

GEOCHRONOLOGICAL STUDIES IN SANTA BARBARA BASIN: ^{55}Fe AS A UNIQUE TRACER FOR PARTICULATE SETTLING

S. Krishnaswami, D. Lal, B. S. Amin,

Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Bombay—400005

and

A. Soutar

Scripps Institution of Oceanography, LaJolla, California 92037

ABSTRACT

Sediments accumulate in the Santa Barbara Basin relatively rapidly: about 3–4 mm yr⁻¹ based on the analysis of varves. These deposits are ideal for studying the applicability of nuclear geochronological techniques in a natural situation. Studies of the depth distribution of several radionuclides, manmade ^{55}Fe and naturally occurring ^{210}Pb and Th isotopes, in recent Santa Barbara sediment layers permit an evaluation of the geochemical behavior of Fe, Pb, and Th in coastal waters and have established the usefulness of ^{55}Fe and ^{210}Pb for dating coastal or near coastal sediments deposited during the last decade and half-century respectively.

The importance of particulate matter in governing the distribution of trace elements in seawater, although realized for a long time, has so far been studied qualitatively only. This poor understanding arises mainly because of the lack of quantitative knowledge of the rates of associated physicochemical and biological processes involved. Until recently, the only quantitative estimate of the natural settling rates of particulate matter in seawater has been based on the radioactive disequilibria exhibited by the ^{238}U daughter nuclides (Bhat et al. 1969).

With the recent introduction into the sea of appreciable quantities of manmade radioisotopes, the scope for such studies has been considerably extended. The isotopes useful for such studies are: ^{239}Pu (half-life 24,400 yr), ^{14}C (half-life 5,700 yr), and ^{55}Fe (half-life 2.7 yr). The application of ^{239}Pu for estimating the settling velocities of oceanic suspended matter (Noshkin and Bowen 1972) and ^{14}C for studying the sinking chronology of marine biological skeletal material (Somayajulu et al. 1969) have been established. The nuclide ^{55}Fe should be useful for estimating

settling velocities of oceanic suspended matter. Although this is generally appreciated, studies have not yet been carried out in any detail with a view toward its applicability as a tracer in natural conditions.

Here we report results of measurements of the depth distribution of ^{55}Fe , ^{210}Pb , and Th nuclides in a box-core collected from the Santa Barbara Basin. These sediments were chosen because of their relatively high sedimentation rates, 3–4 mm yr⁻¹ (Emery 1960; Koide et al. 1972, 1973; Soutar and Isaacs, in prep.) and because the presence of annual varves in them allows the assignment of dates to the various strata.

The results show that the deposition of ^{55}Fe is primarily controlled by the downward flux of particulate matter. A simple adsorption cum Stokes' settling model explains the experimental data quite satisfactorily. Thus, the nuclide ^{55}Fe serves as an ideal tracer for dating sediments deposited a decade ago when appreciable amounts were injected into the oceans.

Additionally this work extends that carried out by Krishnaswami et al. (1971)

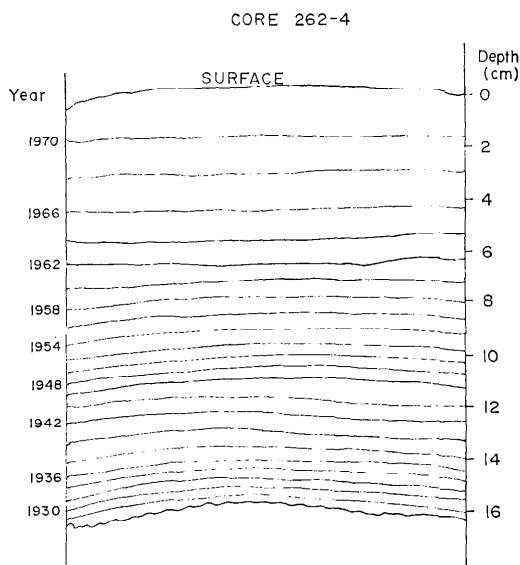


Fig. 1. The varve stratigraphy of the Santa Barbara core. The relatively high layer thicknesses in the top levels reflect higher moisture content and sedimentation rates.

and Koide et al. (1972, 1973) on the applications of ^{210}Pb and Th isotopes as geochronological tools for studying rapidly depositing sediments. The implication of the measured cumulative deposition of ^{210}Pb on the flushing characteristics of the basin is discussed.

