EVOLUTION OF SEDIMENTS AND OCEAN SALINITY

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Summary

The mass-age distribution of Phanerozoic sediments forms an exponential decay curve, reflecting the cannibalistic behavior of the system - new sediments are formed mostly from the erosion of older sediments. Additions to the system from weathering of igneous rocks, and losses through metamorphism and subduction are relatively small in comparison with the overall rate of sediment cycling. Because strata accumulate in thin widespread layers, sedimentary cycling must proceed in such a way that young sediments are more likely to be eroded than older sediments, and selective cycling of different lithologies is impossible. Because of these properties inherent to the system, it is possible to determine the amounts of sediment of each lithology and age eroded to form young sediment. Variations from the expected distribution reflect weathering of crystalline rocks and maturation of older sediments as they are recycled.

The dissolved salt in the ocean constitutes a special reservoir of the sedimentary system. To determine past ocean salinities, we assume that evaporites and saline pore waters on land follow the same rates of sedimentary cycling as other sedimentary materials and that the major sources of salt delivered to the sea have been erosion of evaporite deposits and release of saline sedimentary pore waters. We conclude that during most of the Cenozoic and during all of the earlier Phanerozoic, the ocean was saltier than it is today. In the Paleozoic and Triassic the ocean mean salinities were in the low 50's to high 40's.

Introduction

Assuming that on a global scale the sedimentary system is in steady state, the general decline of sediment mass with age resulting from recycling of older sediment to become younger sediment is approximated by a simple exponential decay

$$y = Ae^{bt} \qquad 1)$$

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 global sediment mass/age distribution.

Using the data of Ronov (1993), and Hay (1994), we find the total surviving Phanerozoic sediment mass to be 2240 x 10^{18} kg. Ronov (1993) also compiled the mass of Vendian and Riphean sediment, to be 285 x 10^{18} kg. The amounts of older Proterozoic and Archaean sediment still preserved as sediment are very small.

Ronov's (1993) compilation of did not include Antarctica. If the amounts of sediment are increased proportionally to the area of the Antarctic to account for the unknown masses, the total sediment mass becomes 2640 x 10^{18} kg. Using this total, we determine the average Phanerozoic zero-age flux rate (A) to be 6.0 x 10^{18} kg / m.y. and the average rate of sediment recycling (b) to be -0.0028 / m.y. This reconstruction method assumes that the total global sediment mass has remained constant during the Phanerozoic. This is reasonable because most younger sediments are derived from cannibalization of older sediments through erosion. The gains to the total sediment mass from weathering and erosion of igneous and crystalline metamorphic rocks are offset by losses to subduction and metamorphism. Hay (1999) showed that the difference between assumptions that the total sediment mass has remained constant or has grown linearly from 0 at 3.8 billion years ago makes very little difference for the Phanerozoic sediment mass.

To estimate fluxes through time, we normalize the Phanerozoic sediment mass by dividing it into the mass of sediment deposited during time intervals of equal length, e.g. the mass of sediment deposited from 0 to 10 Ma, from 10 to 20 Ma, etc. (Wold and Hay, 1990; 1993). Then the original sediment flux during each equal length interval of 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 (equal length) intervals from 0 to n, where there are n+1 intervals in the mass/age distribution. The mass of sediment in the youngest interval is mass[0] and the mass in the oldest interval is mass[n]. Then the total mass of sediment would be the sum of all the interval masses from mass[0] to mass[n]

