the first extensive discussion of sedimentary cycling, developing models for constant sedimentary mass and for linear accumulation of the sedimentary mass. Veizer and Jansen (1979) have shown that the exponential relationship holds for the age distribution of the area of continental basement, the thickness of sedimentary and volcanogenic units, the thickness, area, and volume of sedimentary rocks, and even the cumulative reserves of most mineral commodities. They concluded that "the described exponential relationship is a fundamental law of present day age distribution of geological entities" (p. 342). As such, it obviously has significant ramifications for the interpretation of geologic history.

The papers written in the 1960's and 70's did not take into account the mobility of the earth's crust implied by the theory of plate tectonics. Garrels and

Mackenzie (1971b), assuming permanence of continents and ocean basins, thought that the total mass of sediment (TSM) existing on the earth is about 3200 x 10^{21}g, of this 44% would be PreCambrian, 23% Paleozoic and 33% Mesozoic-Cenozoic. Southam and Hay (1981) reviewed previous work and prepared new estimates of sediment volumes and masses in major sediment reservoirs for an estimated total Phanerozoic sedimentary mass of 2485 $\times$ 10^{21} g. Of this Phanerozoic sedimentary mass (PSM), they determined 35% to be Paleozoic and 65% to be Mesozoic-Cenozoic. The first attempt to work out the total mass-age distribution of all Phanerozoic sediments was that of Gregor (1985) who estimated the PSM to be 2100 $\times$ 10^{21} g. Gregor (1985) compiled sediment masses for the three major reservoirs; the cratons, continental margins and ocean basins. He plotted his mass-age distribution of the Phanerozoic sediments in terms of the duration of geologic Periods. The general shape of the exponential decay can be recognized as well as a peak in the mass of Devonian sediment, but finer details in the mass-age distribution are not apparent.

In figure 1 we show a mass-age distribution of existing Phanerozoic sediments similar to that compiled by Wold and Hay (1990), but including Pleistocene sediments. The estimates of Budyko et al. (1987) were used for sediments of Pliocene to Middle Jurassic age. Masses of older sediments were compiled from the data of Ronov (1982). For the masses of Pleistocene sediments we used the estimate of Hay (1993). The distribution is plotted using the timescales of Berggren et al. (1985), McKerrow et al. (1985) and Snelling (1985). Our new estimate of the total mass of Phanerozoic sediments is 2082.6 $\times$ 10^{21} g. The mass-age distribution of Cenozoic sediments including the Pleistocene is shown in figure 2.

RECONSTRUCTION OF ORIGINAL SEDIMENT FLUX RATES

The reconstruction of ancient sediment mass is based on the assumptions that young sediment is generally unconsolidated, has the greatest areal exposure and thus has the greatest probability of being eroded. Young sediment is therefore recycled more rapidly than old sediment which is more consolidated and has a smaller areal exposure. This assumption is the fundamental principle underlying the theory of sediment recycling.

Wold and Hay (1990) presented a method for reconstructing ancient sediment flux rates. They approximated original Phanerozoic sediment fluxes by fitting an exponential decay curve to the observed mass-age distribution of sediments, then multiplying the ratio of the observed mass to the exponential decay curve mass by the zero-age flux rate predicted by the exponential decay curve. Their method was a good first approximation of the original fluxes and will be compared to the new method discussed below.

A NEW METHOD FOR RECONSTRUCTING ORIGINAL SEDIMENT FLUX RATES

Following Wold and Hay (1990) we assume that on a global scale the sedimentary system is in steady state and has a mass that remains constant because most younger sediments are derived from cannibalization of older sediments through erosion. This implies that gains of sediment mass from weathering, erosion, and deposition of igneous and crystalline metamorphic rocks are exactly offset by losses to subduction and metamorphism. We also assume that no masses of sediment that are significant in terms of the PSM can be stored in ocean water or in the atmosphere. The general decline of sediment mass with age resulting from recycling of older sediment to become younger sediment may be approximated by a simple exponential decay

$$y = Ae^{-bt} \tag{1}$$

where y is the remnant of the original sediment flux at time t, that would be observed today after t m.y. of recycling at a constant rate of erosion b ("average recycling proportionality parameter" of Veizer and Jansen, 1985), and a constant depositional rate, A (the rate at which sediment is being deposited at present). Equation 1 is the average rate of sediment recycling over the time represented by the mass-age distribution. The observed sediment masses in figure 1 have been normalized to 10 m.y. intervals and are shown in figure 3. The existing mass of sediment in each 10 m.y. interval was calculated by determining the existing mass per million years for each of the traditional geologic intervals recognized by Ronov (1982) or Budyko et al. (1987) and summing the mass increments from the portion of each traditional geologic interval within the 10 m.y. interval.

