Preliminary reconstruction of the salinity of the ocean in the Cenozoic and Mesozoic

by

William W. Hay, Boulder, Kiel & Christopher N. Wold, Boulder

with 3 tables

Table of Contents

Abstract

The salinity of the ocean in the past can be reconstructed by using knowledge of the existing evaporite deposits on land and in the offshore. We assume that evaporites on land follow the same rates of sedimentary cycling as other sedimentary materials to determine the flux of salts to the sea. However, the salt can be stored in the ocean until conditions appropriate for deposition occur. We assume that salt removals into the deep offshore, continental margin and marginal sea deposits, are not yet part of the recycling system. We conclude that during most of the Cenozoic salinities have been higher than they are today. Each of the major salt extractions into the offshore has caused a rapid decrease of oceanic salinity by a few per mille. In the Early Cretaceous mean ocean salinities ranged between 38 and 42‰, and the Jurassic and Triassic they were between 43 and 53‰.

Zusammenfassung

Die Salinität des Ozeans in der geologischen Vergangenheit kann unter Verwendung des vorhandenen Wissens über Evaporitablagerungen auf dem Festland und auf den Schelfen rekonstruiert werden. Um den Eintrag des Salzes ins Meer zu bestimmen, nehmen wir an, daß Evaporite auf dem Festland die gleichen sedimentären Recyclingraten haben wie anderes sedimentäres Material. Salz wird im Ozean solange gespeichert, bis die notwendigen Bedingungen für dessen Ablagerung entstehen. Wir nehmen an, daß der Salzentzug durch Ablagerungen auf dem tieferen Schelf, dem Kontinentalrand und in den Randmeeren kein Teil des Recyclingsystems ist. Wir schlußfolgern, daß im überwiegenden Teil des Mesozoikums die Salinitäten höher waren als heute. Jede der großen Salzextraktionen auf dem Schelf verursachte einen

schnellen Rückgang der ozeanischen Salinität von einigen pro mille. In der Unterkreide variierte die mittlere ozeanische Salinität zwischen 38 und 42 ‰, und im Jura und in der Trias lag sie zwischen 43 und 53 ‰.

1. Introduction

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 27×10^6 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.

2. The amount of water in the ocean

There are two ultimate sources for water being supplied to the surface of the earth: outgassing from the earths interior "juvenile water", and water carried by incoming extraterrestrial objects, particularly comets. Based on consideration of 'excess volatiles,' RUBEY (1951) estimated the rate of outgassing of water from the earth's interior at 370×10^{12} kg / yr, assuming it had occurred at the same rate throughout geologic time. In the context of plate tectonics, the "outgassed" material may be mostly the result of recycling of seawater through subduction zones. SOUTHAM and HAY (1981) estimated the water lost to subduction to be 260×10^{12} kg / yr and suggested that most if not all of this is returned as volcanic water emissions. Recently, VON HUENE and SCHOLL (1991) have estimated the global long-term rate of subduction of sediment to be 1 km^3 solid per year. If the pore space is 30%, the mass of subducted water is 300×10^{12} kg / yr. These numbers so closely balance that outgassing of juvenile water must be negligible. Water arriving from outer space has become popular in recent years, but its volume is likely to be less than the amount of juvenile water added.

There are two reservoirs for water outside the ocean large enough to significantly affect the ocean volume: ice and groundwater. The volumes of ice at present and during the last glacial maximum are shown in Table 1. The estimates are from FLINT (1971), partially revised by DENTON and HUGHES (1981a). The amount of water currently present as ice is about 24.4×10^6 km^3. It is mostly in the Antarctic and Greenland ice sheets, but there are also lesser amounts in the Cordillera of North America, the mountains of Scandinavia, and elsewhere.

During the Quaternary as much as 2% of the total ocean volume may have been incorporated into ice sheets. During the Last Glacial Maximum the mean salinity of the ocean was probably about 36.0, but if the DENTON and HUGHES (1981b) "outrageous hypothesis" of a thick sheet of ice floating on the Arctic Ocean were true, the ocean salinity could have been as high as 37.6.