$$TSM = \int_0^n Ae^{bt}\,dt \qquad 2)$$

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

$$TSM = \frac{A}{b}(e^{bn} - 1) \qquad 3)$$

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

$$A = \frac{bTSM}{e^{bn} - 1} \qquad 4)$$

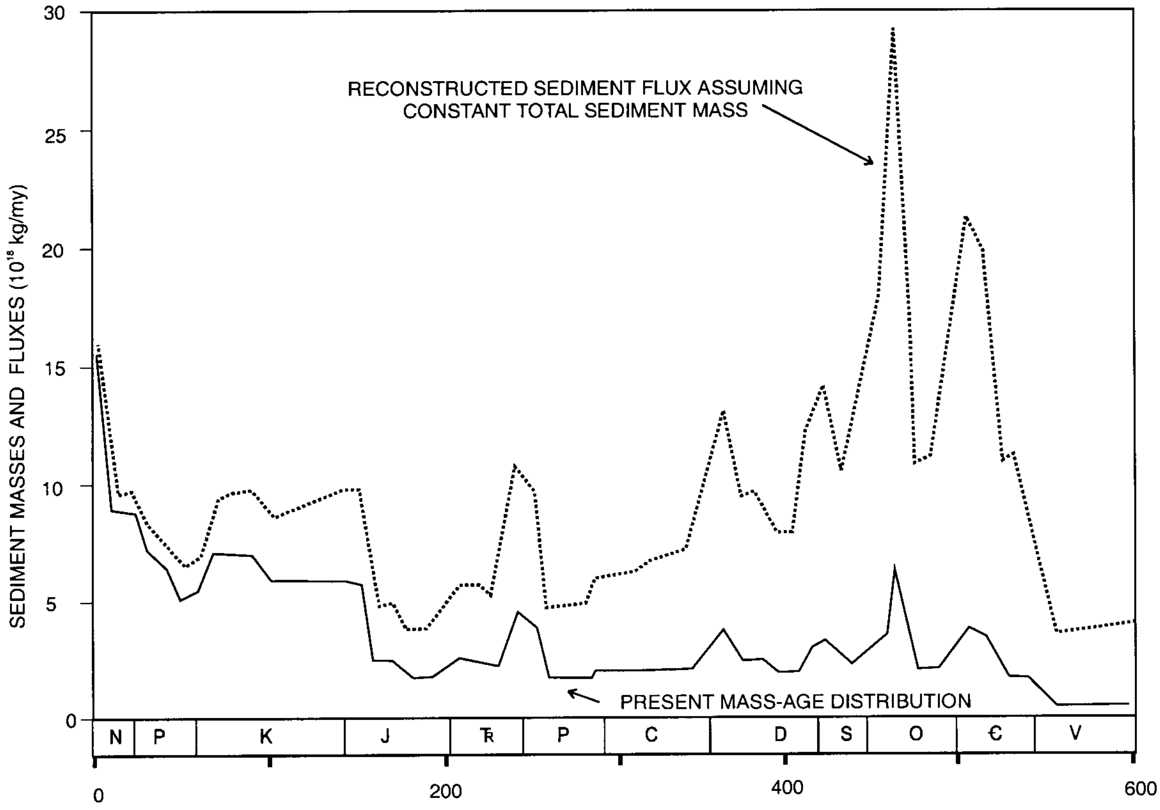

Fig. 1. Mass-age distribution of surviving sediment masses and reconstructed sediment fluxes for the Phanerozoic.

The youngest mass is subtracted from TSM in Equation (4) so that the total proportion of all the older masses will equal one, but TSM remains constant (Wold and Hay, 1993).

Ancient masses of detrital sediments, such as sands and shales, can be reconstructed in the same way as the total sedimentary mass. Being particulate material, they are eroded from one site and deposited at another in a brief period of time. For detrital matter, the rate of erosion must equal the rate of deposition on geological time scales. The same applies to carbonates, although carbonate can be stored briefly in solution in the ocean (Hay, 1999).