The average rate of sediment recycling and zero-age sediment flux rate were calculated from a least-squares fit of an exponential curve (Eqn. 1) to the normalized data (Fig. 3). Because we were able to include the mass of Pleistocene sediments, we could determine the average Phanerozoic zero-age flux rate to be 5.756 $\times$ 10^{21} g m.y.$^{-1}$ and the average rate of sediment recycling to be -2.062 $\times$ 10^{-3} m.y.$^{-1}$. A is slightly greater than the value of 5.735 $\times$ 10^{21} g m.y.$^{-1}$ calculated by Wold and Hay (1990) and b is more positive than their value of -2.102 x 10^{-3} m.y.$^{-1}$. This indicates that the average Phanerozoic recycling rate is slower than what they calculated, although the average zero-age flux rate in our new compilation is higher. The new exponential decay curve ($y = 5.756 e^{[-0.002062t]}$) is a more accurate representation of the average Phanerozoic flux and recycling rates.

Our new reconstruction method keeps the sediment mass constant. The total sediment mass (TSM) includes both the documented Phanerozoic sediment and an estimate of the mass of Proterozoic and Archaean sediments. The older sediment masses were calculated from the area under the exponential decay curve. These are 845.5 $\times$ 10^{21} g for the Proterozoic (570

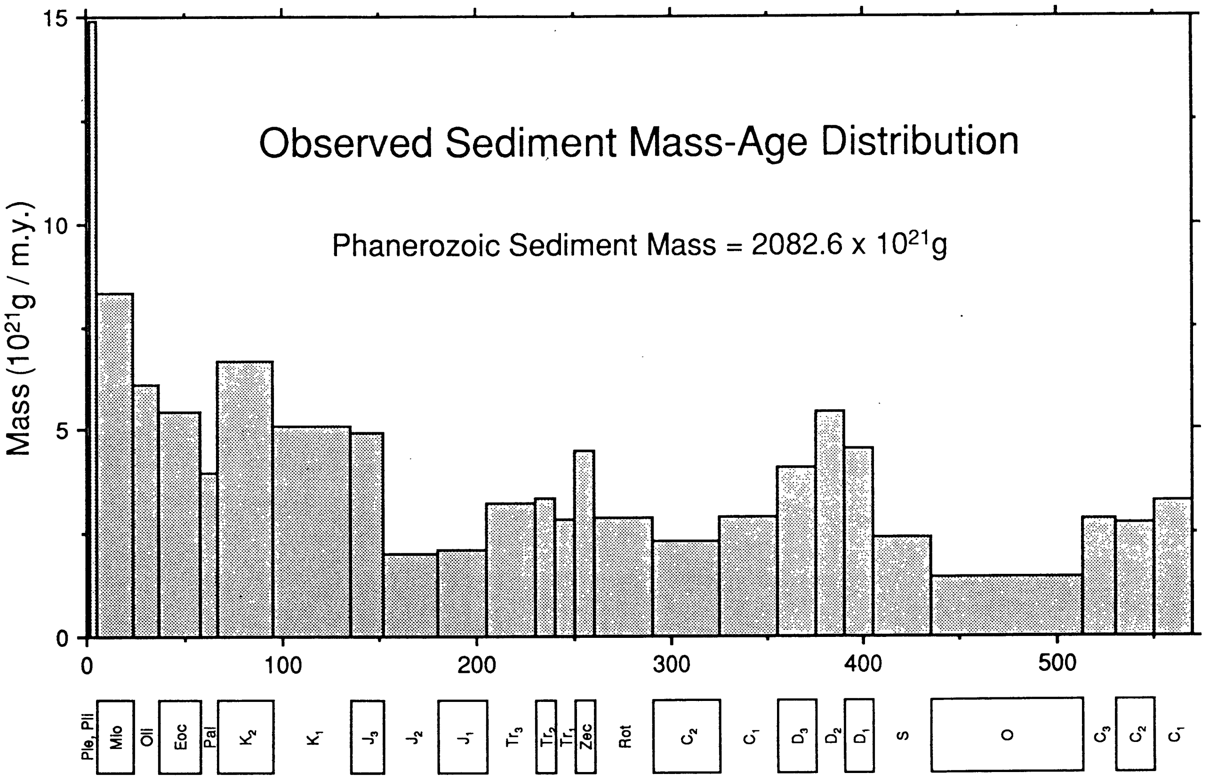

Fig.1. The observed mass - age distribution of existing Phanerozoic sediments compiled from the estimates of Budyko et al. (1987) for the Pliocene to Middle Jurassic, Ronov (1982) for the Middle Jurassic to Cambrian and the new estimate of Hay (1993) for Pleistocene sediments. The timescales of Berggren et al. (1985), McKerrow et al. (1985) and Snelling (1985) were used to display the data and are shown on the bottom of the diagram.