We thank J. V. Jeevraj for assistance in the laboratory work and B. L. K. Somayajulu and S. K. Bhattacharya for discussions.

EXPERIMENTAL TECHNIQUES

The undisturbed 8-inch (20.3 cm) box core we used was collected in September 1971 from the Santa Barbara Basin ($34^{\circ} 12.5' \text{ N}$, $120^{\circ} 00' \text{ W}$) at a water depth of 592 m. Immediately after collection, it was frozen and preserved at ca. -20°C . The core was sliced into 5- by 18-cm sections and X-ray photographed, revealing clearly distinct varves (Soutar and Isaacs, in prep.) over the last 40 years (Fig. 1). At greater depths, the X-ray analysis indicates the interruption of varve sedimentation by a turbidite deposit. The core has been subsampled for radiochemical analysis based on the varve stratigraphy.

To estimate the in situ density of the sediment, we determined moisture content in various sections by drying to constant weight at 110°C . Measurements of ^{55}Fe , ^{210}Pb , and ^{226}Ra were made essentially by the procedures discussed by Krishnaswami et al. (1971). The procedure for Th isotopes is discussed by Bhat et al. (1969). Briefly, the sediment sample (2–5 g dry wt) is leached with boiling 6 N HCl twice and the combined leachate analyzed for the concentrations of Fe, Pb, and Th radioisotopes. In several sections of the core, the residue after HCl treatment was decomposed with HF-HClO₄ and analyzed for ^{210}Pb , ^{226}Ra , and Th: about 95% of ^{210}Pb , 80% of ^{226}Ra , and 70% of Th isotopes are leached out by HCl. For ^{210}Pb , lead carrier equivalent to about 80 mg PbSO_4 was used; ^{234}Th spike was used for Th isotopes. For ^{55}Fe , no carrier was added. The chemical yield of iron was estimated based on the iron content of the leachate as determined by atomic absorption spectrometry. (For radiochemical separations and purification of these isotopes see Krishnaswami et al. 1971.)

Iron-55 was counted in an X-ray proportional counter coupled to a pulse height analyzer: the background in the 4.8–6.8 keV channel was 0.4 cpm. The counting efficiency, based on a ^{55}Fe standard, was 4.1%. The net sample activities ranged between 0.5–1.5 cpm. The ^{210}Pb activities of the samples were estimated from the growth of ^{210}Bi , daughter of ^{210}Pb . The samples were counted in a gas-flow beta counter of 12 counts per hour background. The counting efficiency of the beta counter was estimated to be 25% using ^{210}Pb standard (obtained from A. Hohendorf). Measurements of ^{226}Ra were made using the ^{222}Rn emanation method (Bhat 1970). The ^{222}Rn extraction and counting efficiency was calibrated using a LDGO ^{226}Ra standard and was found to be 205%. The $>100\%$ value for efficiency is because three alpha particles (from ^{222}Rn and its short-lived daughter products ^{218}Po and ^{214}Po) per decay of ^{222}Rn are measured. Thorium isotope activities

were measured by alpha spectrometry (Koide et al. 1973).

RESULTS

Varve stratigraphy

The annual varve layers in core SBB 262-4, as revealed by the X-ray, are shown in Fig. 1. The sedimentation rate has decreased within the section by about 40%, 0.11 g cm⁻² yr⁻¹, during the 1960-1971 strata compared to an average value of 0.07 during 1928-1960 (Fig. 2). The average rate of sedimentation based on varve data is 0.090 g cm⁻² yr⁻¹ during the last 43 years (1928-1971).