Evaporites present a special case because they can be stored for long periods of time in the ocean. Their deposition is episodic and depends on the existence of restricted passages between basins and the open ocean, and the location of the basin within a region where evaporation exceeds precipitation and runoff. Clearly, the rate of erosion is not directly related to the rate of sedimentary cycling and the proportion of evaporites in sediments being eroded. Evaporites deposited in deep offshore settings, such as continental margins (particularly the North and South Atlantic) and marginal seas (Mediterranean, Read Sea and Gulf of Mexico) have not yet been subject to recycling and are excluded from our calculations of the flux of salt to the ocean. Although there is no direct relation between the rates of erosion and deposition of evaporites, both the erosion rate and the deposition rates can be known. Hence we can estimate the mass of evaporite stored in the ocean in solution in the past

Ocean salinity through time

Holser et al. (1980) made a first attempt to track ocean salinity back through time, taking salt extractions into account. They came to the unexpected conclusion that the Cambrian ocean probably had a salinity of about 48‰ and that the ocean has been getting less saline throughout the Phanerozoic. A detailed history of salinity was not presented because they had no idea of how to reconstruct river delivery of salt to the ocean in the past and could only guess that it was somehow related to the erosion of previously buried evaporites. It is easy to estimate the effect of young evaporite extractions on lowering the salinity of the ocean, but the problem of estimating ocean salinity becomes difficult for more ancient times.

The mean salinity of the ocean is a function of how much water and salt are in the ocean. Most studies have assumed that the ocean has always had a mean salinity equal to that of the present-day (34.73‰). Some investigators have made the correction for an ice-free world. Shackleton and Kennett (1975) estimated the water content in the Antarctic and Greenland Ice Sheets to have a volume of 27 x 10^6 km^3. Adding this into the ocean results in an estimated salinity of

34.03‰. These are incorrect assumptions because 1) the volume of water presently in ice sheets and glaciers was overestimated and 2) the significant Late Cenozoic extractions of evaporites in the Red Sea, Persian Gulf-Iran-Iraq, and Mediterranean were not taken into account.

Using a compilation of the existing masses of evaporites prepared by Holser and Wold (Table 1), we reconstructed the masses of evaporites that existed in the past, and the masses eroded and delivered to the ocean for 10 m.y. intervals since the end of the Paleozoic.

Table 1. Major Evaporite Deposits

Age	Basin	Mass (10^{18} kg) NaCl	$CaSO_4$
Miocene	Mediterranean	2.16	0.65
	Carpathians	0.43	0.13
	Iraq-Iran-Persian Gulf	1.73	0.52
	Red Sea	0.22	0.07
U. Cretaceous	Thailand	0.12	0.00
L. Cretaceous	South Atlantic	5.40	1.63
Jurassic	Gulf of Mexico	4.54	1.30
	North Atlantic	3.89	1.12
Triassic	Rot/Muschelkalk, Europe	0.25	0.08
Permian	Zechstein, NW Europe	0.82	0.16
	Delaware Basin, USA	0.07	0.13
	Mid-continent, USA	0.16	0.15
	Precaspian/Volga, Russia	1.21	0.31
	Eastern Andes, Peru	0.11	0.03
Carboniferous	Amazon, Brazil	0.04	0.01
	Paradox, USA	0.02	0.00
	Maritimes, Canada	0.09	0.02
Devonian	Western Canada	0.13	0.05
	Dneper/Donetz/Pripiat, Rus.	0.15	0.10
	Morsovsk Basin, Russia	0.00	0.21
	Northern Siberia	0.03	0.01
	Canning, W Australia	0.03	0.01
Silurian	Michigan Basin	0.06	0.01
Cambrian	Mackenzie, Canada	0.22	0.07
	Eastern Siberia	1.24	0.51
Proterozoic	Hormuz, Iran	1.30	0.36
TOTALS		24.40	7.62

The fluxes of recycled salts to the ocean are based on the assumption that evaporites on land are subject to erosion and those buried in the offshore have been protected from erosion. Using knowledge of the existing evaporite deposits on land and in the offshore and applying the principles of sedimentary cycling, we can estimate the mean salinities of the ocean in the past. To determine the flux of salts to the sea we assume that evaporites on land follow the same rates of sedimentary cycling as other sedimentary materials and comprise 0.953% of the total sedimentary mass. We also assume that salt is stored in the ocean until conditions appropriate for deposition occur, and that salt extractions into the deep offshore, continental margin and marginal sea deposits, are not part of the recycling system

Fig. 2 shows estimates of the salinity of the ocean through the Early Cretaceous, assuming the water volume changes are only those associated with the buildup of the Antarctic and Greenland ice sheets.