to 2500 Ma) and 15.0 × 10^{21} g for the Archaean (2500 to 3800 Ma) sediments (Fig. 4). The original sediment flux during .each of the 10 m.y. intervals in the Phanerozoic can be estimated by successively reconstructing each of the older mass - age distributions. For any given mass - age distribution we can number the normalized intervals from 0 to n, where there are n+1 intervals in the mass - age distribution. We can refer to the mass of sediment in the youngest interval as mass[0] and the mass in the oldest interval as mass[n]. Then the total mass of sediment would be the sum of all the interval masses from mass[0] to mass[n]

$$TSM = \sum_{i=0}^{n} mass[i] \qquad (2)$$

and the mass of sediment in the youngest interval (mass[0]) is the sum of all the sediment that was eroded from each of the older intervals (mass[1] through mass[n]) during the time interval in which mass[0] was deposited

$$mass[0] = \sum_{i=1}^{n} mass[i]_{eroded} \qquad (3)$$

The mass of sediment eroded from each of the older masses during interval 0 is

$$mass[i]_{eroded} = mass[0] x \frac{mass[i]}{TSM - mass[0]} \qquad (4)$$

The youngest mass is subtracted from TSM in Eqn. (4) so that the total proportion of all the older masses will equal one, but TSM remains constant.

The method is illustrated in figure 5 by a series of reconstructed mass - age distributions, the length of

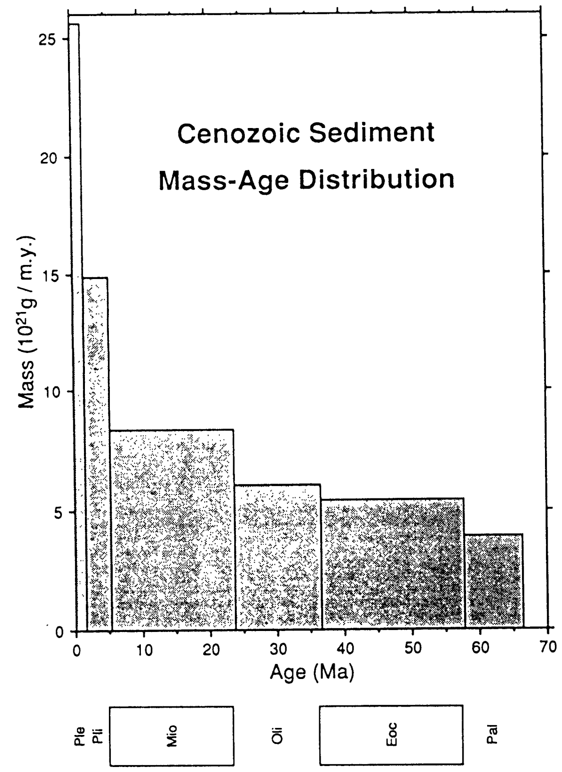

Fig.2. The mass - age distribution of Cenozoic sediments including the mass per m.y. of Pleistocene sediments from Hay (1992). On the bottom of the diagram is the geologic timescale for the Cenozoic after Berggren et al. (1985), McKerrow et al. (1985) and Snelling (1985).