The effects of groundwater storage on the volume of water in the ocean is much less well known. It is probably about an order of magnitude less than the volume changes due to buildup and melting of ice sheets. The possibility of relatively short term changes in the volume of groundwater has been explored by HAY and LESLIE (1990), who concluded that changes in storage equivalent to 30 m of sea level were possible and changes equaling 10 m of sealevel were probable. The maximum possible salinity change due to groundwater storage would be in the order of 0.3‰.

Region	Age	Area 10^{12} m^2	Average Thickness m	Ice Volume 10^{15} m^3	= Water Volume 10^{15} m^3	=) Sealevel m
Antarctic						
	Present	12,53	1880	23,56	21,60	59,84
	Glacial	13,81	1880	25,96	23,81	65,95
Greenland						
	Present	1,73	1520	2,63	2,41	6,68
	Glacial	2,30	1520	3,50	3,21	8,88
Arctic Ocean						
	Present	15,00	3	0,05	0,04	0,00
	Glacial	15,00	1360	20,40	18,71	0,00
Laurentide						
	Present	0,00	0	0,00	0,00	0,00
	Glacial	13,39	2200	29,46	27,01	74,83
Cordilleran						
	Present	0,30	300	0,09	0,08	0,23
	Glacial	2,37	1500	3,56	3,26	9,03
British-Scandinavian-Barents-Kara						
	Present	0,30	300	0,09	0,08	0,23
	Glacial	8,37	2000	16,74	15,35	42,52
Other						
	Present	0,64	300	0,19	0,18	0,49
	Glacial	5,20	300	1,56	1,43	3,96
Totals with thick Arctic ice						
	Present	30,50		26,60	24,39	67,46
	Glacial	60,44		101,17	92,77	205,17
Δ Glacial – Present		29,94		74,57	68,38	137,71
Totals without thick Arctic ice						
	Present	30,50		26,60	24,39	67,46
	Glacial	60,44		80,82	74,11	205,17
Δ Glacial – Present		29,94		54,21	49,71	137,71

Table 1. Late Cenozoic ice volumes, after Flint (1971) and Denton and Hughes (1981a).

3. The amount of salt in the ocean

The major salt extractions of the Cretaceous and Cenozoic are given in Table 2. The total amount of salt removed from the ocean in the Late Miocene was about 6.08 x10^{18} kg, leaving the ocean with its present content of 46.8 x 10^{18} kg. The Late Cenozoic extractions lowered the salinity of the ocean significantly; the Middle Miocene mean ocean salinity must have been about 39.0.

The other major factor affecting ocean salinity is the addition of salt by rivers. Here a major problem arises, because if we assume that salt has been added by rivers at the present rate since the Late Cretaceous, the salinity of the Campanian ocean works out to be only 8.23‰. This brackish value is, of course, wholly incompatible with Cretaceous marine fossils that closely resemble modern marine organisms. The error lies in the assumption that all of the salt in rivers is "juvenile" and that none of it is recycled from the sea. This was the error that JOLY (1899) made when he estimated the age of the earth to be 90 m.y. The residence time of Cl⁻ in the ocean is in the order of 100 m.y., and any estimate of the salinity of the ocean prior to the Late Neogene must take atmospheric and sedimentary cycling into account.

Table 2. Mesozoic and Cenozoic evaporite deposits					
Geologic Age	Volume of Evaporites on Land (Ronov, 1982)	Volume of Offshore Evaporites (Holser & Wold, unpublished compilation)	Mass of Evaporites on Land	Mass of Offshore Evaporites	Total Mass
	m³	m³	kg	kg	kg
Pliocene	1,03E+11	0,00E+00	2,47E+14	0,00E+00	2,47E+14
Miocene	3,67E+13	2,63E+15	8,82E+16	6,30E+18	6,39E+18
Oligocene	5,70E+12	0,00E+00	1,37E+16	0,00E+00	1,37E+16
Eocene	1,58E+14	0,00E+00	3,79E+17	0,00E+00	3,79E+17
Paleocene	1,16E+13	0,00E+00	2,77E+16	0,00E+00	2,77E+16
Upper Cretaceous	8,47E+13	5,70E+13	2,03E+17	1,37E+17	3,40E+17
Lower Cretaceous	4,25E+14	4,00E+15	1,02E+18	9,60E+18	1,06E+19
Upper Jurassic	3,36E+14	1,33E+15	8,06E+17	3,19E+18	4,00E+18
Middle Jurassic	7,80E+12	1,75E+15	1,87E+16	4,20E+18	4,22E+18
Lower Jurassic	1,36E+13	1,75E+15	3,25E+16	4,20E+18	4,23E+18

