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Sediment Budget in a Deep-Sea Core from the Central Equatorial Pacific[1]

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ABSTRACT

Stratigraphic, mineralogic, chemical, and geochronologic measurements on a core from 8°20′N, 153°W show that sediment has been accumulating at a rate of 160 $g/cm^2/10^6$ years. Of this, 125 g is "fresh" Quaternary sediment while the remainder is lower and middle Tertiary material eroded from nearby outcrops. Comparison of the core with 37 others taken within a few kilometers indicates that the measured rate of accumulation has been at least an order of magnitude higher than the regional average. However, comparison with geochemical models suggests that the rate of accumulation in the core has been 1.4–3.5 times lower than the average for all pelagic sediments.

Introduction. During the 1965 Wahine Expedition of the Scripps Institution of Oceanography, a small area southeast of Hawaii (8°20′N, 153′W; Fig. 1) was surveyed in detail. Thirty-eight closely spaced cores (Fig. 2) were collected from this area to evaluate the importance of local variability in the overall pattern of deep-sea sedimentation. The structural setting of the cores and the distribution of Quaternary sediments and manganese nodules have been discussed by Moore and Heath (1966, 1967). Subsequently, studies were made of the stratigraphy (Moore 1968, 1969), of the mineralogy (Heath 1968, 1969), and of the geochemistry (Cronan 1967, 1969b) of selected samples. The studies have clearly shown that the texture and mineralogy of the Quaternary sediment are fairly uniform (Table I) whereas its thickness varies by more than two orders of magnitude. The degree of contamination of Quaternary sediment by locally derived lower and middle Tertiary debris has also been highly variable (Table I).

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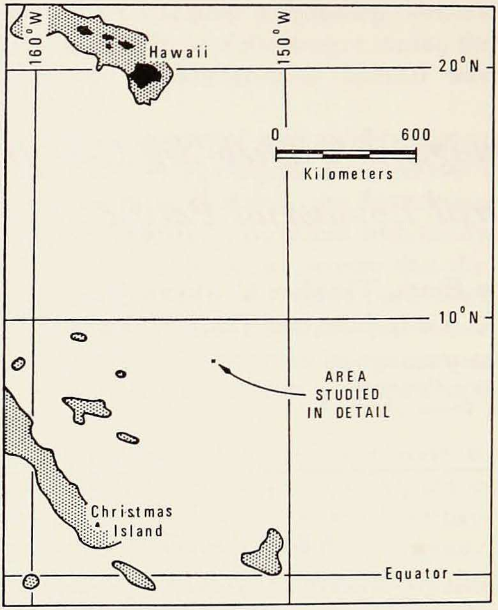

Figure 1. Location of study area (Fig. 2) containing core WAH 24F-8. Stippled areas indicate water that is shallower than 4 km.

If these findings are valid for large portions of the deep oceanic basins, it seems that isolated samples of deep-sea sediment can yield mineralogical data that are close to the average for large surrounding areas and can therefore be used to establish global distribution patterns (Biscaye 1965, Griffin et al. 1968). On the other hand, isolated data on mixing and rates of accumulation may deviate markedly from the local mean (Ku et al. 1968).

Recently, one of us (B. L. K. S.) has determined the rate of accumulation of sediment in core WAH 24F-8 (Fig. 2) by the ionium-thorium method (Goldberg and Koide 1962). The measurements (Fig. 3; Table II) indicate essentially uniform deposition throughout the interval sampled (72 cm). In this paper we use this determination to calculate the absolute rates of accumulation of selected components in the sediment of core WAH 24F-8. The regional validity of these rates can then be evaluated from our knowledge of the pattern of sedimentation in the surrounding area.

Results. The following experimental details of the techniques employed have been reported: the stratigraphic analyses and estimates of mixing (Moore 1968), the mineralogical and textural analyses (Heath 1968), the chemical analysis (Cronan and Tooms 1969), and the ionium-thorium dating (Goldberg and Koide 1962).