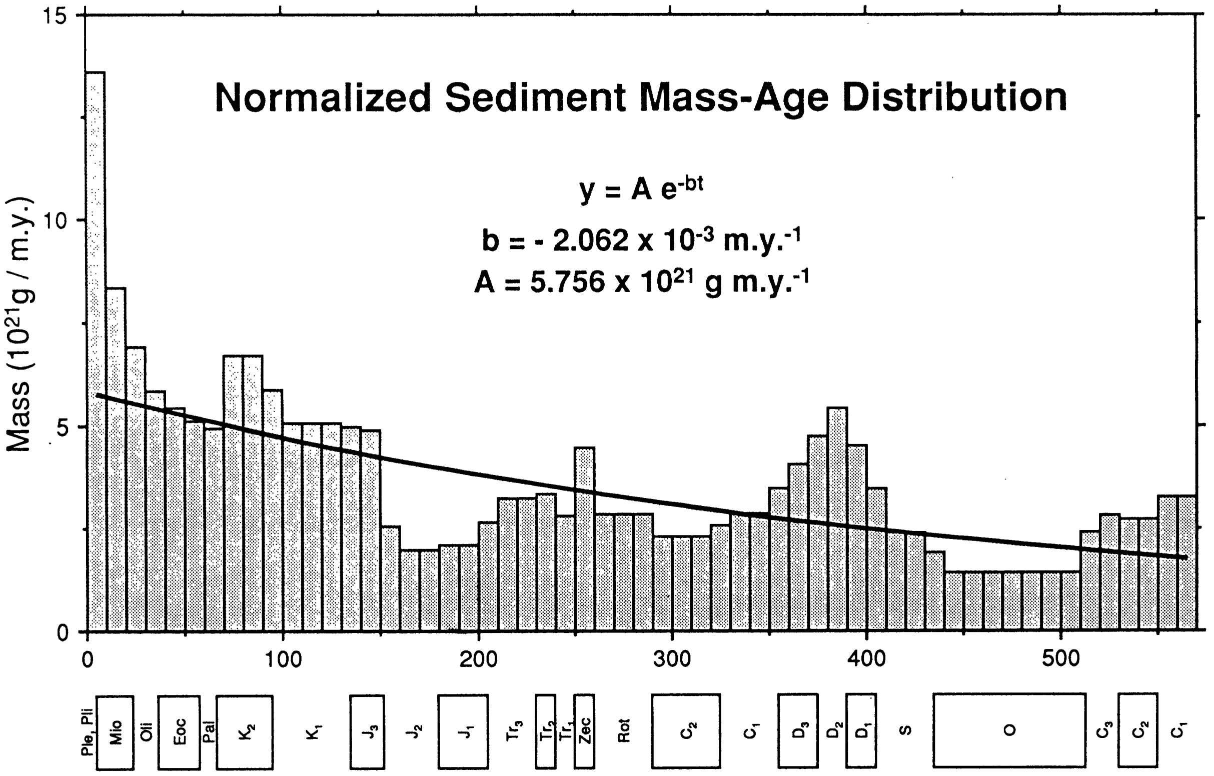

Fig.3. The observed sediment masses normalized to 10 m.y. intervals. The exponential decay curve ($y = A e^{-bt}$) fit to the data represents the average rate of sediment cycling during the Phanerozoic and the zero - intercept of the curve on the y - axis is the average sediment flux rate per m.y. during the Phanerozoic. On the bottom of the diagram is the geologic timescale for the Phanerozoic after Berggren et al. (1985), McKerrow et al. (1985) and Snelling (1985).