Radioisotope data

²¹⁰Pb geochronology—The average sedimentation rate of 0.36 cm yr⁻¹ estimated from the radioactive decay of ²¹⁰Pb_{exc} with depth (calculated assuming that the ²¹⁰Pb_{exc} deposition per unit area and time has remained constant) is in excellent agreement with the value of 0.37 cm yr⁻¹ from varve data. However to observe vari-

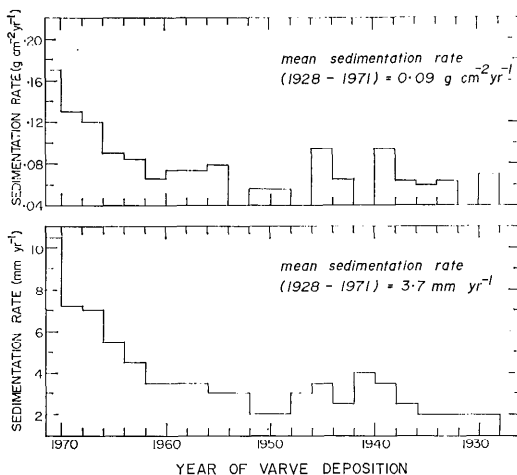


Fig. 2. The measured variation in sedimentation rate in biennial sections of core 262-4 based on varve stratigraphy. Higher sedimentation rate (g cm⁻² yr⁻¹) in the 1960-1971 strata compared to that in 1928-1960 is clearly evident.

ations in the sedimentation rate within the core by the ²¹⁰Pb method analogous to the varve stratigraphy, it is necessary to measure ²¹⁰Pb concentrations in all the sub-

Table 1. Concentrations of ²¹⁰Pb and ²²⁶Ra in core 262-4

Depth (cm)	Year of deposition *	In situ density (g cm ⁻³)	Concentrations [†] (dpm g dry wt ⁻¹)		
			²¹⁰ Pb _{total}	²²⁶ Ra	²¹⁰ Pb _{exc} ‡
0.0-1.6	1970-1971(Sep)	0.16	54.0	NM§	51.0
1.6-3.0	1968-1969	0.18	67.5	3.0	64.5
3.0-4.4	1966-1967	0.17	58.0	3.8	55.0
4.4-5.5	1964-1965	0.16	55.5	3.2	52.5
5.5-6.4	1962-1963	0.17	45.0	NM	42.0
7.8-8.5	1956-1957	0.22	48.0	NM	45.0
9.7-10.1	1950-1951	0.28	35.0	NM	32.0
11.8-12.3	1942-1943	0.26	30.0	3.4	27.0
13.8-14.3	1936-1937	0.25	29.6	NM	26.6
15.4-15.8	1928-1929	0.35	17.6	2.6	14.6

* Based on varve data (Fig. 1).

† Errors in the measurement are less than ± 5%.

‡ ²¹⁰Pb_{exc} = ²¹⁰Pb_{total} - ²²⁶Ra. An average value of 3 dpm g⁻¹ of ²²⁶Ra has been used to estimate ²¹⁰Pb_{exc} activities in samples.

§ Not measured.

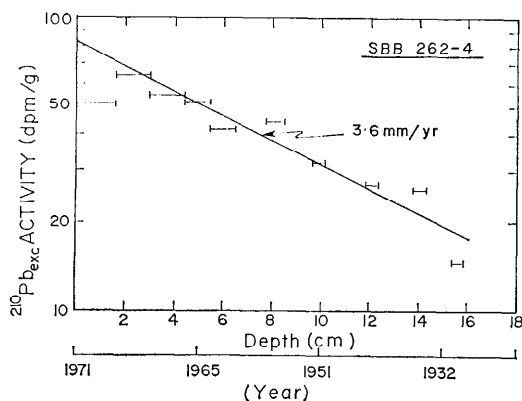


Fig. 3. Activity of ^{210}Pb as a function of depth in the Santa Barbara core. The year designations based on the annual varve counting are also given. The line represents the best fit drawn through data points up to the year 1970.

