RATE AND MASS OF DEEP-SEA SEDIMENTATION.

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ABSTRACT. The average rate of deep-sea sedimentation as found by several independent methods is found to agree very satisfactorily (see table II). Several independent methods for estimating the total mass of deep-sea sediment show results of the same order of magnitude. Former estimates showed divergencies of some 100,000 times. These hopelessly wide limits are now reduced to about one in four (see table IV).

A. RATE OF DEEP-SEA SEDIMENTATION.

ESTIMATES of the rate of sedimentation in the deep-sea have differed to such an extent that the total mass of sediment on the ocean floor has as yet not been evaluated to general satisfaction. On the one hand it has been held that the dredging of Tertiary sharks' teeth proved an almost total lack of deposition over areas occupied by red clay and therefore over most of the deep-sea floor. Others, like Murray and Hjort (1912, p. 170), calculated a rate of deposition for globigerina ooze of 2 to 5 cm. per 10 years from the state of preservation of transoceanic telegraph cables. There is nothing to show that the former observation gives a fair picture of average conditions, for a bottom current may reduce or even entirely prohibit deposition on certain limited areas while elsewhere in still water the sedimentation could be infinitely quicker. The second method leads to an impossibly high figure and is evidently based on erroneous interpretation; the heavy cable sinks into and thus becomes embedded in the mobile sediment, but it is not covered by deposition in a few years time.

We are now in a much better position to judge the rate of abyssal sedimentation, as three or four independent methods for measurement are available and these give comparable results.

Schwinner (1936, p. 149) evaluated the total fall of meteoritic dust on the earth at 500 tons per year. Using the measured content of nickel iron and silicate spherules in red clay and globigerina ooze he found a rate of sedimentation of 0.2 cm. and 4 cm. per thousand years respectively. Schwinner added a correction for oxidation and decomposition of the globules, and compaction. The rate of sedimentation should possibly be divided by about three. In the opinion of the present writer this correction is not justified. Murray and Renard described the crust of magnetite developed around the meteoritic iron during the passage through the atmosphere. The cupule resulting from the contraction of the molten outer crust is generally clearly marked. The preservation of these exterior characteristics is strong evidence against a subsequent attack on the spherules by weathering in the seawater or on the sea floor. The correction introduced by Schwinner will therefore be discarded.

On the other hand the authors of the Challenger Report point out that the red clays, in which the quantity of spherules was determined, contained a relatively large amount of rare products such as shark's teeth, etc. In other red clays a much smaller amount of meteoric dust occurred. The figure calculated by Schwinner is consequently well below the average for all red clays. I will therefore take twice the rate of deposition for red clay, that is 0.4 cm. per 1000 years as the outcome of the "meteorite method".

Lohmann (1909) chose a similar method but used the production of coccoliths as basis for his calculation.

For a sediment rich in these particles ($\pm 60\%$) he found a rate of deposition of 0.1 cm. per 1000 years. (According to Correns (Symposium, 1939, p. 388) the original estimate of 0.2 mm. was halved.) As globigerina ooze contains on an average about 1/10 to 1/20 of this amount of coccoliths—as far as I have been able to ascertain—the rate of deposition would amount to 1 to 2 cm. per 1000 years.

W. Schott (1939) used a general stratification of the deep-sea deposits in the tropical Atlantic and southwestern Indian Ocean. Taking the upper stratum as representing Post-

TABLE I.

Sedimentation according to Schott, in centimeters.

		Blue mud	Glob. ooze	Diatom ooze	Red clay
Average Thickness	Atl. O.	36	24		17
	Ind. O.		12	11	
Smallest, average, and largest per 1000 years.	Atl. O.	0.9 *1.8* 3.3	0.5 *1.2* 2.1		<0.5 *<0.9* 1.[illegible]
	Ind. O.		0.3 *0.6* 1.0	0.3 *0.5* 0.7	

Glacial time, thus having been formed in 20,000 years, he found the values given in table I.

The lower values of the Indian Ocean are attributed by Schott to a smaller contribution of sediment from the continents. But the thickness of the Post-Glacial layer increases northwards in the Indian Ocean. It is 6 cm. at the southern boundary of the globigerina ooze, increasing to 15-20 cm. at 40° Southern latitude. It appears likely, therefore, that around the equator the Atlantic average of 24 cm. is attained also in the Indian Ocean. Probably the southern margin of the globigerina ooze has gradually migrated southward. The Post-Glacial stratum would thus represent an ever shorter period on approaching higher latitudes. This interpretation appears more probable for a pelagic deposit, as it is only in minor degree dependent on supply of terrigenous matter.