Because the chloride ion is rare in igneous rocks, it has been used to evaluate the relative proportions of atmospherically recycled sea salt, sedimentary recycling of salt, and the input of juvenile chlorine to the atmosphere and river water. The bursting of bubbles generated by breaking waves injects droplets of seawater from the sea surface into the air. Evaporation of the water leaves the salt as an aerosol. Sea salt aerosol is concentrated below 1 to 2 km above the ocean surface and decreases exponentially with height (RYAN and MUKHERJEE, 1975). The salt is hygroscopic, and serves as a nucleus for raindrops. Hence rainwater has a small content of sea salt, the amount decreasing away from its source. The Cl- concentration ranges from > 8 mg / liter over the ocean to 1 mg / liter in coastal regions, to 0.1 mg / liter or less in the continental interiors (JUNGE and WERBY, 1958; STALLARD and EDMOND, 1981; DREVER, 1982; BERNER and BERNER, 1987). HOLLAND (1978) estimated the average chloride concentration [Cl-] in North American rivers as 8 ppm. He concluded that if Cl- in North American rivers was derived solely from atmospheric precipitation, [Cl-] would be 1-4 ppm depending on distance from the coast. He estimated that at present about 25% of the salt in rivers comes from the sea through atmospheric cycling and about 75% comes from the erosion of evaporite deposits. On a global scale this implies an annual delivery of about 0.1×10^{12} kg/yr of sea salt recycled through the atmosphere and about 0.3×10^{12} kg/yr of recycled sedimentary evaporites.

The total amount of evaporites on the continental blocks and potentially subject to erosion and recycling has been estimated by RONOV (1982) to be 6.084×10^{6} km³. Following ZHARKOV (1981) in assuming the evaporite deposits contain on the average about 80% NaCl and 20% CaSO$_4$, this equals 14.114×10^{18} kg, almost one third of the ocean's present content of salt. Applying the global average sediment recycling rate of WOLD and HAY (1993) to the evaporites suggests a long term rate of erosion of evaporites of 0.06×10^{12} kg / yr. This is about one fifth the present rate of delivery of salt to the ocean. The present rate of delivery is abnormally high because Quaternary rates of sediment delivery to the sea are generally four to five times higher than long term rates (HAY, 1994). This long term rate of delivery implies a long term salinity increase of 0.043‰ / m.y. Had no salt extractions taken place this rate of delivery would produce the present mass of salt in the ocean in about 800 million years. If nothing else had occurred, the salinity at the beginning of the Early Cretaceous would have been 6.45 ‰ less than today. More refined estimates of the effect of sedimentary recycling on changes in salinity of the ocean requires a detailed analysis of the global rates of erosion and deposition and the temporal distribution of evaporites.

Does the addition of juvenile Cl- play a significant role? Present volcanic emissions of Cl- into the troposphere and stratosphere are about 500 times smaller than the input of Cl- into the ocean from rivers. BARTELS (1972) estimated annual volcanic emissions of 7.6×10^{9} kg Cl- / yr from chlorine measurements for the Greenland icecap. ANDERSON (1974) estimated 1.7×10^{9} kg Cl- / yr in total volcanic emissions. Thus "juvenile chloride" is orders of magnitude less than the atmospheric and sedimentary recycling and can be neglected in reconstructing Phanerozoic salinities.

4. Sedimentary recycling of salt: The key to reconstructing past ocean salinity

The loss of NaCl through deposition of halite is the most significant removal from the ocean and also, because of the commercial value of salt, the best known. The largest evaporite deposits are formed by geologically short-lived ocean extraction events in marginal marine basins. The extractions are very irregularly distributed in time (HAY and WOLD, 1990). Some of the major extractions are related to continental rifting (SOUTHAM and HAY, 1981), others to times when meridional temperature gradients are maximal (HAY and WOLD, 1990). Evaporite deposition also occurs in geographically closed drainage basins from evaporation of meteoric water and runoff. This implies that the total flux of salt to and from the ocean during each interval of geologic time is equal to the amount of older evaporites eroded minus the volume of evaporites formed during the interval.