sections of the core. The measured ^{210}Pb concentrations in this core are in close agreement with the values published earlier (Koide et al. 1972, 1973) on samples collected from nearby locations. As observed by Koide et al. (1973), ^{210}Pb activity in the top 1.6-cm section of this core is about 20% lower than the activity levels in the 1.6–3.0-cm section (Table 1, Fig. 3). The observed deficiency of ^{210}Pb in the top section could be attributed to a slightly higher rate of sedimentation of mud during this period. This is evident from the varve data which clearly indicates a relatively high sedimentation rate during two recent years, $0.17 \text{ g cm}^{-2} \text{ yr}^{-1}$, compared to an average value of 0.10 in the 1962–1970 strata (Fig. 2). It must be pointed out that Craig et al. (1973) have observed a distinct ^{210}Pb deficiency in the deep waters compared to its parent ^{226}Ra , clearly indicating that the ^{210}Pb is removed from seawater and rapidly accommodated in sedimentary phases. The possibility of its mobilization within the sedimentary column and subsequent diffusion into the overlying waters seems unlikely.

The integrated activity of $^{210}\text{Pb}_{\text{exc}}$ in the sedimentary column has been calculated using the relation

$$\Sigma ^{210}\text{Pb}_{\text{exc}} (\text{dpm} \cdot \text{cm}^{-2}) = A_0 \rho L,$$

Table 2. Thorium isotope concentrations in HCl leach in core 262-4

Year of deposition*	^{232}Th (ppm wt)	$^{228}\text{Th} : ^{232}\text{Th}^+$ activity ratio
1970-1971(Sep)	3.5	1.92 ± 0.08
1968-1969	6.0	1.33 ± 0.05
1966-1967	7.0	1.22 ± 0.04
1964-1965	4.9	1.04 ± 0.07
1962-1963	-	1.1 ± 0.07

* Based on Varve data (Fig. 1).

+ At time of plating; November 1972.

where A_0 is the extrapolated $^{210}\text{Pb}_{\text{exc}}$ activity at the surface, ρ is the in situ density, and L is the depth at which the concentration of $^{210}\text{Pb}_{\text{exc}}$ becomes A_0/e . With $A_0 = 80 \text{ dpm g}^{-1}$, $\rho = 0.24 \text{ g cm}^{-3}$, and $L = 12 \text{ cm}$, $\Sigma ^{210}\text{Pb}_{\text{exc}} = 230 \text{ dpm cm}^{-2}$. The measured integrated deposition of $^{210}\text{Pb}_{\text{exc}}$ is about an order of magnitude more than that expected from its total input, comprising atmospheric fallout via wet precipitation, which is about $5\text{--}10 \text{ dpm cm}^{-2}$, and its production from the radioactive decay of ^{226}Ra in the water column which corresponds to 7 dpm cm^{-2} based on measured ^{226}Ra concentration of $0.12 \text{ dpm liter}^{-1}$ (Chung 1971). If the measured excess deposition of ^{210}Pb in the core is due to its input from the shelf area and subsequent deposition from the water entering the basin, we estimate that on average the basin is flushed with a minimum of 20 times its volume during the mean life of ^{210}Pb . This estimated flushing time of water in this basin agrees with data of Sholkovitz and Gieskes (1971) and Emery (1960) who have reported an upper limit of 5 years for the residence time of water in Santa Barbara Basin.

Th isotope chronology—In agreement with the results of Koide et al. (1973) we have observed a measurable excess of ^{228}Th activity over its parent ^{232}Th in the acid leaches of the core (Table 2). To determine the origin of the excess ^{228}Th , we

Table 3. Depth distribution of ⁵⁵Fe in core 262-4

Year of deposition	Iron content (% wt)	⁵⁵ Fe concentration [†]	
		dpm g ⁻¹ core	dpm g ⁻¹ Fe
1970-1971(Sep)	2.4	2.2	91.5
1968-1969	3.0	3.6	120
1966-1967	3.0	6.9	230
1964-1965	2.7	10.4	384
1962-1963	2.5	1.9	75
1960-1961	NM	< 0.1	< 3.8 ‡
1958-1959	NM	< 0.6	< 22 ‡
1956-1957	NM	< 0.35	< 13.5 ‡
1950-1951	NM	0.11	4.0 ‡
1942-1943	NM	< 0.12	< 4.4 ‡
1936-1937	NM	< 0.12	< 4.4 ‡

* All measurements refer to November 1972.