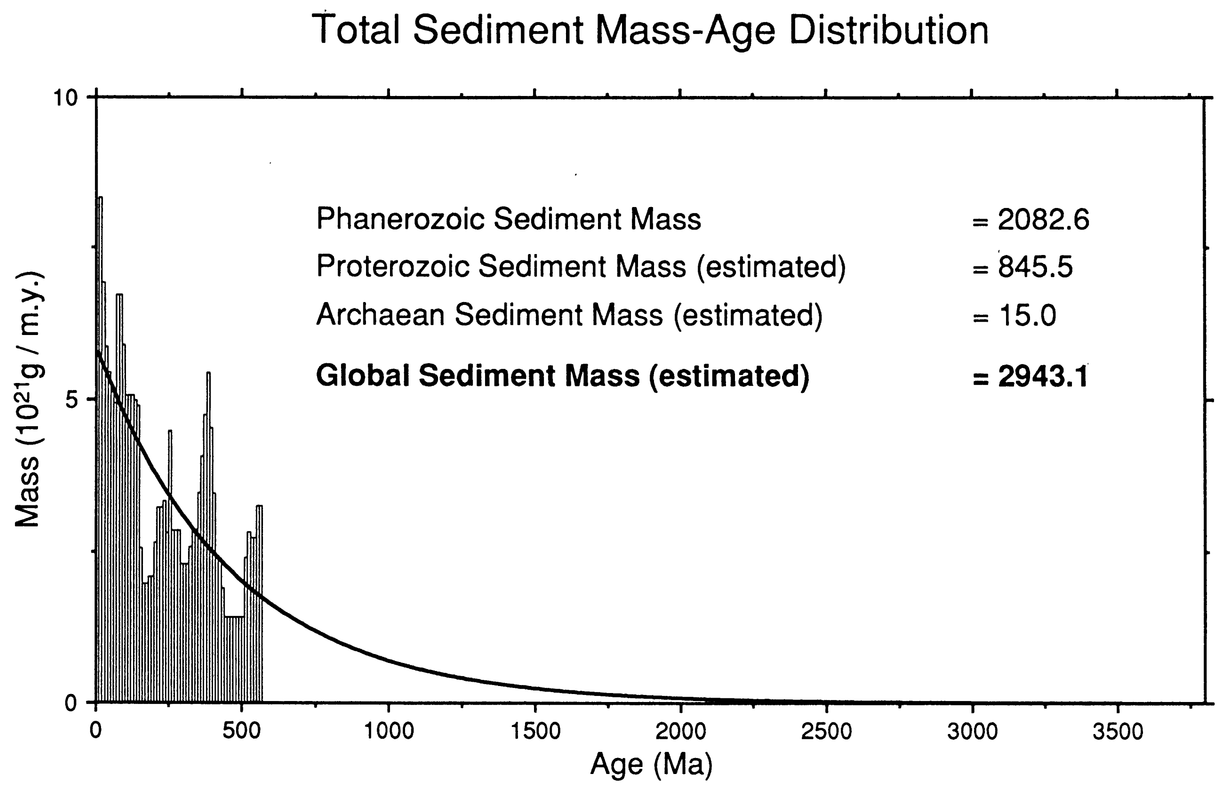

Fig.4. The total sediment mass - age distribution includes the documented mass - age distribution of Phanerozoic sediment and an estimate of the mass of Proterozoic and Archaean sediments. The older sediment masses were estimated directly from the area under the exponential decay curve.

each is kept constant at 570 m.y. (the duration of the Phanerozoic). In each older reconstruction, the sediment masses in corresponding 10 m.y. intervals are greater as illustrated by the increasing height of the major peaks in sediment flux during the Cretaceous (K), Permian (P), Devonian (D) and Cambrian (C). The part of each mass-age distribution older than 570 Ma is represented by the exponential curve because we have not compiled any Precambrian sediment masses. The original flux has been estimated (Fig. 6) from reconstruction of the sediment mass-age distributions at the time of each of the 56 age intervals that are older than the present interval (0 to 10 Ma).

DISCUSSION AND CONCLUSIONS

The original sediment flux rates for each 10 m.y. interval are shown reconstructed using our new and old methods in figure 7. The difference between the flux rates reconstructed using both methods is also shown in figure 7. The new reconstruction method is a fine-adjustment of our old method (Wold and Hay, 1990) with differences in reconstructed sediment fluxes that are less than $\pm 0.5 \times 10^{21}$ g my^{-1} per 10 m.y. interval (Fig. 7). In our original reconstruction method the original sediment flux for a given time interval (t[i] to t[j]) was calculated from multiplying the ratio of the observed mass (m[ij]) to the exponential decay curve mass (m^*[ij]) by the zero-age flux rate predicted by the exponential decay curve.

Our old method, although a good first-approximation, depended almost entirely on the average rates predicted by the exponential decay curve. The zero-age flux rate (A) was held constant and the rate of sediment cycling (b) during each time interval was always proportional to the average rate of sediment cycling. In our new method TSM is initially calculated and then held constant throughout the reconstructions. The original flux rate (A) and sediment cycling rate (b) for each interval varies proportionally to TSM and the young flux being used to reconstruct the mass-age distribution. The sediment flux and cycling rates are more dynamic in this new model and can predict original sediment fluxes exactly while conserving the total sediment mass.

The rapid increase in sediment masses during the Cenozoic is to a large extent a reflection of the distribution of sediments on the ocean floor. The creation and subduction of ocean crust produces an area-age distribution that is almost linear. Because of the mass-age distribution of ocean crust, and because at any given time a significant proportion (± 10%) of the global sedimentary mass resides on ocean crust, there will always appear to be an unusually large amount of sediment having an age less than 50 m.y. However, as discussed by Hay (1993) even taking this into account, the Pleistocene rates of sediment cycling are high compared to older cycling rates. Much of the Pleistocene sediment mass resides on the ocean floor and is not likely to be recycled soon. The very large masses of Pleistocene sediment are related to the frequent changes of climate that accelerates weathering, or to late Cenozoic uplift in many parts of the world that may be the cause of development of the northern hemisphere ice sheets, or to offloading of older sediment from the continental shelves in response to lower sea levels during glacial times, or to a combination of all of these factors.