The original size of older evaporite deposits can be estimated using the methods for reconstruction of ancient sediment masses described by WOLD and HAY (1990, 1993). Their methods allow the past erosion rates of different lithologies to be estimated, and can be used to reconstruct the history of recycling of evaporite deposits and the salinity history of the ocean. The method can be summarized as follows:

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

$$y = A \ e^{-bt} \tag{1}$$

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 global sediment mass/age distribution.

WOLD and HAY (1993) used the data of RONOV (1982), BUDYKO et al. (1987), and HAY (1994) for existing Phanerozoic sediment masses to determine the average Phanerozoic zero-age flux rate to be 5.756 $\times 10^{21}$ g / m.y. and the average rate of sediment recycling to be -2.062 x 10^9 / m.y. The exponential decay curve (y = 5.756 $e^{-0.002062 \ t}$) is the most current representation of the average Phanerozoic flux and recycling rates.

This reconstruction method keeps the total global sediment mass constant. 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. 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 x 10^{21} g for the Proterozoic (570 to 2500 Ma) and 15.0 x 10^{21} g for the Archaean (2500 to 3800 Ma) sediments. We can 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]

$$TSM = \sum_{i=0}^{n} m[i], \tag{2}$$

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

123

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

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

$$m[i]_{eroded} = m[0] \times \frac{m[i]}{TSM - m[0]}. \qquad (4)$$

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. 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 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 deposition of evaporites. However, the amount of evaporites eroded must be related to the general rate of sedimentary cycling and the proportion of evaporites in sediments being eroded. According to RONOV'S (1982) data, evaporites are 0.953% of the total sedimentary mass. 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 the 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 the mass of evaporite stored in the ocean in solution can be determined and from this the paleosalinity can be estimated.

Table 3 shows the existing masses of evaporites, the reconstructed 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. 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. It also 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 about 35‰. Early Cretaceous mean ocean salinities were in the range 38.5 to 42‰. Jurassic mean ocean salinities ranged mostly between 45 and 50‰, and Triassic values were about 53‰. The implications of these higher salinities for the thermohaline circulation of the ocean are discussed in HAY and WOLD (1997).

5. Discussion

It had been suggested that more easily weathered sediments, such as evaporites, should be recycled more readily than others, and that sediments of some ages are specially protected against erosion (GARRELS and MACKENZIE, 1971). Selective, preferential erosion of evaporites would complicate or invalidate the method of reconstruction used here. However, on a global basis stratigraphic units are always very thin compared with their areal extent and can only be eroded 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

Table 3. Masses of water and salt, and estimates of the salinity of the ocean through the Cenozoic and Mesozoic

