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^{14}C DEPTH PROFILES AS INDICATORS OF TRENDS OF CLIMATE AND $^{14}C/^{12}C$ RATIO

ROBERT H BROWN

Geoscience Research Institute, Loma Linda University, Loma Linda, California 92350

ABSTRACT. Composite curvature averages for ^{14}C age depth profiles of deep ocean sediment, continental sediment, and soil each indicate a global trend for ^{14}C age increment per cm depth to increase with ^{14}C age over the range for which a definitive statistical sample is available. The global trend indicated for peat profiles is constant ^{14}C age increment per cm depth over the past 10,000 ^{14}C yr. Correlation coefficients between changes in ^{14}C yr/cm and maximum profile thickness contradict compaction as an adequate explanation for the global trend indicated by sediment and soil profiles. This trend must be explained by additional factors such as progressively decreasing contamination from older carbon, increasing cosmic ray intensity, decreasing geomagnetic intensity, diminishing ^{12}C in the active biosphere during profile accumulation, and climate factors affecting the rate of accumulation. The diverse trend of peat profiles may indicate climatic conditions more favorable to peat growth during the earlier portion of the past 10,000 yr.

INTRODUCTION

A tendency for ^{14}C age profiles of sedimentary features to be concave toward the ^{14}C age axis has been noted in the literature and interpreted variously as an indication of compaction (Stuiver, 1967), contamination by older carbon (Nambudiri *et al,* 1980), and change in the biosphere $^{14}C/^{12}C$ ratio (Lal & Revelle, 1984). Decomposition is an additional contributor to a similar tendency for peat accumulations (Clymo, 1984).

DATA BASE

In order to determine universal trends, I made a search of all the ^{14}C age profile data in the literature. The analysis reported here is limited to profiles for which at least seven data points have been reported and for which a cubic regression with a Coefficient of Determination (Alder & Roessler, 1977, p 231) of at least 0.70 can be obtained. Exceptions were made to include 3 continental sediment and 2 peat profiles with 6 well-spaced, precisely-determined data points. Six continental sediment and 5 soil profiles were rejected for failure to meet the 0.70 Coefficient of Determination criterion. Sixteen continental sediment, 5 soil, and 9 peat profiles that had a Coefficient of Determination >0.70 were rejected on the basis of clear evidence that the feature had been disturbed or because the range of data was too restricted to adequately establish a representative profile.

ANALYTICAL PROCEDURE

Each profile in the data base was represented by either a linear or a cubic regression, according to which gave the lowest Standard Error of Estimate (Alder & Roessler, 1977, p 226–228). From the regression equation the slope in ^{14}C yr/cm and the normalized second derivative (second derivative divided by the first derivative) in %/cm was calculated for intervals of 2500 ^{14}C yr over the portion of the 2500 to 35,000 ^{14}C yr range covered by the primary profile data.

For each profile a plot was made showing the primary data points, the

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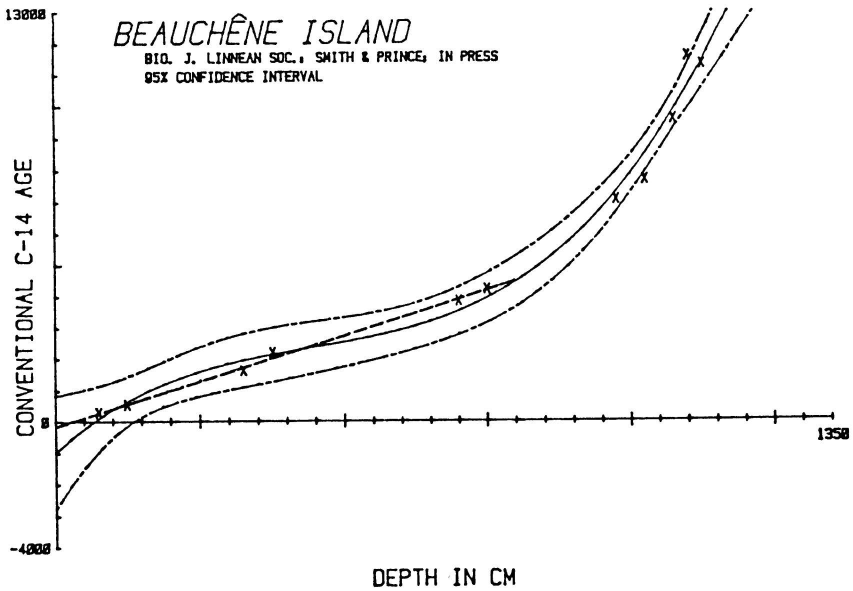