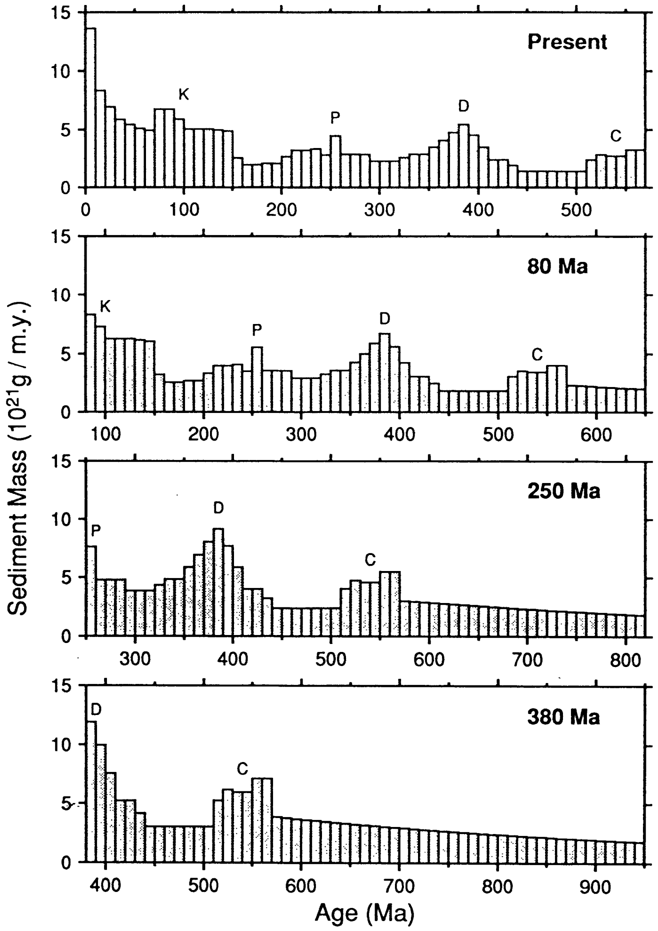

Fig.5. A series of reconstructed mass-age distributions where the length of each is kept constant at 570 m.y. (the duration of the Phanerozoic). The part of each mass-age distribution older than 570 Ma is represented by the exponential curve because of the lack of data on Precambrian sediment masses. In each older reconstruction, the sediment masses in corresponding 10 m.y. intervals are greater, as illustrated by the increasing height of the major peaks in sediment flux for each older reconstruction. Each peak in the rate of sediment flux and recycling rate is indicated by the letters: K - Cretaceous; P - Permian; D - Devonian; and C for the Cambrian.

It has been suggested that some sediments, such as evaporites, are recycled more readily than others, and that sediments of some ages are specially protected against erosion (Garrels and Mackenzie, 1971b). Because the stratigraphic units are always very thin compared with their areal extent, they must be removed sequentially. Although evaporites are more soluble than other rocks and can be dissolved by groundwaters in the subsurface, their removal means that the overlying strata must collapse, and this does not appear to have happened often. Halite is very light and mobile, and may push upward through other sediments to reach the region of active groundwater flow, but only a small part of the deposit can be lost through dissolution of diapirs. In fact, it could be argued that evaporites are the best candidates for rocks that are preferentially preserved, because they are often deposited in rifts early in the development of passive margins, and hence tend to be deeply buried. As Hay and Wold (1990) noted, the greatest masses of evaporites correspond to the greatest sediment masses. The greatest sediment masses mean that large amounts of detrital sediment are being deposited. The flux of detrital sediment is a function of elevation, and the presence of mountains and plateau uplifts causes the earth to have more differentiated climate. Because