Geologic Age	Base of 10 m.y. Interval	Average mass of H2O in the ocean	Evaporite flux to ocean = 0.00953 x total reconstructed sediment flux x 10 my	Mass of salt in the ocean, removing river delivery of recycled sedimentary salt	Salinity of the ocean, taking only removal of recycled sedimentary salt into account	Salt flux out of the ocean into evaporite deposits	Mass of salt in the ocean, taking deposition of evaporites into account	Average salinity of the ocean, taking recycled sedimentary salts and evaporite deposition into account
	Ma	kg	kg	kg	S (‰)	kg	kg	S (‰)
Plio-Pleistocene	0	1,349E+21		4,853E+19	34,723		4,853E+19	34,723
Miocene	10	1,351E+21	1,297E+18	4,723E+19	33,778	1,683E+18	4,891E+19	34,939
	20	1,356E+21	8,333E+17	4,640E+19	33,083	3,538E+18	5,162E+19	36,669
Oligocene	30	1,367E+21	7,115E+17	4,568E+19	32,339	1,676E+18	5,258E+19	37,040
Eocene	40	1,367E+21	6,188E+17	4,507E+19	31,915	6,010E+16	5,202E+19	36,661
	50	1,367E+21	5,876E+17	4,448E+19	31,512	2,596E+17	5,169E+19	36,438
Paleocene	60	1,367E+21	5,638E+17	4,391E+19	31,125	1,464E+17	5,128E+19	36,154
	70	1,367E+21	5,558E+17	4,336E+19	30,743	7,960E+16	5,080E+19	35,830
Late Cretaceous	80	1,367E+21	7,705E+17	4,259E+19	30,213	1,297E+17	5,016E+19	35,394
	90	1,367E+21	7,922E+17	4,180E+19	29,668	1,334E+17	4,950E+19	34,946
	100	1,367E+21	7,155E+17	4,108E+19	29,175	8,494E+17	4,963E+19	35,037
	110	1,367E+21	6,319E+17	4,045E+19	28,739	5,818E+18	5,482E+19	38,557
Early Cretaceous	120	1,367E+21	6,464E+17	3,980E+19	28,292	5,957E+18	6,013E+19	42,134
	130	1,367E+21	6,616E+17	3,914E+19	27,835	3,074E+17	5,978E+19	41,897
	140	1,367E+21	6,662E+17	3,847E+19	27,374	3,149E+17	5,943E+19	41,661
Late Jurassic	150	1,367E+21	6,707E+17	3,780E+19	26,910	3,203E+18	6,196E+19	43,359
	160	1,367E+21	3,590E+17	3,744E+19	26,661	3,137E+18	6,474E+19	45,215
Middle Jurassic	170	1,367E+21	2,806E+17	3,716E+19	26,467	2,729E+18	6,719E+19	46,846
	180	1,367E+21	2,834E+17	3,688E+19	26,270	2,567E+18	6,947E+19	48,361
Early Jurassic	190	1,367E+21	3,021E+17	3,658E+19	26,061	2,595E+18	7,176E+19	49,877
	200	1,367E+21	3,054E+17	3,627E+19	25,849	2,632E+18	7,409E+19	51,411
	210	1,367E+21	3,931E+17	3,588E+19	25,576	2,669E+18	7,636E+19	52,906
	220	1,367E+21	4,843E+17	3,540E+19	25,239	1,183E+18	7,706E+19	53,365
Triassic	230	1,367E+21	4,928E+17	3,490E+19	24,897	5,357E+17	7,710E+19	53,393
	240	1,367E+21	5,181E+17	3,438E+19	24,536	6,012E+16	7,665E+19	53,092
	250	1,367E+21	7,215E+17	3,366E+19	24,034	6,108E+16	7,599E+19	52,659

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 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 most sediment is deposited in continental margins where they become deeply buried and hence are selectively preserved. The Devonian peak which was recognized by GARRELS and MACKENZIE (1971) as a major anomaly, has been considered as possibly due to selective preservation. WOLD and HAY (1993) tested the hypothesis of selective preservation of sediments in continental margin settings. BUDYKO et al. (1987) and RONOV (1982) had separated deposits associated with the continents into two major categories, "platform" and "geosynclinal". They used the term "platform" for the relatively undeformed sediments on the cratonic interior of the continental blocks and the term "geosynclinal" for the deposits of mountain belts and continental margins (edge of continental cratons). WOLD and HAY (1993) reasoned that if continental margin sediments are selectively preserved, then the ratio of "geosynclinal" to "platform" sediments should increase with age. They found no such trend in the data, and concluded that their relationship appears to be random.

6. Conclusions

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. The reconstruction of paleosalinities indicates that during most of the Cenozoic mean ocean salinities have been higher than they are today. Each of the major salt extractions into the offshore caused a rapid decrease of oceanic salinity by a few per mille. In the Early Cretaceous mean ocean salinities ranged between 38 and 42‰, and the Jurassic and Triassic they were between 43 and 53‰.

Acknowlegements

References

ANDERSON, A. T. (1974): Chlorine, sulfur, and water in magmas and oceans. - Geological Society of America Bulletin, 85:1485-1492.

BARTELS, O. G. (1972): An estimate of volcanic contributions to the atmosphere and volcanic gases and sublimates as the source of radioisotopes ^{10}Be, ^{35}S, ^{32}P, and ^{23}Na.- Health Physics, 22:387-392.

BERNER, E. K., and BERNER, R .A. (1987): The Global Water Cycle: Geochemistry and Environment. Prentice-Hall, Englewood Cliffs, N.J., 397 pp.

BUDYKO, M. I., RONOV, A. B., and YANSHIN, A. L., (1987): History of the Earth's Atmosphere. Springer-Verlag, New York, New York, 139 pp.