† Errors are less than ± 10%.

‡ Calculated assuming 2.7% by weight of Fe.

measured the concentration of its immediate parent ²²⁸Ra in the acid leach of the top 0-1.6-cm section of the core. The concentration of ²²⁸Ra was less than 0.5 dpm g⁻¹ even after making allowance for the leaching efficiency of Ra isotopes by HCl. The deficiency of ²²⁸Ra, with respect to its parent ²³²Th, implies that ²²⁸Ra has migrated from the sediment layer (Moore 1969) to the overlying water column, where it decays to ²²⁸Th. The ²²⁸Th thus produced gets quickly deposited on the sediments, since Th is known to be chemically reactive in marine environments.

From the measured ²²⁸Th:²³²Th activity ratios, a crude estimate of the sedimentation rate for core 262-4 has been made, based on the assumption that the activity ratio of ²²⁸Th:²³²Th at the time of deposition to the sediments has remained constant during the last decade. The estimated sedimentation rate corresponds to about 0.5-0.6 cm yr⁻¹ for the 1964-1971 strata, compared to an average value of about 0.7 cm yr⁻¹ based on annual varve counting for the same period (Fig. 2).

⁵⁵Fe—The measured concentrations of ⁵⁵Fe in the various subsections of the core are given in Table 3. The occurrence of ⁵⁵Fe in the environment is due to nuclear

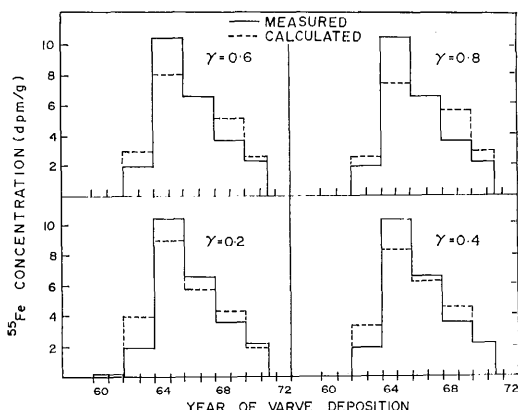


Fig. 4. The measured ⁵⁵Fe activity (dpm/g sediment) is shown in biennial sections of core 262-4 based on varve stratigraphy. The year designations according to varves are from winter to winter and hence include a month or two from the previous year. The layer accumulated during November 1963-1964 is designated 1964. (For abbreviation only the last two digits of the "varve year" are presented.) The dotted lines represent the calculated ⁵⁵Fe concentration based on relation 9 as a function of the value of the exponent γ . Actual accumulation rates during different years deduced from varve data are used for calculation.

weapons testing; principal injections of ⁵⁵Fe occurred in two separate series during 1952-1958 and 1961-1962. (Only limited measurements of ⁵⁵Fe fallout exist in the literature for the pre-1960 era and hence the pattern of fallout of ⁵⁵Fe during 1952-1958 is not well understood.)

The ⁵⁵Fe depth distribution in the core shows a distinct peaked distribution. The data presented in Table 3 and Fig. 4 show that the maximum ⁵⁵Fe activity (dpm g⁻¹) occurs in the strata corresponding to the years 1964-1965. Very large concentrations of ⁵⁵Fe were observed in the rains during spring 1963 (Hoang 1969) subsequent to major atmospheric detonations in October-November 1961. Hence the observed peak in 1964-1965 should be correlated with atmospheric fallout of 1963. The small measured ⁵⁵Fe activity in the 1962-1963 section of the core could be due to a small amount deposited on the basin floor during 1963. Alternately one could attribute it to a small admixture of activity

from the 1964–1965 section during sampling; sampling accuracy is of the order of 0.5 to 1 mm while the annual accumulation is 3.6 mm (Fig. 2).