Piggot and Urry (1942) recently developed by far the most accurate and trustworthy method of calculating the rate of deposition. They determined the radioactivity at a large number of points along deep-sea cores. The activity is caused by a constant amount of uranium and by an additional amount of ionium and radium. The latter two elements are reduced in time from their initial ratio to the amounts that are in radioactive equilibrium with the available uranium. The authors mentioned show how mathematical analysis of the variation of radioactivity with distance from the surface in the sample core leads to a dating of each point analysed. The younger parts can be dated to within one or two hundred years. Thus for the same volcanic ash in two samples an age of 13,300 and 13,100 years are found. The greatest age that can be ascertained with any degree of accuracy is 300,000 years.

The assumption is made that the ratio in which uranium, ionium, and radium are deposited at any one place in the oceans has remained constant during the period represented in the sample, although a different ratio is found for various areas and various types of deposit. The objection might be raised, that sedimentary petrography shows how in general the vertical variation is greater than the horizontal variation. Therefore a gradually or abruptly varying ratio for the three elements at one point of the sea floor might appear more probable. It should be kept in mind, however, that most of the factors causing vertical variations in continental sediments do not influence pelagic deposits. Much thicker strata may form on the floors of the ocean, without alteration in the nature or distance of the source, than in continental basins. Moreover, the deposition of the radioactive elements has not yet been elucidated, but is evidently not that of normal settling of particles. What factors would cause variation in the ratio of deposition can therefore not yet be evaluated. Finally the very regular curves representing the radioactivity with depth ascertained by Piggot and Urry, even where lithological strata are passed, form strong evidence in favor of their assumption of a constant ratio of deposition at the site of each bottom sample (core).

Up to the time of writing only a few cores have been treated by this method. The results for a core of red clay taken 500 km. off the coast of California is 0.5 cm., and for a globigerina ooze in the Caribbean sea of 0.6 cm., per 1000 years. In the northern Atlantic the blue mud close to the coast of Newfoundland, at the end of the Labrador current, shows 24 cm. per 1000 years and another core to the east of the Mid-Atlantic ridge 11 cm. In the center of the western basin the average rate for a terrigenous globigerina ooze was ascertained at 4 cm. per 1000 years.

In the East Indies Miss Neeb (1943, p. 234) was able to recognize the volcanic ash deposited from the eruption of the Tambora on Soembawa in 1815 and that of the Oena Oena volcano in the Gulf of Tomini of 1899. Four Tambora samples showed an average deposition of at least 23 cm. in 115 years, of which half was volcanic, one third terrigenous materials and one tenth lime. The rate of deposition is thus found to be 200 cm. per 1000 years, of which 100 cm. are ash, 75 cm. terrigenous, and 20 cm. $CaCO_3$ (coral, limestone detritus, pelagic tests, etc.). An Oena Oena core showed 2 cm. in 30 years or 66 cm. per 1000 years.

The average of 90 cm. non-volcanic material per 1000 years is probably too high for the whole Moluccan area, as the samples were taken close to larger islands (north of the Lesser Sunda Islands and between Borneo and Celebes).

Only in the one core of Oena Oena material could Miss Neeb determine the rate of sedimentation of globigerina tests. She found 0.072 cm. per 30 years or 2.4 cm. per 1000 years. As globigerina oozes contain—besides tests—a certain amount of terrigenous matter, a figure of 3 cm. per 1000 years may be assumed for that type of deposition in the East Indies.

Kuenen (1943, p. 31) attempted to estimate the average deposition from the denudation in the Moluccan area. He obtained 50 cm. terrigenous matter. For estimating the average rate of sedimentation of tests, shells, etc. in the Moluccas we can use the average percentage of $CaCO_3$, 19.7% (against 45.9% for all Challenger samples). This amount must be somewhat too high, because the calcareous matter is deposited more slowly and is therefore overestimated. On the other hand 1.4% must be added for siliceous organisms. Therefore 19% $CaCO_3$ will be assumed. Added to the 50 cm. terrigenous matter we obtain 62 cm. per 1000 years for blue mud. As detrital lime is included twice by this method 60 cm. is the ultimate figure. Using the percentage of volcanic ash in the sediments and starting from the estimated contribution by volcanoes, double this amount is found, but this method is more open to doubt. Hence the figure of 70 cm. per 1000 years for blue mud will be assumed. (For all deposits including volcanic matter 80 cm.)

Revelle and Shepard (1939, p. 273) deduced the rate of sedimentation in basins off the Californian coast at 25 cm. per 1000 years from the denudation. As loss to the open ocean should be subtracted, a figure of 20 cm. per 1000 years appears more probable.

In the Black Sea (Trask 1939, p. 488) a yearly rhythm of 0.2 mm., consisting of a light and a dark stratum, is found in bottom samples. The rates of sedimentation obtained by the examination of core samples all need a correction. The strata on the sea floor are reduced in thickness on being forced into the sampler. Piggot and Urry established experimentally that this reduction is of the order of 20%.

