

Estimation of Particle Flux and Remineralization Rate from Radioactive Disequilibrium Measurements

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1. Abstract

Reactive radionuclides, such as the thorium isotopes, show measurable deficiencies in the oceanic water column because of their removal by chemical scavenging due to the particle flux. Measurement of the deficiency, coupled with measurement of the radionuclide concentration in particles, allows a determination of the effective particle sinking velocity. Results to date suggest that the effective particle sinking velocity is remarkably invariant with depth. This leads to the tentative suggestion that POC concentration profiles may, to a good approximation, be used directly to determine length scales for the remineralization of sinking organic matter. Further measurements are in progress to test this idea and to evaluate its limitations. Knowledge of the remineralization length scale is essential to an evaluation of the efficiency of the biological pump as a means for deep sequestering of carbon in the ocean.

2. Thorium-230 mass balance

Because of the conservative nature of uranium in seawater, its concentration is nearly the same everywhere in the ocean. Thus the rate of production of the ^{234}U daughter, ^{230}Th , is nearly constant at every point. This production at any depth z must be balanced by the sum of radioactive decay and the vertical gradient of the particulate ^{230}Th flux:

$$\lambda^{234}\text{U} = \lambda(^{230}\text{Th}_{\text{diss}} + ^{230}\text{Th}_{\text{part}}) + S \frac{\partial ^{230}\text{Th}_{\text{part}}}{\partial z}$$

where λ is the radioactive decay constant of ^{230}Th , ^{234}U and ^{230}Th are concentrations, and S is the particle sinking velocity. In the case of ^{230}Th , its half-life is so long and its concentration (both dissolved and particulate) in seawater so low that its decay in the water column is negligible, and we have the simple relationship

$$S = \frac{\lambda^{234}\text{U}}{\partial ^{230}\text{Th}_{\text{part}} / \partial z}$$

Thus the particle sinking velocity varies inversely with the particulate ^{230}Th concentration gradient.

This was first demonstrated during GEOSECS by Krishnaswami et al. (1976), who obtained the results shown in **Figure 1** from the analysis of particles collected by filtration. Their data are limited by low sampling resolution, and their measurements, by alpha counting, were also of limited precision, but they do show clearly the expected increase, roughly linear, in particulate ^{230}Th concentration with depth and suggest a mean sinking velocity on the order of 1-2 meters per day.

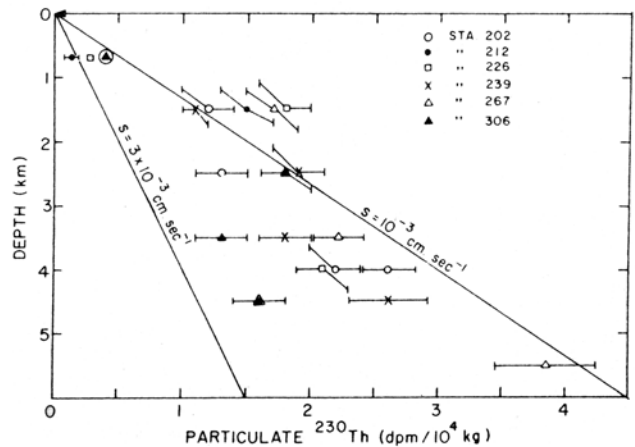


Figure 1

We have recently obtained the results shown in **Figure 2** for a station in the western North Pacific. Our sampling resolution is better, and the precision of our measurements, based on inductively coupled plasma mass spectrometry (ICP-MS), is much better. (The error bars are contained within the symbols.) It is remarkable how almost perfectly linear the profile is, indicating a sinking velocity that is nearly invariant with depth. There is a hint of curvature, as indicated by the quadratic fit, in the direction of increasing sinking velocity with depth. This is the direction that would be expected for particles that are losing organic matter by remineralization and thus increasing in density (cf. Berelson, 2002), though it is not clear that the quadratic is statistically a better fit than the linear. In any case, the implied increase in sinking velocity is small, ~35% over the entire water column and less than ~10% over the mesopelagic zone (~100-1500 m), which is the main focus of our interest. The mean sinking velocity is ~2 meters per day, similar to the result of Krishnaswami et al.

We do not yet have particulate ^{230}Th profiles from other parts of the ocean that would confirm this result, but we do have a number of profiles of dissolved or total ^{230}Th concentration (**Figure 3**) that consistently show strong linearity down to at least 2000 meters depth. This suggests that the near constancy of particle sinking velocity will hold at those locations as well, though it will require analysis of particulate matter samples to confirm this and to quantify the sinking velocity at each location.