DISCUSSION

It becomes evident (Fig. 4) that the 1963 atmospheric peak in fallout of ^{55}Fe appeared in sediments in the Santa Barbara Basin only during 1964 or 1964 and 1965, a delay of at least a year with respect to fallout. The ^{55}Fe activity drops to a value of $60 \pm 5\%$ between successive biennial sections. Taking into account the radioactive decay of ^{55}Fe in 2 years, this corresponds to a decay-corrected fallout of about 35% in successive 2-year intervals. This pattern is consistent with that expected on the basis of observed atmospheric fallout for ^{55}Fe and ^{90}Sr (Athavale et al. 1967; Hoang 1969).

It follows then that the ^{55}Fe activity injected in the near coastal regions was removed to the sediments with a delay of 1–2 years. The most likely mechanism for this phase lag would be the quick adsorption of ^{55}Fe onto particulate matter present in seawater and its subsequent slow removal to the sea floor by gravitational settling. The delay of 1–2 years corresponds to a mean particle size range of 4.5–3.2 μ for the case of a 600-m water column. This deduced particle size is in agreement with the published value of 4.5 μ as the median diameter for the basin floor sediments (Emery 1960).

The cumulative ^{55}Fe activity in the core in layers deposited during 1960–1971, as observed in November 1972, is 5.5 dpm cm^{-2} . This value is 5–6 times more than that expected from fallout via overhead rains in Santa Barbara Basin (see Krishnaswami et al. 1971). Once again, as with ^{210}Pb , there is an excess deposition of ^{55}Fe on the basin floor; this excess is however smaller in the case of ^{55}Fe by factors of 2–3. This discrepancy between relative cumulative deposition rates of ^{210}Pb and ^{55}Fe could be attributed to the more reactive nature of lead in the coastal water environments.

In view of the qualitative agreement between the observed values of ^{55}Fe concentrations in the basin sediment and that expected from the particulate settling model proposed, we present here a quantitative calculation for adsorption cum Stokes' settling model for ^{55}Fe , with a view to obtaining an insight into the role played by particles of different size in transporting the ^{55}Fe activity.

In our model calculations we assume that ^{55}Fe once injected into the ocean surface is quickly adsorbed on the particulate matter present in seawater and settles to the ocean floor, the amount of ^{55}Fe adsorbed being proportional to the surface area of the particles. Additionally we assume that the average sedimentation velocity of these particles can be taken as the Stokes' settling velocity.

The actual size distribution of particles in Santa Barbara Basin waters is not known. However, the size distribution of the particles in seawater, which are eventually deposited on the ocean floor can be theoretically deduced from a knowledge of the particle size distribution in sediments (Krishnaswami and Lal 1973). For the case of a particle size spectrum:

$$M_s(> D) = K_s D^{-\gamma}, \quad (1)$$

where M_s is the cumulative mass fraction in sediment due to particles of size greater than D cm, the corresponding expected particle size distribution in water is

$$N_w(> D) = Q D^{-(\gamma+5)}, \quad (2)$$

where Q is a constant given by the relation

$$Q = \frac{24\gamma K_s S}{\pi\rho A(\gamma+5)}$$

and other symbols are S = sedimentation rate ($\text{g cm}^{-2} \text{yr}^{-1}$); ρ = density of particles (g cm^{-3}); and A = Stokes' settling constant, in the relation $V = AD^2/4(\text{cm}^{-1} \text{yr}^{-1})$.

Based on the deduced size distribution of particles in seawater, the rate of ^{55}Fe deposition on the basin floor can now be calculated.

The flux of particles, F ($\text{No. cm}^{-2} \text{yr}^{-1}$) settling on the ocean floor is

$$dF = dN_v V = -(A/4)(\gamma + 5) Q D^{-(\gamma+4)} dD. \quad (3)$$

The assumption that ⁵⁵Fe adsorption on particulate matter is proportional to the surface area of the particles allows one to deduce the rate of deposition of ⁵⁵Fe on the ocean floor, dF^{55} :

$$dF^{55} = -(A/4)(\gamma + 5) Q C \pi D^{-(\gamma+2)} dD, \quad (4)$$

where C is the ⁵⁵Fe activity adsorbed per unit surface area of particle (dpm cm⁻²).