Fig 1. Peat profile from Beauchêne Island, Falkland Islands (data from Smith & Prince, in press). Dashed adjustment to regression line provides most reasonable estimate of slope and curvature at 2500 ^{14}C yr (see also Smith & Clymo, 1984).

regression line, and the 95% confidence boundaries for the regression line (Mendenhall *et al*, 1981, Chap 11) (Fig 1). If the slope (^{14}C yr/cm) at either of the extreme data points appeared questionable the regression line was extrapolated as a straight line of slope compatible with the interior section (Fig 1), and the curvature (%/cm) in the questionable region(s) was presumed to be zero.

Global averages of ^{14}C yr/cm and %/cm for each ^{14}C age interval of 2500 yr were obtained for each category of profile (Figs 2–5). Since a global average ^{14}C yr/cm has little significance, the ^{14}C yr/cm averages are useful only as trend indicators. Consequently, only those profiles which yield ^{14}C yr/cm determinations for two or more adjacent 2500 ^{14}C yr intervals are included in the ^{14}C yr/cm averages. Since the nature of the regression process makes the curvature of a regression line highly uncertain at either extreme of the primary data range, %/cm values in the vicinity of the data extremes were included in Figures 2 to 5 only if the corresponding slope of the regression line was justifiable by the complete set of primary data points, *ie,* zero curvature estimates based on a subjective extrapolation were not included in the global %/cm averages. This restriction minimized possible biasing of the averages toward curvature by questionable data. If it had significantly distorted the global averages the upper and lower portions of Figures 2 to 5 would not have the compatibility indicated by the dashed %/cm lines.

For each category of profiles the coefficient of correlation between the slope of the ^{14}C yr/cm secant (increment in ^{14}C yr/cm divided by the corre-

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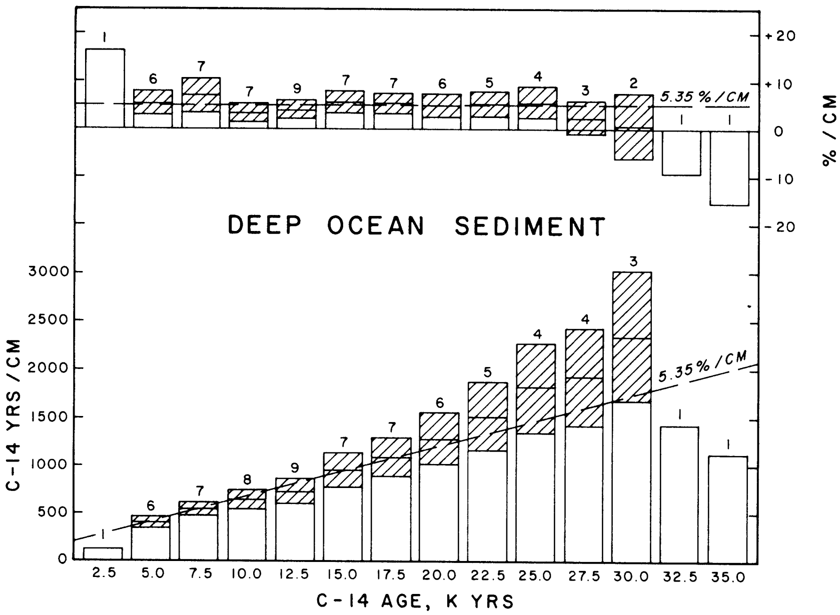

Fig 2. Graphic summary of global curvature and slope characteristics of deep ocean sediment profiles

