Age Determination of Pacific Chalk Ooze by Radiocarbon and Titanium Content

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Abstract

Measurements have been carried out on the average radiocarbon activity of a sediment core of eupelagic chalk ooze and the age of the lower boundary was calculated by integration of the radiocarbon decay function.

In such cores where constancy of the rate of minerogenous accumulation is indicated and can be checked by lateral control, the titanium content, calibrated in terms of absolute age by means of radiocarbon measurement, can be used for dating as far back in time as the constancy of the rate of minerogenous sedimentation can be proved.

1. Principles of age measurement in core 61 B of the Swedish Deep Sea Expedition

In the works of JOLY (1908), PETTERSSON (1930), PIGGOT (1944) and URRY (references in URRY 1948) the possibilities have been demonstrated for dating samples of pelagic clays on the basis of their content of ionium supported radium. The radiocarbon method (LIBBY, ANDERSON, ARNOLD, ENGELKEMEIR, GROSSE, HAMILL, INGHRAM, KIRSHENBAUM, REID and WEINHOUSE 1946—51) has opened new possibilities especially with regard to the dating of highly calcareous deep sea deposits.

If cores of deep sea sediments are to be used for geochronological purposes their facies relationships and stratigraphy should be well known. Furthermore such cores ought to be correlated members of coherent profiles through the deep sea bottom, as this makes it possible to recognize layers deposited under abnormal conditions. Finally, if the half-life of the radioelement used is comparatively short, an area with a comparatively high rate of accumulation has to be chosen for sampling.

The sediment cores raised by the Swedish Deep Sea Expedition under the leadership of Professor H. Pettersson provide an excellent material for studies of deep sea sedimentation. The closely spaced samples from the vast, stable Central Pacific area (cf. GUTENBERG and RICHTER 1949, p. 90) have been investigated and the results have made it possible to find a series of sequences which correspond in detail to the demands put forth above (ARRHENIUS 1950 a and b). For the present purpose a member of this series was chosen, which had an exceptionally high rate of calcium carbonate accumulation, viz. the core 61 (10.3 m long, raised with the Kullen-

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berg piston corer) together with 61 B (0.5 m long, raised with a short open tube corer according to PHLEGER 1951), both from lat. 0° 6′ S, long. 135° 58′ W and 4437 m depth. In core 61 the uppermost layer is missing, owing to the sampling technique, but in 61 B the topmost layer is also present. This material was prepared for radiocarbon analysis in the spring of 1949.

The cores 61—61 B have been closely correlated with other cores in a profile extending from lat. 6° 44′ N to 3° 00′ S and it has been possible to prove that at the locality 61 the changes in the rate of minerogenous sedimentation were smaller than the analytical error during the time of deposition of core 61 B. This conclusion is based upon measurements of the total amount of biogenous material on one hand and of minerogenous material on the other hand, accumulated at different localities along the section and between definite relative time limits.

A closer description of the sedimentation in the East and Central Pacific will be published in the Reports of the Swedish Deep Sea Expedition, Vol. V.

As a measure of the minerogenous component the concentration of titanium recalculated for salt free sediment has been used. Titanium is especially useful for this purpose as its concentration in the minerogenous component appears to be practically constant over the area in question and high enough to allow an easy and accurate determination. Furthermore titanium does not appear to be affected by secondary dissolution in this environment.

The close proportionality between the concentration of titanium and minerogenous matter in eupelagic deposits was first demonstrated in the fundamental works of CORRENS (1935) and REVELLE (1944) and was later stressed by KOCZY (1950 and 1951) who used Correns' measurements. With regard to the possibilities of estimating the rate of minerogenous sedimentation, which were conspicuous from these works, the analysis of titanium was included in the 1948 working program for treating the sedimentary material of the Swedish Deep Sea Expedition (G. ARRHENIUS, 1950 a).

In connection with his work on the core 241 from the Equatorial Atlantic Ocean, WISEMAN (1950) has also pointed out the possibility of using the concentration of titanium for estimating the clay component. He apparently based an interpretation of Late Pleistocene chronology (1951) on the vertical distribution of minerogenous matter assuming a constant rate of deposition of such matter.

It should be emphasized in this connection that a constant rate of sedimentation and a constant titanium content of the minerogenous component should not be looked upon as a general rule for deep sea sediments but must be proved in all cases. A section through the East Pacific from lat. 0° to 17° N and at an approximate distance of 800 nautical miles from the American coast did not reveal the high regularity of minerogenous sedimentation found in the Central Equatorial area. Frequent examples of irregularities in the rate of minerogenous deposition are found on rises and ridges and in throughs and pits of the Atlantic, Pacific and Indian Oceans.