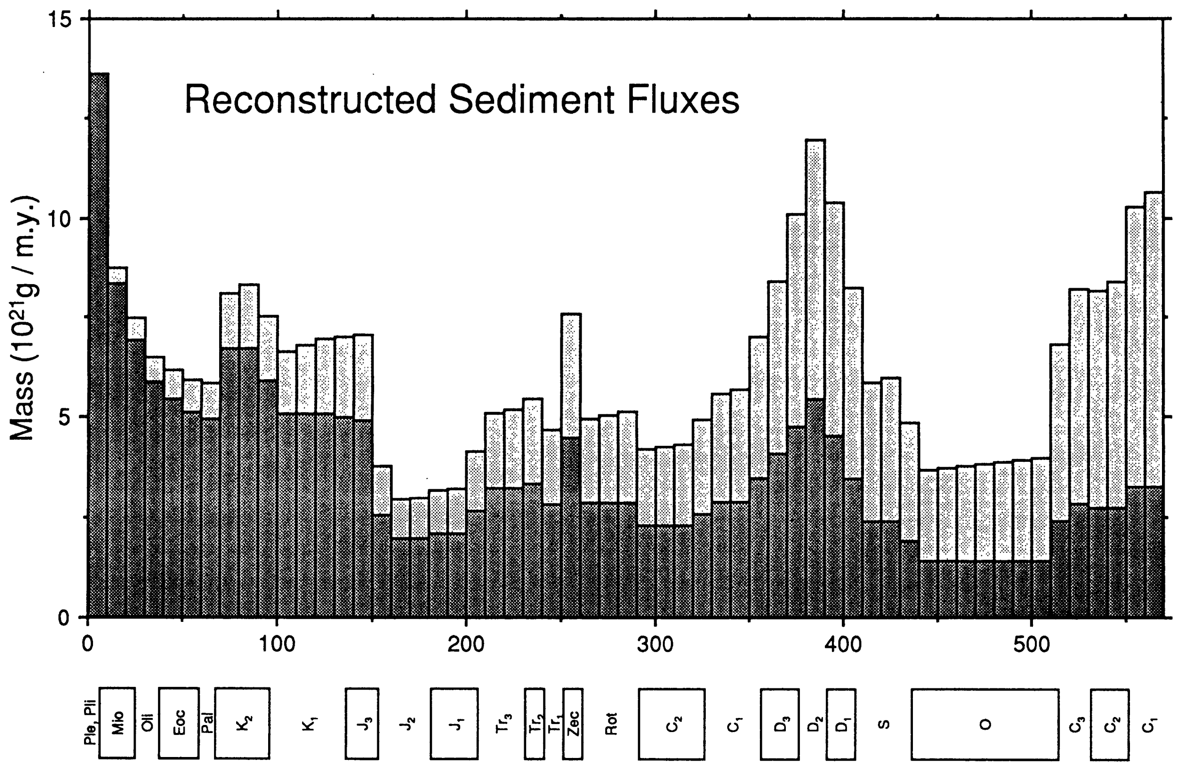

Fig.6. The observed and original sediment flux rates during the Phanerozoic. The observed sediment fluxes are shaded dark gray on the lower part of the diagram and the initial fluxes are equal to the total height of each bar. The original fluxes have been estimated from the successive reconstruction of sediment mass - age distributions. On the bottom of the diagram is the geologic timescale for the Phanerozoic after Berggren et al. (1985), McKerrow et al. (1985) and Snelling (1985).

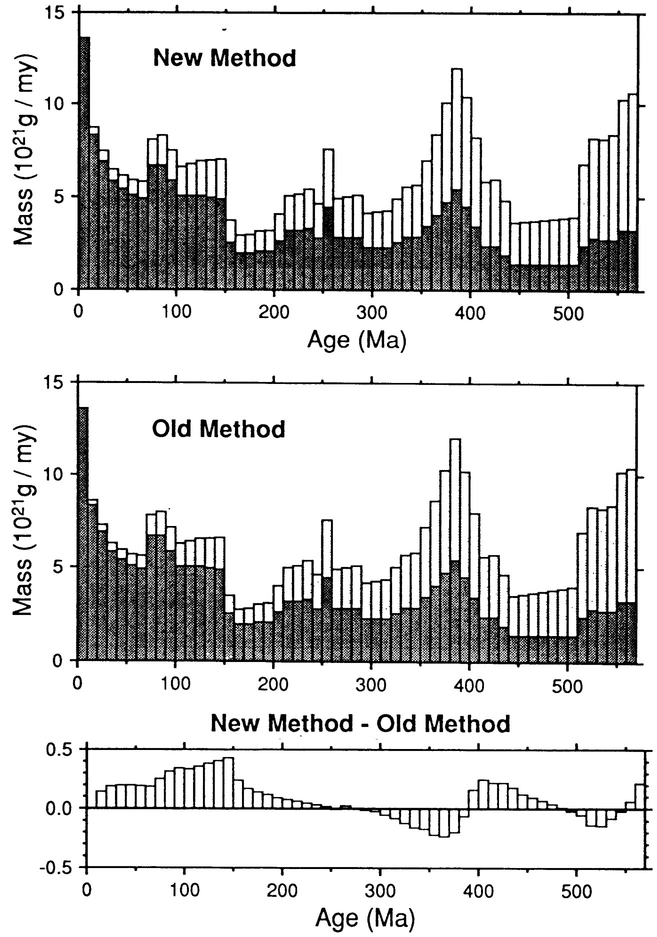

Fig.7. The observed and original sediment flux rates for each 10 m.y. interval reconstructed using our new and old methods. The observed sediment fluxes are shaded dark gray on the lower part of the upper two diagrams and the initial fluxes are equal to the total height of each bar. The difference between the flux rates reconstructed using both methods is shown on the bottom of the diagram. The differences in reconstructed sediment fluxes that are less than ±0.5 x 10^{21}g m.y.$^{-1}$ per 10 m.y. interval.

of these interrelations, they concluded that the deposition of evaporites occurred at times when the relief was maximal, and when maximal aridity might occur.