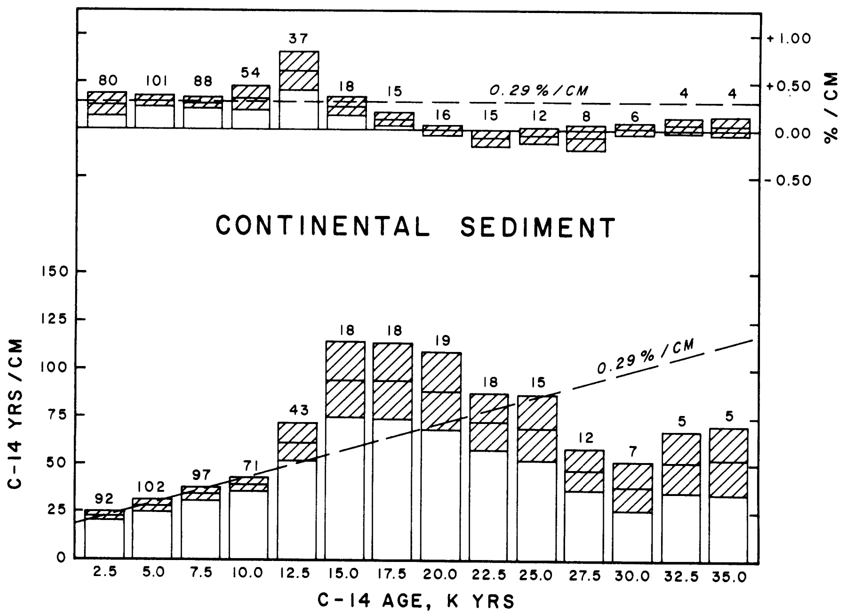

Fig 3. Graphic summary of global curvature and slope characteristics of continental sediment profiles

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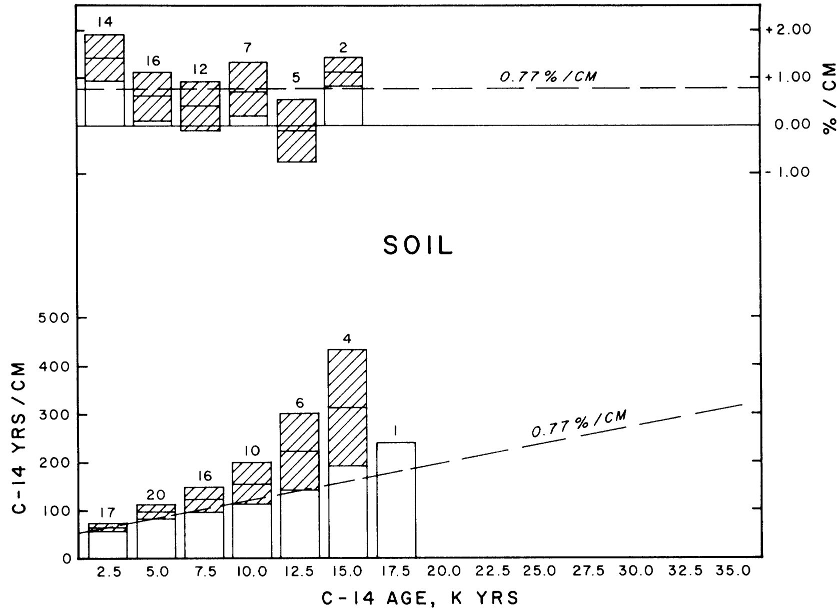

Fig 4. Graphic summary of global curvature and slope characteristics of soil profiles