From relation 4, we can obtain the amount of ⁵⁵Fe depositing on the basin floor at any time t , by substituting for D and dD as

$$D = 2(H/At)^{1/2} \quad (5)$$

and

$$dD = -(H/A)^{1/2} t^{-3/2} dt, \quad (6)$$

where t is time taken for a particle of diameter D to settle through H cm, the depth of water column. Note that in this calculation we are considering a pulse injection of ⁵⁵Fe at $t = 0$,

$$dF^{55} = P t^{(\gamma-1)/2} dt, \quad (7)$$

where

$$P = (A/4)(\gamma + 5) C \pi Q (H/A)^{-(\gamma+1)/2} 2^{-(\gamma+2)}.$$

The above relation, which gives the instantaneous differential flux with respect to $t = 0$ when particles and ⁵⁵Fe activity are mixed, does not take into account the decay of ⁵⁵Fe in transit through the water column and until the time of measurement

$$dF^{55} = P t^{(\gamma-1)/2} e^{-\lambda T} dt, \quad (8)$$

where T is the time between injection and measurement. The corresponding concentration of ⁵⁵Fe (dpm) per gram sediment, J , (dpm g⁻¹) is:

$$J = P' t^{(\gamma-1)/2} e^{-\lambda T} dt, \quad (9)$$

where $P' = P/S$, S being the sedimentation rate.

Based on available data on the particle size distribution of the laminated Santa Barbara sediments (Hulsemann and Emery 1961) and those measured for core 262-4, the values of the constants K_s and γ have been estimated: values of γ range between 0.4 and 0.6 and those of K_s be-

tween 3×10^{-3} and 3×10^{-2} . The expected depth distribution of ⁵⁵Fe in Santa Barbara Basin sediments has been calculated individually for the various years of fallout 1962–1965 using relation 9, and contributions from each year's fallout are summed to obtain the cumulative distribution pattern. The upper limit of particle size satisfying relation 1 of the size spectrum in our calculation is taken to be equal to 15μ ; the corresponding deposition of particles at the water-sediment interface occurs after ⁵⁵Fe injection at time $t = 4H/AD^2 = 0.1$ yr (for $H = 5.9 \times 10^4$ cm and $D = 15 \mu$).

The ⁵⁵Fe fallout data from Hoang (1969) for the latitude belt of 30–40° N have been used. Since the value of C in relation 7 is unknown, calculation of absolute concentrations of ⁵⁵Fe (dpm g⁻¹ sediment) is not possible. Hence in Fig. 4 the calculated depth distribution for different values of γ , 0.2–0.8, is based on a normalization corresponding to the integrated fallout equal to the atmospheric fallout.

From Fig. 4 it is evident that the agreement between the measured and calculated distribution exists for γ values of 0.4–0.6, consistent with the measured values in sediments. The model calculations predict that ⁵⁵Fe activity, once injected into the ocean surface, is in large part removed to the sediments very quickly—about 1–2 years. If similar processes are operative in the open ocean areas for the removal of iron from seawater, we estimate that the residence time of iron in seawater is of the order of 10–20 years. Bhat et al. (1969) have deduced similar values for the residence time of Th isotopes in seawater based on particulate settling models.

CONCLUSIONS

The average sedimentation rates based on the annual varve counting method and those deduced from radiometric data, ²¹⁰Pb_{exc} and (²²⁸Th:²³²Th) ratios, are mutually consistent. The average sedimentation rate for the Santa Barbara core 262-4 is 0.37 cm yr⁻¹ in the samples studied, for sediments deposited after 1928.

The integrated deposition of ^{210}Pb in the core is at least an order of magnitude in excess of the expected values from its in situ production and atmospheric fallout. This excess, if attributed to the renewal of basin water, necessitates that the basin is flushed with 20 times its volume during the mean life of ^{210}Pb .

The ^{226}Ra concentrations (Chung 1971; Chung and Somayajulu, in prep.) and the hydrographic data profiles (Sholkovitz and Gieskes 1971) in Santa Barbara waters are similar to those in adjacent open ocean seawater. Hence it follows that the basin water is replaced not by water from the catchment area but by the shoreward movement of open ocean waters. The seawater entering the basin could be the dense water upwelling from the outside basin (Sholkovitz and Gieskes 1971) or surface seawater. In either case, the origin of the measured ^{210}Pb and ^{55}Fe excess in the basin sediment is intriguing. A detailed investigation of the basin is obviously needed.