DENTON, G. H., and HUGHES, T. J. (1981a): The Last Great Ice Sheets. Wiley Interscience, New York, N. Y., 484 pp.

DENTON, G. H., and HUGHES, T. J. (1981b): The Arctic Ice Sheet: An outrageous hypothesis. - In DENTON, G. H., and HUGHES, T. J. (eds.), The Last Great Ice Sheets. Wiley Interscience, New York, N. Y., 437-467.

DREVER, J. I. (1982): The Geochemistry of Natural Waters. Prentice-Hall, Englewood Cliffs, New Jersey,

388 pp.

FLINT, R. F. (1971): Glacial and Quaternary Geology. John Wiley & Sons, New York, New York, 892 pp.

GARRELS, R. M., and MACKENZIE, F. T. (1971): Gregor's denudation of the continents. Nature, 231: 382-383.

HAY, W. W. (1994): Pleistocene-Holocene fluxes are not the Earth's norm. - In HAY, W. W. (ed.) Material Fluxes on the Surface of the Earth. National Academy Press, Washington, D. C., 15-27.

HAY, W. W., and LESLIE, M. A. (1990): Could possible changes in global groundwater reservoir cause eustatic sea-level fluctuations. - In REVELLE, R. (ed.) Sea-Level Change. National Academy Press, Washington, D.C., 161-170.

HAY, W. W., and WOLD, C. N., (1990): Relation of selected mineral deposits to the mass/age distribution of Phanerozoic sediments. - Geologische Rundschau, 79: 495-512.

HOLLAND, H. D. 1978. The Chemistry of the Atmosphere and Oceans. Wiley, New York, New York, 351 pp.

HOLSER, W. T., HAY, W. W., JORY, D. E., and O 'CONNEL, W. J (1980): A census of evaporites and its implications for oceanic geochemistry. - Geological Society of America, Abstracts with Programs 12: 449.

JOLY, J. (1899): An estimate of the geological age of the Earth. - Transactions of the Royal Society Dublin [2] 7:23-66.

JUNGE, C. E., and WERBY, R. T. (1958): The concentration of chloride, sodium, potassium, calcium, and sulfate in rain water over the United States. - Journal of Meteorology 15:417-425.

RONOV, A. B. (1982): The earth's sedimentary shell (Quantitative patterns of its structure, compositions, and evolution). - International Geology Review 24:1365-1388.

RUBEY, W. W. (1951): Geologic history of sea water. - Geological Society of America Bulletin 62:1111-1148.

RYAN, J. A., and MUKHERJEE, N. R. (1975): Sources of atmospheric gaseous chlorine. - Reviews of Geophysics and Space Physics 11· 650-658.

SHACKLETON, N. J., and KENNETT, J. P. (1975): Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: Oxygen and carbon isotope analyses on DSDP sites 277, 279, and 281. - Initial Reports of the Deep Sea Drilling Project, 29. U.S. Government Printing Office, Washington, D.C., 743-755

SOUTHAM, J. R., and HAY, W. W. (1981): Global sedimentary mass balance and sea level changes. - In EMILIANI, C. (ed.) The Sea, 7, the Oceanic Lithosphere. Wiley-Interscience, New York, New York, 1617-1684.

STALLARD, R. F., and EDMOND, J. M. (1981): Chemistry of the Amazon, precipitation chemistry and the marine contribution to the dissolved load at the time of peak discharge. - Journal of Geophysical Research 86: 9844-9858.

VEIZER, J., and JANSEN, S .L. (1985): Basement and sedimentary cycling - 2: Time dimension to global tectonics. - Journal of Geology, 93: 625-664.

VON HUENE, R., and SCHOLL., D. W. (1991): Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust. - Reviews of Geophysics 29: 279-316.

WOLD, C. N., and HAY, W. W. (1990): Estimating ancient sediment fluxes. - American Journal of Science, 290: 1069-1089.

WOLD, C. N., and HAY, W. W. (1993): Reconstructing the age and lithology of eroded sediment. - Geoinformatics 4: 137-144.

ZHARKOV, M. A. (1981): History of Paleozoic Salt Accumulation. Springer Verlag, New York, New York, 308 pp.

Paläontologie, Stratigraphie, Fazies Heft 5

Karl-Armin-Tröger-Festschrift