The idea that sediments of a particular age might be selectively preserved rests on the assumption that at certain times more sediments are deposited in geosynclinal regions, become deeply buried, and hence are selectively preserved. The Devonian peak, which was recognized by Garrels and Mackenzie (1971 b) as a major anomaly, has been considered as possibly due to selective preservation. If it is true that geosynclinal sediments are selectively preserved, then the ratio of platform to geosynclinal sediments should decrease with age. Figure 8 shows the ratio of the masses of sediment preserved in geosynclines to the masses preserved on the platforms. The scatter of points is striking, but it might be argued that there is a general trend that can be interpreted as favoring a slightly greater chance toward preservation of sediments in the geosynclinal regions. The Devonian does not stand out as being a time of unusually large amounts of sediments being concentrated in the geosynclines. The times when the ratio of geosyncline to platform sediment masses are greatest and least do not correspond to times when preserved total sediment masses are greatest or least, but any relationship appears to be random.

Because neither rocks of a particular lithology or age can be selectively protected from erosion, it is possible to reconstruct mass-age distributions for different lithologies. Detrital rocks dominate the sedimentary system in terms of mass, and can be regionally confined as a closed system. The recycling rate of detrital rocks can be used on both global and regional scales to reconstruct past sediment fluxes of both detrital and chemically or biologically precipitated materials.

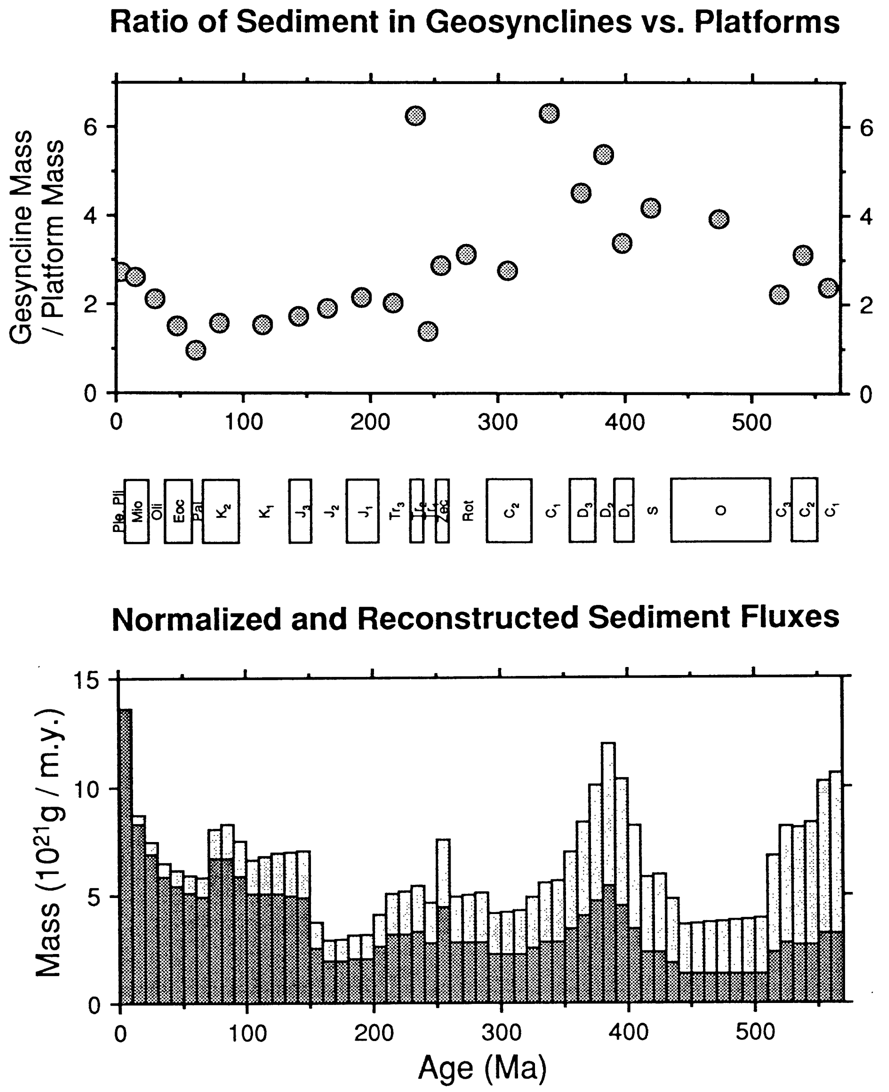

Fig.8. The top of the diagram shows the ratio of the global Phanerozoic sediment in continental platforms vs. geosynclines. In the middle is the geologic timescale for the Phanerozoic after Berggren et al. (1985), McKerrow et al. (1985) and Snelling (1985) and on the lower part of the diagram is the normalized and reconstructed Phanerozoic sediment masses.

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