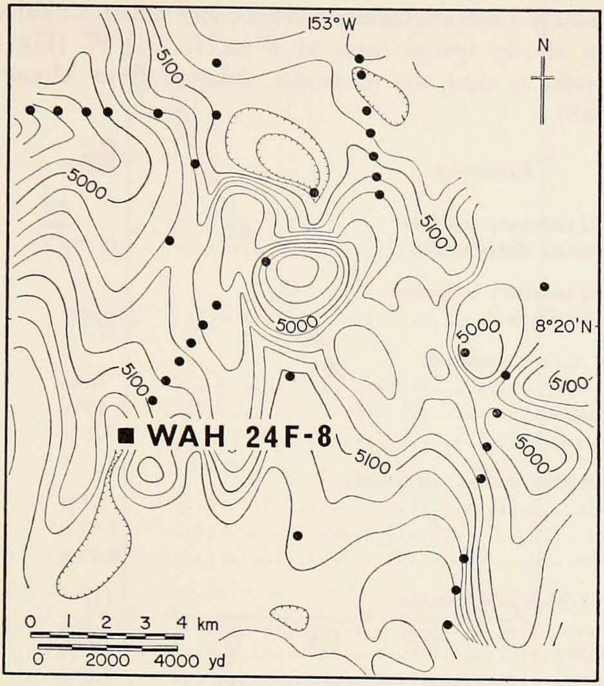

Figure 2. Topographic setting of core WAH 24F-8 and its relation to other nearby cores (solid dots). Contours in corrected meters: interval 20 m.

A straight line fitted by least squares to the ionium-thorium data (Fig. 3) yielded a rate of accumulation of 5.5 mm/1000 years (5.5 m/10^6 years). The wet density of the sediment in the core was very uniform (range: 1.20–1.22 g/cc). The mean accumulation rate of the solid phases was 0.16 g/cm^2/1000 years, or 160 g/cm^2/10^6 years.

Contamination of the Quaternary sediment by material eroded from nearby lower and middle Tertiary outcrops has been a complex function of topography, small-scale tectonics, and local variations in the pattern of sedimentation (Moore 1969). However, at a single location such as WAH 24F-8, the extent of mixing appears to have been remarkably uniform for a period of almost 200,000 years represented by the core (Table III). If the nonbiogenous components of the reworked Tertiary sediments were redistributed in the same way as the included microfossils, it is possible to calculate the rates at which "fresh" and reworked sediment have accumulated at WAH 24F-8 (Table III).

Cronan's (1967) analytical data for several elements in this core, together with the deduced rates of accumulation of the elements determined, are summarized in Table IV. The uniform mineralogy of samples from WAH 24F-8

Table I. Summary of stratigraphic, textural, and mineralogical data for sediment from closely spaced cores at 8°20′N, 153°W (Fig. 2). Standard deviations refer to data, not to means. Adapted from Moore (1968) and Heath (1968).

Parameter	Mean	Mean ± 1 standard deviation
*Thickness of Quaternary sediment (arithmetic normal distribution)	41 cm	4–77 cm
*Thickness of Quaternary sediment (log-normal distribution)	15 cm	2.7–76 cm
Components of surface sediment		
Quaternary	76%	59–94%
Oligocene-Miocene	18%	4–32%
Eocene	5.4%	0.5–10.3%
Grain-size parameters (Stokes diameters)		
25th percentile	5.7 μ	5.2–6.2 μ
Median	1.42 μ	1.34–1.51 μ
75th percentile	0.43 μ	0.41–0.45 μ
Mineralogy of 2-20-μ size fraction		
Quartz	12.1%	11.4–12.8%
Total plagioclase	11.5%	10.2–12.8%
Plagioclase An_{0-75}	8.3%	7.8– 8.8%
Pyroxene	3.4%	3.1– 3.7%
Mineralogy of < 2-μ size fraction		
Montmorillonite	46%	38–54%
Illite	36%	31–40%
Chlorite	11%	9–13%
Kaolinite	7%	6– 9%

* The distribution of thicknesses in Quaternary sediment is strongly positively skewed if treated as arithmetic normal but almost symmetrical if treated as log-normal. Thus, parameters derived from the latter treatment probably yield a better description of sedimentation in the area. Since the distribution is open (not all cores penetrated the full Quaternary section), statistical parameters have been derived graphically (Inman 1952).

and from other cores in the vicinity (Heath 1968) suggests that extrapolation of the results from a single analysis is justified.

The mineralogical data (Table V) refer either to the 2-20-μ or to the less-than-2-μ size fractions. Together, these two fractions form 90–92% of all samples. The boundary at 2 μ corresponds fairly closely to a natural break between the fine-grained clay minerals and the coarser more-equidimensional minerals like quartz, feldspars, and pyroxenes. The abundances of clay minerals in the less-than-2-μ fractions, estimated according to Biscaye's (1965) convention, may contain systematic errors (Biscaye 1965, Heath 1968). The 2-20-μ minerals, determined by X-ray diffraction, using an α-alumina inter-