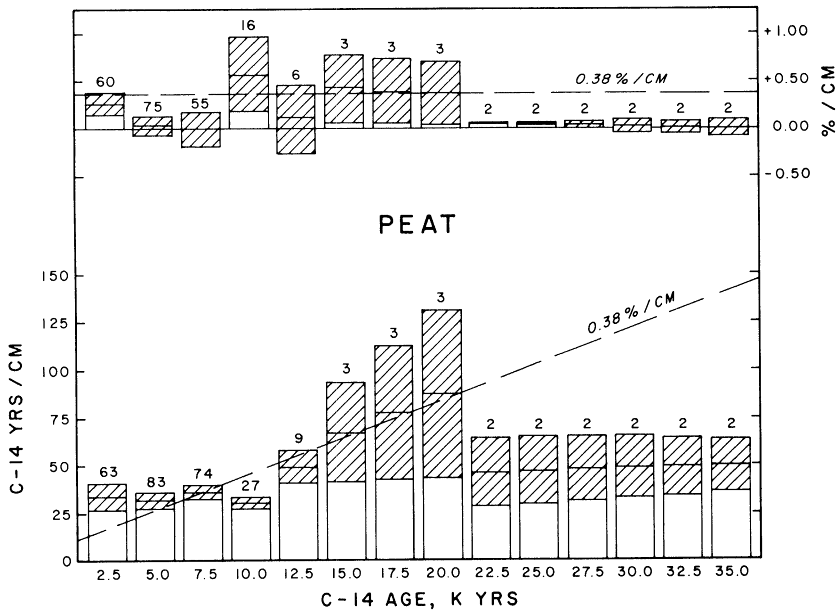

Fig 5. Graphic summary of global curvature and slope characteristics of peat profiles

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sponding increment in profile depth over the range of the primary data) and the maximum reported profile depth was calculated.

RESULTS

The first data column in Table 1, under the heading N, gives the total number of profiles in each category that are included in the analyses described in Figures 2 to 5. The fourth data column indicates the adequacy with which the profiles are represented by a cubic regression, as measured by the Coefficient of Determination (Alder & Roessler, 1977, p 237). All profiles are represented by a cubic regression in this column. The second data column lists the number of profiles for which a straight-line regression yields a lower Standard Error of Estimate than does a cubic regression and which are treated as constant ^{14}C yr/cm and zero %/cm in the analyses represented by Figures 2 to 5. The next to the last column of Table 1 lists the smallest and the greatest maximum depth for which a ^{14}C age was reported in the N selected profiles of each category. The last column lists the Correlation Coefficient between the slope of the ^{14}C yr/cm secant and the maximum depth for each category.

In Figures 2 to 5 the bar graphs represent mean values plus and minus one standard deviation (cross-hatched area) of the expected mean. The number at the top of each bar is the number of profiles that contributed to the represented mean.

DISCUSSION

Figures 2 to 5 confirm the preliminary observation that, although some ^{14}C age profiles are linear and a relative few are convex toward the ^{14}C age axis, there is a predominant tendency toward an increase in ^{14}C yr/cm with profile depth, at least in sediment and soil accumulations. Lack of an

TABLE 1
Summary of data base

	N	Linear profiles	Average no. of data points per profile	Mean Coefficient of Determination ($\pm 1\sigma$)	Maximum depth range (cm)	Correlation Coefficient ^{14}C yr/cm secant slope with max depth
Deep ocean sediment	10	0	10.5	$0.991^{+0.007}_{-0.058}$	14 - 55	-0.18
Continental sediment	160	19	11.7	$0.986^{+0.111}_{-0.045}$	35 - 8010	-0.10
Soil	25	1	11.9	$0.973^{+0.017}_{-0.046}$	75 - 285	-0.47
Peat	114	30	10.6	$0.985^{+0.011}_{-0.033}$	78 - 1770	+0.16

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adequate statistical sample prevents a conclusion with respect to the possibility that peat profiles also may have the same tendency for ^{14}C ages >10,000 BP. Although many peat profiles are concave toward the ^{14}C age axis below 10,000 BP (Fig 1, eg), there are sufficient convex examples for the data analysis in this report to clearly establish a linear relationship as the most probable over the past 10,000 ^{14}C yr. (The 60-sample %/cm average at 2500 years in Figure 5 may be biased from failure to recognize all peat profiles that should be extrapolated as straight lines at the lower end of the primary data range. Additional extrapolation of this nature would not change significantly the 63-sample ^{14}C/yr average at 2500 ^{14}C years.)