The results obtained by the various methods are summarized in table II.

The averages of the rate of sedimentation for each of the various types of deep-sea deposits as found by independent methods fit each other remarkably well. The divergence of estimates that used to run to at least 100,000 times, now appears to be reduced to 5 times for red clay or globigerina ooze. The larger divergences for blue mud are doubtless due to actual differences in the rate of sedimentation in various localities. Even the rates of deposition calculated from denuda-

TABLE II.

Rates of oceanic sedimentation according to various methods.

	Red clay	Glob. ooze	Blue mud	Diat. ooze
Meteorites	*0.4*	*4*		
Coccoliths		*1–2*		
Glacial strata				
(Atl. + Indian)	0.9	1.0	1.8	0.5
Corrected	*1.1*	*1.2*	*2.2*	*0.6*
Radioactivity	0.5	0.6 (4)	10 (24)	
(Atl. Pacific)				
Corrected	*0.6*	*0.7 (4.8)*	*12 (29)*	
Moluccas		3	95	
Corrected		*3.6*	*110*	
Calculated			70	
Yearly rhythm				
(Black Sea)			20	
Corrected			*24*	
Off California				
Calculated			*20*	

tion, are in fair accordance with the values found by measurement for the same region.

The principal need at present is for more extensive application of the method used by Piggot and Urry, especially to red clays from the central Pacific and deposits from the southern oceans. Nevertheless the order of magnitude is now established beyond doubt for the Quaternary period.

A vexed problem is whether the present rate of pelagic sedimentation is representative of the whole geologic past, or at least since the Precambrian, or whether the high relief of the continents and the Glacial Epoch have caused as great an increase of sedimentation in the deep-sea as must be assumed for denudation on land.

Reasons were given in my paper of 1941 for strongly doubting that the glacial epoch has caused a substantial increase in pelagic sedimentation. In my opinion an average rate of deposition in the deep-sea of 0.5 cm. per 1000 years for the geological past is the best estimate that can at present be made.

B. MASS OF DEEP-SEA SEDIMENTATION.

The most important method for estimating the total amount of sediments in the earth was employed by Clarke (1924, pp. 23-

36). First the average composition of igneous rocks is determined. From the average composition of shale, sandstone, and limestone the relative amounts of these products of weathering are ascertained. It is then found that a large proportion of the sodium is missing from the sedimentary rocks. The sodium in the oceans is supposed to represent the leached-out material that has gradually accumulated during the weathering of more and more igneous material. By a simple calculation the known store of sodium in oceanic waters is then converted to the total mass of weathered igneous rock. Clarke's conclusion was that 3.7×10^8 km.^{3} of sediment is the highest figure possible.

Goldschmidt (1933) averaged a number of Norwegian boulder clays and assumed that these must give a fair picture of the average composition of the earth's crust. He found almost the same composition as Clarke had calculated.

But later Kuenen (1941) pointed out several corrections that should be applied to Clarke's calculations, and in consequence the minimum amount was found of $5\frac{1}{2} \times 10^8$ km.^{3} Incidentally a much closer resemblance between assumed source material and resulting sediments was obtained (see table III).

Table III.

	Average composition of rocks								
	I	II	III	IV	V	VI	VII	VIII	IX*
	Shale	Sandst.	Limest.	Red clay	Terrig. clay	Globig. ooze	Source	All sediment	% difference
SiO_2	58.11	78.31	5.19	54.48	57.05	26.64	57.83	58.16	+ ½
Al_2O_3	15.40	4.76	0.81	15.94	17.22	9.75	15.68	15.93	+ 1½
F_2O_3	6.70	1.40	0.54	9.60	7.60	3.75	8.17	8.54	+ 5
MnO	trace	trace	0.05	0.99	0.12	0.27	0.17	0.64	?†
MgO	2.44	1.16	7.89	3.31	2.17	1.38	3.77	3.58	− 5
CaO	3.10	5.50	42.57	1.96	2.04	28.87	5.87	6.26	+ 7
Na_2O	1.30	0.45	0.05	2.05	1.05	0.98	3.47	1.89	−45
K_2O	3.24	1.32	0.33	2.85	2.25	1.32	2.59	2.82	+ 9
TiO_2	0.65	0.25	0.06	0.98	1.27	0.29	0.98	0.94	− 5
P_2O_5	0.17	0.08	0.04	0.30	0.21	0.18	0.28	0.26	− 8

* Differences between column VII and VIII in percentage of each constituent of the source material.

† Large discrepancy owing to reasons given in my paper of 1941.