These reconstructions indicate that today's average ocean salinity is the lowest of the Cenozoic and Mesozoic. Earlier Cenozoic mean ocean salinities were in the range of 36‰ and 37‰. Late Cretaceous mean ocean salinities were similar to those of today, about 35‰. Early Cretaceous mean ocean salinities were in the range 38.5‰ to 42‰. In the Jurassic, Triassic, and Paleozoic they were between 43‰ and 52‰. The implications of these higher salinities for the thermohaline circulation of the ocean are discussed in Hay and Wold (1997).

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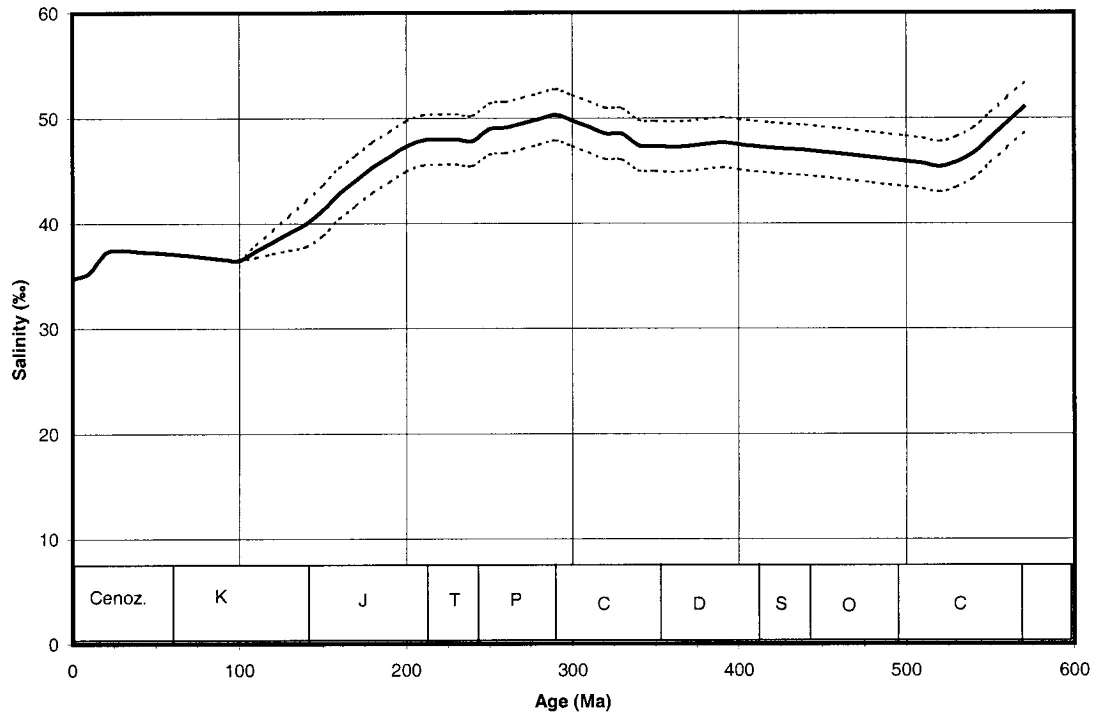

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Fig. 2. Reconstruction of the mean salinity of the ocean through the Phanerozoic, based on reconstruction of evaporite fluxes. Dotted lines indicate the uncertainty due to lack of precise knowledge of the masses of salt in the Gulf of Mexico and Atlantic.