It should also be pointed out that a smooth bottom topography or freedom from volcanism, as in parts of the stable Central Pacific area or in parts of the Indian and Atlantic oceans, might considerably reduce the probability for tectonic disturbances, sediment slumping and abnormal dilution with pyroclastic material but is by no means a guarantee for a constant rate of minerogenous sedimentation. Redepositional changes in this rate by as much as 50 % appear in the eupelagic environment generally not to be accompanied by changes in grain size or by qualitative changes in the composition of the clay material. The only possibility of checking changes in the rate of minerogenous sedimentation in a pelagic environment therefore seems to be a quantitative comparison of corresponding layers in several sediment cores along a profile of wide geographical range.

The biogenous components of the sediment consist mainly of skeletal remains of calcium carbonate from foraminifera and coccolithophoridae and of silica from radiolaria and diatoms. The aim of the present investigation was to use the radiocarbon of the calcium carbonate for dating purposes. The possibility, however, that the calcium carbonate had exchanged ions with the bottom water after deposition could not be ignored. In such a case it would not be possible to use the radio-

carbon content of the carbonate for age calculations. An important means for controlling secondary exchange is furnished by the palaeothermometric method of UREY based upon the temperature sensibility of the ratio between the oxygen isotopes O^{16} and O^{18} (UREY, LOWENSTAM, EPSTEIN and MCKINNEY, 1951). If the calcite had exchanged all its carbonate with carbonate ions from the deep sea bottom water or from the interstitial sediment water, a temperature of a few degrees centigrade ought to be indicated by the oxygen isotope distribution of the calcite. If, on the other hand the shells have not been subjected to any exchange of carbonate after the death of the organisms, the temperature indicated should be that of the surface layer of the ocean. If partial replacement of the original calcite had taken place some intermediate temperature would be found.

Measurements of the oxygen isotope distribution carried out by Dr S. Epstein gave the following results in core 61: 0—2 cm 21° C, 10—11.5 cm 21°, 20 cm 19.5°, 200 cm 17.5°; all measurements with an estimated standard deviation of 5° C. All temperatures found thus coincide within the limits of the experimental error with an assumed average temperature for the biotope of tropical planktonic foraminifera which are most abundant in the uppermost 100 m layer of the ocean (PHLEGER 1951). It is thus very probable that no considerable exchange of the shell carbonate took place after deposition on the deep sea bottom and the radiocarbon measurements might safely be used as a basis for age calculations. This conclusion refers to core 61 only and the results may not directly be applied to other types of deep sea deposits or other localities. It is, however, probable that the stability of the carbonate characterizes all bathyal pelagic deposits with a very high content of calcite, poor in humus and not affected by rising juvenile solutions.[1]

The stratigraphy of core 61 and 61 B indicated 3 cm/1,000 years as the order of magnitude of the average rate of Post-Glacial sedimentation at this locality. The half life level of C^{14} would under such conditions be found at approx. 17 cm depth. For the radiocarbon analysis approx. 100 g of calcium carbonate are required. Due to the small dimensions of the core (3 cm diameter) and to the fact that material had to be used also for other analyses it was, in this case, impossible to extract and analyse samples from definite time levels and to construct a decay curve from the results. Instead a coherent sample from 0 to 45 cm depth in core 61 B was subjected as a whole to radiocarbon analysis and the result was used as a basis for the age calculation. The principles of this calculation appear from fig. 1. If N_m is the average activity value obtained from analysis of a homogenous sediment column, deposited with a constant rate of accumulation and if T is the age of the lower boundary of the column then the product

$$N_m \cdot T = \int_0^T N_0 \cdot e^{-\lambda t} \cdot dt \quad \text{if} \quad N_t = N_0 \cdot e^{-\lambda t}$$

is the disintegration function.