While compaction is a likely contributor in many situations, a fully adequate explanation of the ^{14}C yr/cm ordinates in Figures 2 to 4 would require the ratio of average density at profile depths associated with 15,000 and 2500 ^{14}C yr to be 3.2, 4.2 and 4.8 for deep ocean sediment, continental sediment, and soil, respectively (ratio of ^{14}C yr/cm ordinates, extrapolating to 2500 ^{14}C yr in Fig 2). Such ratios are not supported by observation and are unreasonable since they are greater than the density of either granite or basalt. The adequacy of an explanation based on compaction alone is brought into further question by the lack of correlation between change in ^{14}C yr/cm and associated profile thickness, as shown by the last two columns of Table 1.

If contamination by older carbon (Nambudiri *et al,* 1980) is to be an adequate explanation, the degree of contamination must progressively decrease with time. While allowance should be made for this possibility at some locations over some periods of time, it does not appear to be a universally adequate explanation. Such an explanation for the sediment and soil ^{14}C age profile shape tendency appears to require a progressively increasing $^{14}C/^{12}C$ ratio in the supporting environment and/or progressively more rapid real time accumulation rates. Since codeveloping peat, soil, and sediment features share a common $^{14}C/^{12}C$ ratio in their supporting environment, the diverse character of peat profiles indicated in Figure 5 seems to be accounted for most readily by differences in the real time accumulation rate.

It is unfortunate that the peat profile data from lower latitude regions of the earth are insufficient to establish peat profile shape trends prior to 10,000 yr BP. The data between 12,500 and 35,000 ^{14}C yr (Fig 5) are provided by only one peat profile each from Spain, Greece, and India.

The expectation that peat profiles should be more sensitive to compaction than sediment or soil profiles is supported by the +0.16 correlation coefficient listed in Table 1. This positive coefficient (0.26 to 0.63 more positive than for sediment and soil profiles) in connection with a group average linear profile over the 0 to 10,000 ^{14}C range (Fig 5) favors the hypothesis that peat growth rates, on average, have decreased during this time, since the accumulation profile would have to be convex toward the ^{14}C age axis to produce a linear profile for a peat deposit that has experienced compaction and/or decomposition.

To eliminate an increasing $^{14}C/^{12}C$ ratio as a possible factor in producing the profile characteristics displayed in this analysis, it would be necessary to have a world-wide climatic trend favoring an increase in average

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sediment and soil accumulation rates coincident with a decrease in average peat accumulation rates (assuming that a peat profile accumulated at a constant rate would exhibit curvature due to compaction and/or decomposition).

It would be desirable to use for regression analysis only profiles defined by nine or more well-distributed data points, but since ensemble averages rather than individual profile specifications are of interest in this investigation it seems to be more desirable to have the larger and more representative statistical sample provided by including profiles with 7 and 8 data points.

CONCLUSIONS

The data at hand seem adequate to establish that, although there is wide variation between individual profiles, there is a global tendency for ^{14}C age profiles of sediment and soil accumulations to exhibit an increase in ^{14}C yr/cm with depth. Increasing compaction with depth, increasing contamination by older carbon with depth, increasing $^{14}C/^{12}C$ ratio in the supporting environment during accumulation, and increasing accumulation rate during feature development, individually or in varying combinations, are the probable causes for this profile characteristic. Limitations on density variation with profile depth and lack of correlation between change in ^{14}C yr/cm and profile thickness eliminate compaction as an adequate cause. A universal progressive reduction in contamination by older carbon is highly improbable. Therefore, within the scope of this investigation increasing $^{14}C/^{12}C$ ratio and/or increasing accumulation rate appear to be the dominant and only potentially adequate causes. Considerations outside this investigation, particularly dendrochronologic correlations with ^{14}C age (eg, Kromer *et al,* 1986), appear to limit changes in $^{14}C/^{12}C$ ratio to only a minor, rather than a dominant role.

The data at hand also establish a global tendency for ^{14}C age profiles of peat to be linear, on average, with a greater tendency toward positive correlation between individual profile change in ^{14}C yr/cm and profile thickness, compared with profiles for sediment and soil. With consideration of the profile curvature expected as a consequence of decomposition and compaction, and that would have been produced by an increasing $^{14}C/^{12}C$ ratio, these characteristics can be explained on the basis of a global decrease in average peat deposit accumulation rates over at least the last 10,000 ^{14}C years.

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