Several considerations were brought forward by Kuenen (1941) that render an even larger total mass of sediments probable. We will accept 7×10^8 km.^{3} as the outcome of geochemical calculation for all sedimentary material in the earth's crust. For the deep-sea deposits 5 x 10^8 km.^{3} is thus established, because continental sediments are of the order of 2 x 10^8 km.^{3}

A second geochemical trend in sedimentation was indicated by Steidtmann. The relative amounts of the various types of sediment as measured in a large number of sections is found to be very different from that calculated by Clarke. If this method is applied to the data assembled by Kuenen (1941) the following results are obtained. The calculated ratio of shale: sandstone: limestone is 20 : 3 : 2 and the measured ratio is 20 : 12 : 14. If no lime had been deposited in the deep-sea the loss of clay and quartz to that environment would amount to 74% of the source material. Taking the total mass of sediments on the continents as 2 x 10^8 km.^{3} the deep-sea sediments would amount to 6 x 10^8 km.^{3} To this must be added 12½ times the volume of calcareous matter deposited in the deep-sea, or roughly 2½ x 10^8 km.^{3} This method leads us to a total mass of deep-sea sediment measuring 8½ x 10^8 km.^{3}

A third method is to estimate the total amount of denudation and to add production from volcanic eruptions (Kuenen, 1937). The outcome by this procedure is 10 x 10^8 km.^{3} Admittedly this figure is only a very rough estimate, but it goes to show, that no inadmissible assumptions are required to account for a total mass of sediment that is several times 10^8 km.^{3}

A fourth method of approach is by the percentage of TiO_2 and P_2O_5 contained in the source materials and in various types of sediment. From our table III it will be seen that, compared to the source material, the continental deposits, shale, sandstone, and limestone, show a marked deficiency in both these elements. In order to balance this loss a considerable amount of terrigenous deep-sea clay is required in the case of titanium, and an even larger quantity of red clay in the case of phosphorus.

The accuracy of the data does not appear sufficient to warrant an exact calculation of the amount of deep-sea deposits from these two elements alone, but one may conclude that the volume is several times that of the continental sediments. With Clarke's original estimates no less than 50 and 40% of the TiO_2 and P_2O_5 contained in the source material is unaccounted for. Only by incorporating an ample mass of deep-sea deposits can the geochemistry of these two constituents be brought into balance.

The fifth method for estimating the total mass of sediment is to use the rate of sedimentation of deep-sea oozes and to multiply this by the age of the earth. As the relief of the continents is greater than was generally the case in the past, and as epicontinental seas are at present poorly developed, a smaller average rate of sedimentation will be assumed for the past. From table II an average rate of sedimentation at present in the deep sea (in which red clay plays a predominant part) of 1 cm. per 1000 years follows. An estimate of ½ cm. for the past appears a reasonable deduction. Calculated as solid mass this would come to 1/7 cm. per 1000 years. In the course of 2×10^9 years this would amount to 2.9 km. This works out at $8\frac{1}{2} \times 10^8$ km.^{3}

In order to illustrate the surprising agreement between the 5 independent estimates of the total mass of deep-sea deposits on the floor of the oceans, the results are brought together in table IV.

TABLE IV

Total mass of deep-sea deposits according to various methods of calculation (without pore-space).

1.	From the Na in the ocean	5×10^8 km^3
2.	From the composition of continental sediments	8.5×10^8 km^3
3.	From denudation and volcanic eruptions	10×10^8 km^3
4.	From the geochemistry of TiO_2 and P_2O_5 ... several times	2×10^8 km^3
5.	From the rate of sedimentation	8.5×10^8 km^3

It is difficult to say which of these results may be considered most trustworthy. The last method certainly starts from the most definitely established figures, viz. the present rate of sedimentation. But the extrapolation over earlier periods with different climatic and physiographic conditions is open to doubt. Although the present author is inclined to believe that pelagic sedimentation is not open to such large variations as continental deposition, one cannot feel quite safe on this score. The third and fourth methods are definitely no more than checks that can only confirm the conclusions from other sources in a general way. It is gratifying in any case that no flat contradiction is encountered. The second method is capable of yielding fairly trustworthy results, but more accurate knowledge of the composition of continental sediments is needed. It is most improbable, however, that future corrections would bring alterations in the order of magnitude. The first method has the advantage over the fifth of not involving much in the way of extrapolation on major points. But the initial composition of the oceans is postulated as fresh without proof. Furthermore the sodium content of the deeply-buried oceanic sediments is a point on which we are not sufficiently informed. But here again a drastic change in the estimate is not probable. All the corrections added by Kuenen amounted only to trebling the amount deduced by Clarke. Concerning the sodium method it appears to the present writer that the extrapolation—involved in the use of present pelagic sedimentation—to early periods even beyond the Cambrian is amply justified.

In conclusion, the total mass of deep-sea deposits is estimated at six to eight times 10^8 km.^{3} The thickness of the strata on the ocean floor must be between 1 and 5 km., most probably around 3 km.

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