In the actual case, however, the rate of sedimentation has not been constant, the changes being caused by changes in the rate of biogenous sedimentation. As the minerogenous rate of sedimentation appears to have

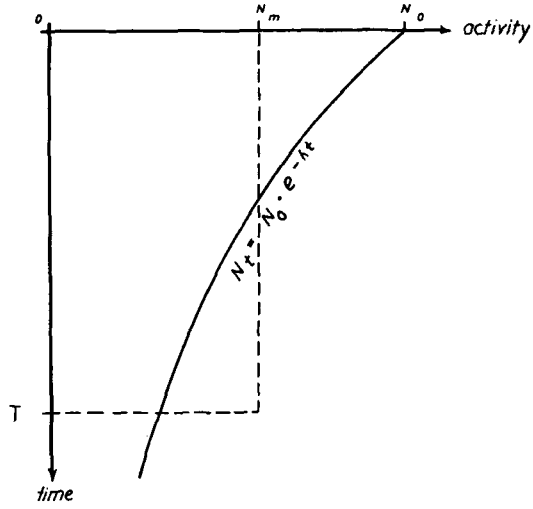

Fig. 1. Principles of age calculation. T is the age of the lower boundary of an ideal sediment column, which, subjected as a whole to radiocarbon analysis, yields the activity N_m. The curve represents the radiocarbon decay function. As is easily seen, the surface of the rectangle $N_m \cdot T$ is equal to the surface limited by the coordinate axes, the line $y = T$ and the decay curve.

[1] It might be pointed out in this connection that radiocarbon measurements in autochtonous eupelagic carbonate deposits are not affected by the source of error recently indicated by BARTLETT (1951) as influencing the isotopic composition of tufa and lake marl.

been constant in the case of core 61 B and its neighbours and as the concentration of titanium is proportional to the concentration of minerogenous matter (see above pp 223—224 and Vol. V, Rep. Swed. Deep Sea Exp.), the integral over the titanium concentration as a function of the depth in the sediment will be proportional to the time interval between the integration limits. The relative age of any level in core 61 B is thus expressed by the titanium integral from the present sediment surface to the level in question.

A factor which must be taken into consideration in the age calculation is, that due to the changes in the balance between the biogenous production of calcium carbonate and of silica the amount of calcium carbonate and therefore of radiocarbon deposited per time unit varies with time. As the calcium carbonate concentration has been measured in closely spaced samples from core 61 B, corrections for the varying carbonate deposition can easily be applied.

The calculation must also take into account the fact that at different levels of the sediment column samples of varying size had been extracted for other chemical and palaeontological analyses previous to the radicarbon analysis. The corrections for this stepwise variation in size of the samples were applied in the same way as the corrections for carbonate content.

The variations in composition of the samples investigated were not big enough to require a correction for the varying specific gravity of the deposit.

2. Constants and experimental values

Assay of modern calcium carbonate shell $N_0 = 16.2 \pm 0.5$ disintegrations/min/g of C.

Half life of $C^{14} = 5\,568 \pm 30$ years.

Assay of column 61 B $N_m = 6.18 \pm 0.24$ disintegr/min/g of C.

The results of the measurements of carbonate, titanium and mass of sediment are shown in table 1 together with the calculated cumulative fractions of the total time T. The core was divided into 22 elementary samples, or strips, for each of which the same measurements were made. The concentrations of carbonate and titanium and the mass values all refer to salt free sediment.

Table 1

Sample depth cm	$[CaCO_3] \cdot 10^3$ (q_i)	$[TiO_2] \cdot 10^5$	Mass of sample in dg (p_i)	Cumul. fraction of total time T (f_i)
0 — 2	762	33	12	0.054
2 — 4	764	31	55	0.104
4 — 5.5	766	30	13	0.141
5.5— 7	780	24	42	0.170
7 — 8.5	795	18	32	0.192
8.5—11.5	795	18	83	0.236
11.5—13.5	794	19	24	0.267
13.5—15.5	805	18	55	0.296
15.5—17	817	17	21	0.316
17 —17.5	840	22	14	0.325
17.5—19	862	27	27	0.358
19 —21	808	44	55	0.430
21 —22.5	755	61	14	0.504
22.5—23	757	57	13	0.527
23 —25.5	760	38	138	0.604
25.5—27.5	763	22	79	0.640
27.5—32	768	22	248	0.738
32 —33.5	773	23	71	0.766
33.5—38.5	778	26	275	0.872
38.5—40	783	29	73	0.908
40 —43	799	25	166	0.969
43 —45	815	20	55	1.000

3. Calculation of the results

Notations:

mass of material in the i:th strip p_i
fraction of carbonate in „ „ q_i
time limits of „ „ t_{i-1}, t_i
$t_i = f_i \cdot T$

T is the age of the lowest level of the column. The index i varies from 1 through 22, and $f_0 = 0$, $f_{22} = 1$.

To derive an equation that will permit the determination of T, it is simplest to start with the assumption that the quantities needed are known as continuous functions of the time t along the column.