Since the major hydrographic properties of water in Santa Barbara Basin and open seawater are similar, it follows that the geochemical behavior of isotopes like ^{210}Pb and ^{55}Fe in the open ocean and the basin areas would also be similar; i.e. these nuclides can be expected to be quickly removed from seawater, even open ocean waters, limited only by the available amount of particulate matter.

Analogous to that of ^{210}Pb , the cumulative deposition of ^{55}Fe on the basin floor is 5–6 times more than its precipitation via overhead rains. This ^{55}Fe excess deposition is relatively small compared to that of ^{210}Pb , which reflects the more chemically reactive nature of ^{210}Pb in these environments.

Based on the particulate settling model, the residence time of iron in open ocean areas has been estimated to be of the order of 10 years. Detailed studies of ^{55}Fe distribution in these sediments should prove valuable for deducing particle size distributions and their settling velocities in seawater.

REFERENCES

- ATHAVALE, R. N., D. LAL, AND RAMA. 1967. The measurement of tritium activity in natural waters. 2. Proc. Ind. Acad. Sci. **65**: 73–103.
- BHAT, S. G. 1970. On the natural radioactivity in the hydrosphere. M.S. thesis, Bombay Univ. 98 p.
- , S. KRISHNASWAMI, D. LAL, RAMA, AND W. S. MOORE. 1969. $\text{Th}^{234}/\text{U}^{238}$ ratios in the ocean. Earth Planet. Sci. Lett. **5**: 483–491.
- CHUNG, Y. 1971. Pacific deep and bottom water studies based on temperature, radium and excess radon measurements. Ph.D. thesis, Univ. Calif., San Diego. 239 p.
- CRAIG, H., S. KRISHNASWAMI, AND B. L. K. SOMAYAJULU. 1973. Pb^{210} - Ra^{226} radioactive disequilibrium in the deep sea. Earth Planet. Sci. Lett. **17**: 444–454.
- EMERY, K. O. 1960. The sea off southern California. Wiley.
- HOANG, C. T. 1969. Study of the fallout of artificial Fe-55. Ph.D. thesis, Paris Univ. 100 p.
- HULSEMANN, J., AND K. O. EMERY. 1961. Stratification in recent sediments of Santa Barbara Basin as controlled by organisms and water character. J. Geol. **69**: 279–290.
- KOIDE, M., K. W. BRULAND, AND E. D. GOLDBERG. 1973. Th-228/Th-232 and Pb-210 geochronologies in marine and lake sediments. Geochim. Cosmochim. Acta **37**: 1171–1183.
- , A. SOUTAR, AND E. D. GOLDBERG. 1972. Marine geochronology with Pb-210. Earth Planet. Sci. Lett. **14**: 442–446.
- KRISHNASWAMI, S., AND D. LAL. 1973. Oceanic particulate matter size distribution in water and in sediments. J. Mar. Biol. Ass. India (in press).
- , J. M. MARTIN, AND M. MEYBECK. 1971. Geochronology of lake sediments. Earth Planet. Sci. Lett. **11**: 407–414.
- MOORE, W. S. 1969. Measurement of Ra^{226} and Th^{228} in sea water. J. Geophys. Res. **74**: 694–704.
- NOSHIKIN, V. E., AND V. T. BOWEN. 1972. Concentrations and distributions of long-lived fallout radio nuclides in open ocean sediments, in press. In Proc. IAEA Symp. (Interaction of radioactive contaminants with constituents of marine environment).
- SHOLKOVITZ, E. R., AND J. M. GIESKES. 1971. A physical-chemical study of the flushing of Santa Barbara Basin. Limnol. Oceanogr. **16**: 479–489.
- SOMAYAJULU, B. L. K., D. LAL, AND S. KUSUMGAR. 1969. Manmade C-14 in deep Pacific waters: transport by biological skeletal material. Science **166**: 1397–1398.

Submitted: 23 March 1973

Accepted: 20 July 1973