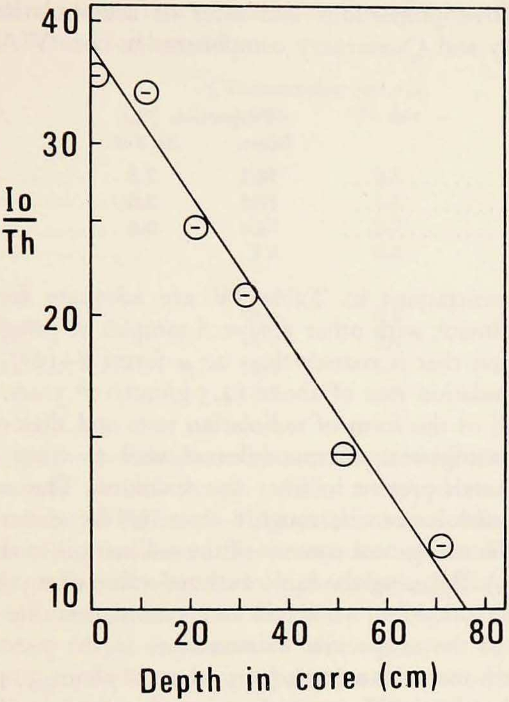

Figure 3. Logarithm of the activity ratio Io (Th^{230}): Th^{232} versus depth for core WAH 24 F-8. The least-squares-fit straight line is equivalent to an accumulation rate of 5.5 mm/1000 yrs.

nal standard, should be relatively free of systematic errors. The 2-20-μ material is probably largely of eolian origin (Rex and Goldberg 1958, Windom 1969) whereas the less-than-2-μ fraction could include nepheloid material introduced to the area by bottom currents (Jacobs and Ewing 1969).

Note that neither the mineralogy nor the chemistry of the sediment is fully defined. The abundances of the major elements—silicon, aluminium, the alkalis, alkali earths, and oxygen—have not been determined. However,

Table II. Thorium isotopes in sediment from core WAH 24F-8 (8° 18′ 16″N, 153° 02′ 50″W). Analysis by B. L. K. Somayajulu.

Sample interval (cm)	Th^{232} (ppm)	$\frac{Th^{230}}{Th^{232}}$	$\frac{Th^{228}}{Th^{232}}$
0– 2	5.5	35.1	1.31
10–12	5.3	33.8	1.00
20–22	3.8	24.6	1.02
30–32	5.6	21.0	1.00
49–53	2.7	14.4	1.12
70–72	3.7	11.6	1.08

Table III. Relative proportions and rates of accumulation of lower and middle Tertiary and Quaternary components in core WAH 24F-8. After Moore 1968.

Component	Proportion (%)		Accumulation rate ($g/cm^2/10^6$ yrs.)
	Mean	St. dev.	
Quaternary	78.1	2.5	125
Oligocene-Miocene	17.5	2.0	28
Eocene	4.4	0.6	7

the element concentrations in Table IV are adequate for comparing the WAH 24F-8 sediment with other analyzed samples of pelagic deposits.

The size fraction that is coarser than 20 μ forms 8–10% of the sediment and has an accumulation rate of about 14.5 $g/cm^2/10^6$ years. This fraction is dominated by opal in the form of radiolarian tests and diatom frustules. Also present are ferromanganese micronodules as well as trace amounts of fish debris and of minerals present in finer-size fractions. The rate of accumulation of the micronodules can be roughly estimated by assuming that approximately 88% of the manganese content of the sediment is in this form (Chester and Hughes 1966). By using the same authors' value of 23% for the manganese content of micronodules, we obtain an accumulation rate of 6.2 $g/cm^2/10^6$ years. The bulk of the unspecified minerals are in the 2-20-μ size fraction, of which they form more than 60% (equivalent to about 30 $g/cm^2/10^6$ years). Clay minerals, the dominant components of this "missing" material, could not be reliably estimated because grains of opal and other more or less equidimensional minerals interfered with the preparation of consistently oriented aggregates for X-ray diffraction analysis. Although the precision of the estimates is poor, it appears that the only major difference between the relative proportions of the principal clay minerals in the 2-20-μ and less-than-2-μ fractions is a reduction of montmorillonite by 30–50% in the coarser material.

Table IV. Analytical data at 58–60 cm and rate of accumulation of trace elements in core WAH 24F-8.

Element	Concentration (wt. %)	Accumulation rate ($g/cm^2/10^6$ yrs.)
Fe	3.45	5.5
Mn	1.02	1.6
Ni	0.05	0.08
Co	0.01	0.02
Cu	0.02	0.03
Pb	0.002	0.003
V	0.02	0.03
Cr	0.005	0.008
Ti	0.30	0.48
P	0.09	0.14
Mo	0.004	0.006

Discussion. The data for WAH 24F-8 (Tables III–V) are strictly applicable to only the few square centimeters sampled by the coring tube. To what extent can these data be extrapolated to the surrounding few square kilometers shown in Fig. 2, or even

Table V. Abundances and rates of accumulation of selected minerals in core WAH 24F-8. After Heath 1968.