Suppose that $c(t)dt$ is the mass of the carbonate contained between the levels of the core that correspond to times t and $t + dt$. With N_0 = the radioactivity of modern carbonate per unit mass, the total activity of the core becomes:

$$N_{tot} = N_0 \cdot \int_0^T c(t)\, e^{-\lambda t}\, dt \qquad (1)$$

and the activity per mass unit carbonate:

$$N_m = N_0 \cdot \frac{\int_0^T c(t)\, e^{-\lambda t}\, dt}{\int_0^T c(t)\, dt} \qquad (2)$$

But $c(t)dt = q(t) \cdot m(t)dt$, where $m(t)dt$ is the mass of all material between the levels t and $t + dt$, and $q(t)$ the fraction of carbonate in the same portion. The variation of $m(t)$ thus accounts both for the variations in the rate of sedimentation and for the variations in the area of the cross-section which occur because material was extracted from the core for other experimental purposes, prior to this investigation. $q(t)$ depends also on the variation of the rate of accumulation of silica.

Inserting this in (2) and removing the denominators we get:

$$N_m \int_0^T q(t)\, m(t)\, dt = N_0 \int_0^T q(t)\, m(t)\, e^{-\lambda t} dt \qquad (3)$$

or, by writing the integrals as sums of integrals over the elementary strips:

$$N_m \sum_{i=1}^{i=22} \int_{t_{i-1}}^{t_i} q(t)\, m(t)\, dt =$$

$$= N_0 \sum_{i=1}^{i=22} \int_{t_{i-1}}^{t_i} q(t)\, m(t)\, e^{-\lambda t} dt \qquad (4)$$

Supposing now that $q(t)$ and $m(t)$ are constant over each strip, we get:

$$N_m \sum_{i=1}^{i=22} q_i m_i (t_i - t_{i-1}) =$$

$$= \frac{N_0}{\lambda} \sum_{i=1}^{i=22} q_i m_i \left[\exp(-\lambda t_{i-1}) - \exp(-\lambda t_i)\right] \qquad (5)$$

As $m_i(t_i - t_{i-1}) = p_i$, and $t_i = f_i \cdot T$, we finally get:

$$\frac{N_m}{N_0} \cdot \lambda T \cdot \sum_{i=1}^{i=22} p_i q_i =$$

$$= \sum_{i=1}^{i=22} \frac{p_i q_i}{f_i - f_{i-1}} \left[\exp(-\lambda T f_{i-1}) - \exp(-\lambda T f_i)\right] \qquad (6)$$

Putting:

$$u(t) = \sum_{i=1}^{i=22} p_i q_i \left\{ \frac{N_m}{N_0} \lambda t - \frac{\exp(-\lambda t f_{i-1}) - \exp(-\lambda t f_i)}{f_i - f_{i-1}} \right\},$$

the upper age limit T is the positive root of the equation $u(t) = 0$.

Although this equation might conceivably have several positive roots, it can be shown that this is not the case by study of the exact equation (3), which can have only one positive root. This conclusion is valid also for discontinuous $q(t)$, $m(t)$, such as we have assumed here, and the equation $u(t) = 0$ does therefore determine T unambiguously.

The value of T was found to be 14 162 years. The accuracy of this result is discussed in the next section.

For the numerical work, the digital relay computer BARK was used.[1] A program for the evaluation of u was so arranged that, with only slight modifications, it could also be used to calculate the different partial derivatives necessary for the error estimation. (See next section). Once this program had been set up, each new value of u was computed in about 5 1/2 minutes. It was therefore easy to compute both u and the derivatives for several neighbouring values of t, which gave a convincing guarantee against accidental errors of computation.

4. Sources of error and their influence

If, for the purposes of the present section, we introduce the notation:

dx = the standard deviation of x, we get the following formula for dT.

$$dT^2 = \left(\frac{\partial T}{\partial \tau}\right)^2 d\tau^2 + \left(\frac{\partial T}{\partial N_0}\right)^2 dN_0^2 +$$

$$+ \left(\frac{\partial T}{\partial N_m}\right)^2 dN_m^2 + \sum_{i=1}^{i=22} \left(\frac{\partial T}{\partial p_i}\right)^2 dp_i^2 +$$

$$+ \sum_{i=1}^{i=22} \left(\frac{\partial T}{\partial q_i}\right)^2 dq_i^2 + \sum_{i=1}^{i=21} \left(\frac{\partial T}{\partial f_i}\right)^2 df_i^2$$

[1] For a description of the BARK and its performance, see G. KJELLBERG and G. NEOVIUS, (1951).

or,

$$dT^2 = \left(\frac{\partial T}{\partial \tau}\right)^2 d\tau^2 - \frac{1}{\left(\frac{\partial u}{\partial t}\right)^2_{t=T}} \cdot$$

$$\cdot \left\{ \left(\frac{\partial u}{\partial N_0}\right)^2 dN_0^2 + \left(\frac{\partial u}{\partial N_m}\right)^2 dN_m^2 + \right.$$

$$+ \sum_{i=1}^{i=22} \left(\frac{\partial u}{\partial p_i}\right)^2 dp_i^2 + \sum_{i=1}^{i=22} \left(\frac{\partial u}{\partial q_i}\right)^2 dq_i^2 +$$

$$\left. + \sum_{i=1}^{i=21} \left(\frac{\partial u}{\partial f_i}\right)^2 df_i^2 \right\}_{t=T}$$

The derivatives were computed according to the formulae:

$$\frac{\partial T}{\partial \tau} = \frac{T}{\tau}$$

$$\frac{\partial u}{\partial N_0} = - \sum_{i=1}^{i=22} p_i q_i \frac{N_m \lambda T}{N_0^2}$$

$$\frac{\partial N_m}{\partial u} = \sum_{i=1}^{i=22} p_i q_i \frac{\lambda T}{N_0}$$

$$\left(\frac{\partial u}{\partial t}\right)_{t=T} = \lambda \sum_{i=1}^{i=22} p_i q_i \left\{ \frac{N_m}{N_0} + \right.$$

$$\left. + \frac{f_{i-1} \cdot \exp(-\lambda T f_{i-1}) - f_i \cdot \exp(-\lambda T f_i)}{f_i - f_{i-1}} \right\}$$

$$\frac{\partial u}{\partial p_i} = q_i \cdot \left\{ \frac{N_m}{N_0} \cdot \lambda T - \right.$$

$$\left. - \frac{\exp(-\lambda T f_{i-1}) - \exp(-\lambda T f_i)}{f_i - f_{i-1}} \right\}$$

$$\frac{\partial u}{\partial q_i} = \frac{p_i}{q_i} \cdot \frac{\partial u}{\partial p_i}$$

$$\frac{\partial u}{\partial f_i} = \frac{p_i q_i}{f_i - f_{i-1}} \cdot$$

$$\cdot \left\{ \frac{\exp(-\lambda T f_{i-1}) - \exp(-\lambda T f_i)}{f_i - f_{i-1}} - \right.$$

$$- \lambda T \exp(-\lambda T f_i) \left. \right\} - \frac{p_{i+1} q_{i+1}}{f_{i+1} - f_i} \cdot$$

$$\cdot \left\{ \frac{\exp(-\lambda T f_i) - \exp(-\lambda T f_{i+1})}{f_{i+1} - f_i} - \right.$$

$$\left. - \lambda T \exp(-\lambda T f_i) \right\}$$

(For the computation of the derivatives $\frac{\partial u}{\partial t}$, $\frac{\partial u}{\partial p_i}$, $\frac{\partial u}{\partial q_i}$, $\frac{\partial u}{\partial f_i}$ the BARK was used.)

The following numerical results were obtained. The units employed are: τ and T in years, N_m and N_0 in disintegrations per min per g C, p_i in hectograms, q_i and f_i dimensionless fractions.[1]

$$\frac{\partial T}{\partial \tau} = 2.54$$

$$\frac{\partial u}{\partial t} = 0.48712 \cdot 10^{-4}$$

$$\frac{\partial u}{\partial N_0} = - 0.0509$$

$$\frac{\partial u}{\partial N_m} = 0.1333$$

and

i	$\frac{\partial u}{\partial p_i}$	$\frac{\partial u}{\partial q_i}$	$\frac{\partial u}{\partial f_i}$
1	− 0.7689	− 0.0121	+ 0.0716
2	− 0.6577	− 0.0474	+ 0.0675
3	− 0.5743	− 0.0097	+ 0.0526
4	− 0.5204	− 0.0280	+ 0.0660
5	− 0.4844	− 0.0195	+ 0.0996
6	− 0.4270	− 0.0446	+ 0.0900
7	− 0.3637	− 0.0110	+ 0.0613
8	− 0.3223	− 0.0220	+ 0.0554
9	− 0.2913	− 0.0075	+ 0.0242
10	− 0.2785	− 0.0046	+ 0.0330
11	− 0.2530	− 0.0079	+ 0.0552
12	− 0.1680	− 0.0114	+ 0.0410
13	− 0.0766	− 0.0014	+ 0.0128
14	− 0.0294	− 0.0005	+ 0.0683
15	+ 0.0165	+ 0.0030	+ 0.0896
16	+ 0.0635	+ 0.0066	+ 0.1219
17	+ 0.1141	+ 0.0368	+ 0.1078
18	+ 0.1576	+ 0.0145	+ 0.1045
19	+ 0.1992	+ 0.0704	+ 0.0942
20	+ 0.2389	+ 0.0223	+ 0.0590
21	+ 0.2680	+ 0.0557	+ 0.0504
22	+ 0.2946	+ 0.0199	