Mineral	Concentration (wt. %) Mean	St. dev	Accumulation rate ($g/cm^2/10^6$ yrs.)
2-20-μ fraction			
Quartz	12.2	0.4	6.0
Total plagioclase	11.8	1.1	5.8
Plagioclase An_{0-75}	8.8	0.7	4.4
Pyroxene	3.8	0.3	1.9
<2-μ fraction			
Montmorillonite	30.4	3.3	29.1
Illite	44.5	2.4	42.6
Chlorite	15.3	0.4	14.6
Kaolinite	9.7	0.5	9.3

to the surrounding few hundred or thousand square kilometers? If the data in Table I constitute a valid sample of the surveyed area, it appears that the constitution of the WAH 24F-8 material is not markedly different from that in the surrounding sediment. However, the measured rate of accumulation is at least an order of magnitude higher than the local average (if the distribution of sediment thicknesses is taken to be log normal; Table I). Because of the very large dispersion of the thickness data, it is doubtful whether the existing sample coverage forms an adequate basis for estimating an "average" rate of deposition for the area. What these data do point to, however, is the difficulty of using the budget for WAH 24F-8, or for any other isolated core, as a basis for calculating meaningful rate constants and partition coefficients for the geochemical cycle.

By comparing the element concentrations in Table IV with the averages of Goldberg and Arrhenius (1958) and Cronan (1969b) and with the values derived from mass-balance calculations by Horn and Adams (1966), we see that the WAH 24F-8 sediment is close to a "typical" pelagic clay. Only Mn, Ni, and Mo are somewhat anomalous in that they are slightly enriched in this core relative to their average abundances in pelagic clays. This enrichment may reflect the presence of the ferromanganese micronodules mentioned previously, since Ni and Mo seem to be concentrated in this phase (Cronan 1969a).

If this core does represent "typical" pelagic sediment, what does the budget reveal about published geochemical material balances? Let us consider only the models of Goldberg and Arrhenius (1958) and Horn and Adams (1966), since their results are fairly close to the published extremes. Horn and Adams have concluded that the abundance and distribution of elements in various types of sediment and in the ocean result from the weathering of 2.04×10^{24} g of crustal igneous rock whereas Goldberg and Arrhenius have arrived at an estimate of 9.4×10^{23} g. Horn and Adams have assumed that the amount of pelagic clay is 86% of 3.38×10^{23} g and that this is deposited over an area of 2.68×10^{18} cm² (about 53% of the earth's surface). This is equivalent to 1.1×10^{5} g/cm². Goldberg and Arrhenius have arrived at a mass of pelagic sediments of 2.3×10^{4} g/cm² for the entire earth, equivalent to 4.4×10^{4} g/cm² for the area used by Horn and Adams.

Our value of 125 g/cm²/10⁶ years for Quaternary (i.e., "fresh") material deposited at WAH 24F-8 yields periods of accumulation of 350 million years (Goldberg and Arrhenius 1958) and 870 million years (Horn and Adams, 1966). Since neither of the models under consideration is concerned with recycled components, the period of accumulation should refer to the present reservoir of pelagic sediment.

The distribution and age of ancient pelagic sediments (Ewing et al. 1966, Riedel 1970) in combination with recent advances in our understanding of global tectonics (Isacks et al. 1968, Le Pichon 1968, Heirtzler et al. 1968) suggest that the lifetime of the pelagic reservoir should be no more than 200 miilion years.

The excessive ages derived from the geochemical models could be explained by systematic errors in their compositional values. Since few analytical data are available for pre-Quaternary sediments, recent changes in the abyssal regions would introduce errors that could invalidate the mass terms of a geochemical balance. It is more likely, however, that the excessive ages calculated from the Goldberg-Arrhenius and Horn-Adams models indicate a slower-than-average rate of accumulation at WAH 24F-8.

If we take the lifetime of the pelagic reservoir to be 200 million years and assume that it covers an area of 2.68×10^{18} cm² (Horn and Adams 1966), the mean rate of sedimentation of new pelagic sediment must be 180 g/cm²/10⁶ years to satisfy the Goldberg-Arrhenius model and 440 g/cm²/10⁶ years to satisfy the Horn-Adams model. In other words, the accumulation rate in core WAH 24F-8 is 1.4–3.5 times lower than the average for all pelagic sediments.

Since we have already concluded that the sedimentation rate at this site is anomalously high compared with nearby cores, it appears that sediment in the surveyed area is accumulating between one and two orders of magnitude more slowly than in the pelagic realm as a whole. It is not clear whether this results from a lower-than-average supply of sediment or whether a major fraction of the sediment reaching the area is carried away by the northward-moving Antarctic Bottom Water (Lynn and Reid 1968).

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