[1] In section 3 N_0 and N_m were defined as disintegrations per min. per g $CaCO_3$. It is, however, obvious that the choise of unit does not matter, as long as N_0 and N_m are measured with the same unit.

The value of the standard deviation of each variable is known from the measurements, except for p_i and q_i, where one should also take into account the error involved in the assumption that $q(t)$ and $m(t)$ are constant over each strip. This leads to estimated s.d.:s for the q_i, larger than would result from the measurements alone, while the errors of the p_i are not affected. The argument proving this, and the procedure by which the standard deviations of the q_i were estimated (with the aid of differences from table 1), will be omitted, as it will soon appear that neither group of errors contributes appreciably to the total error dT.

After these corrections had been made, the standard deviations of the p_i, q_i and f_i were taken to be, respectively:

$1 \cdot 10^{-3}$, between $3 \cdot 10^{-3}$ and $9 \cdot 10^{-3}$, $1 \cdot 10^{-3}$

The standard deviations of the other variables are given in section 2. Inserting the values of derivatives and s.d.:s in equation (7), one obtains:

$$dT = 843$$

and we should therefore write:

$$T = 14\,200 \pm 900 \text{ years.}$$

The following list gives the influence of each separate source of error.

$$\left| \frac{\partial T}{\partial \tau} \cdot d\tau \right| = 76$$

$$\left| \frac{\partial T}{\partial N_0} \cdot dN_0 \right| = 522$$

$$\left| \frac{\partial T}{\partial N_m} \cdot dN_m \right| = 657$$

$$\sqrt{\sum_{i=1}^{i=22} \left(\frac{\partial T}{\partial p_i}\right)^2 \cdot dp_i^2} = 35$$

$$\sqrt{\sum_{i=1}^{i=22} \left(\frac{\partial T}{\partial q_i}\right)^2 \cdot dq_i^2} = 8$$

$$\sqrt{\sum_{i=1}^{i=21} \left(\frac{\partial T}{\partial f_i}\right)^2 \cdot df_i^2} = 7$$

It is evident that the errors dN_m and dN_0 dominate completely, and in particular that the errors in p, q and f are negligible.

5. Possibilities for extrapolation of the results and further use of the integration method for age determination

The possibilities of extrapolating laterally the results gained from core 61 B depend upon whether isochronous key levels can be found and traced through the sedimentary sequence of the oceans. The investigations of the Swedish Deep Sea Expedition has shown that this condition is fulfilled in certain types of calcium carbonate lithofacies where detailed correlation can be carried out over distances exceeding 1 700 nautic miles. The world encircling net of stations of the Swedish Deep Sea Expedition provides a material which is highly promising for the establishment of a global marine geochronology (cf. PETTERSSON, 1950).

The possibilities for extrapolating backwards in time from the radiocarbon age determination of core 61 B depend upon the ability to evaluate the rate and changes of rate of biogenous and minerogenous sedimentation in the same way as was done with core 61 B. This work has not yet been completed but as far as can be judged from present results, the vertical extrapolation can be carried down to the lower Pleistocene or upper Pliocene in the East Pacific chalk ooze profile. This mostly corresponds to the entire depth of the sequence sampled with the Kullenberg piston corer.

The easiest way of extending the radiocarbon time scale backwards in time appears to be to control the constancy of minerogenous sedimentation and, in such cases where constancy is found, to calibrate the titanium integral in terms of absolute time. The age of any depth level can thereafter be calculated from the corresponding titanium integral. Constancy of minerogenous sedimentation can be expected and proved only in exceptional cases. In regions where no such constancy is found the dating can be acquired through correlation with key localities such as number 61 of the Swedish Deep Sea Expedition. Correlation methods for deep sea sequences will be described in detail in Vol. V of the Reports of the Expedition.

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