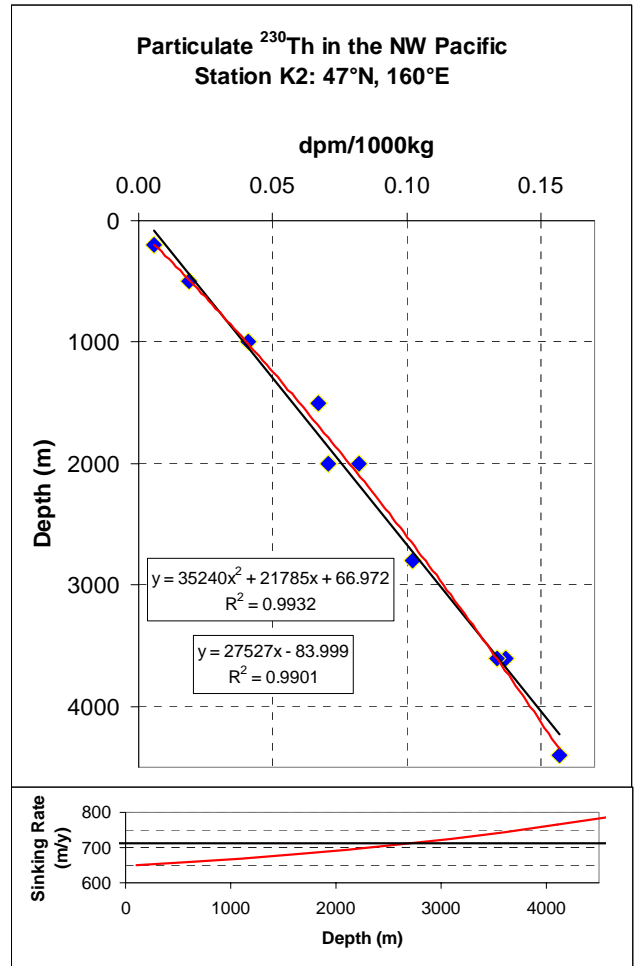


Figure 2

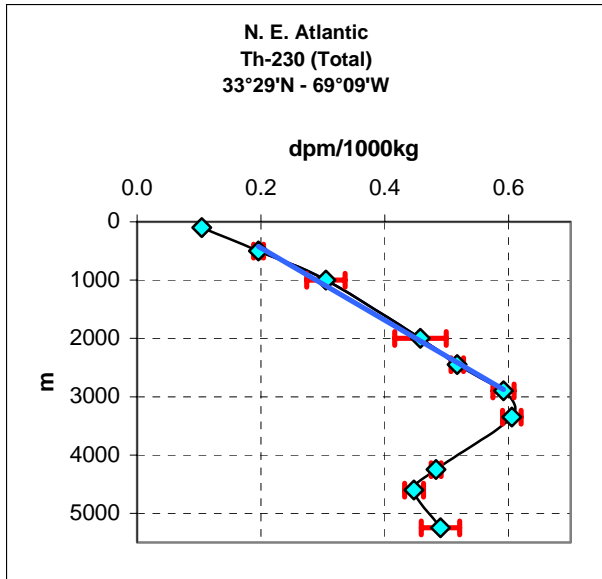


Figure 3a

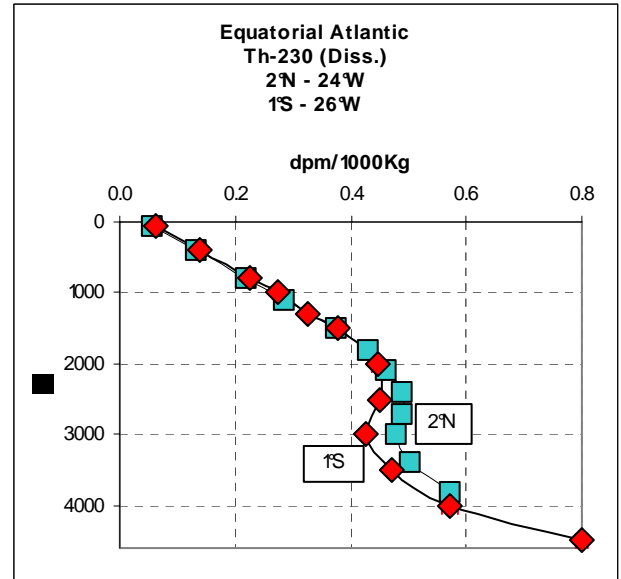


Figure 3b

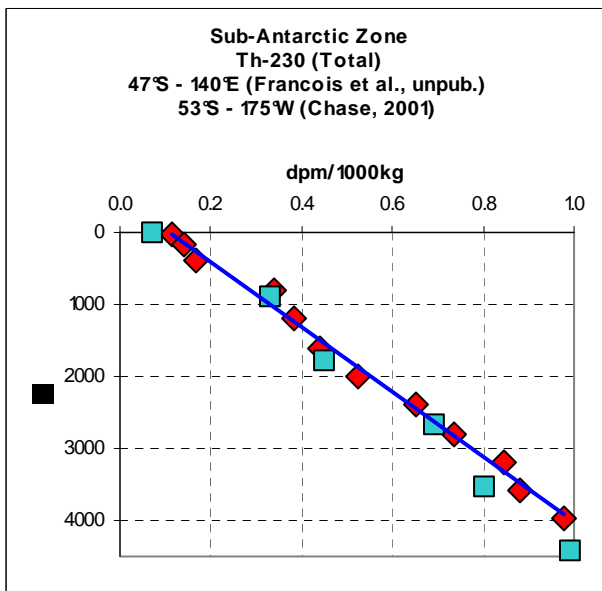


Figure 3c

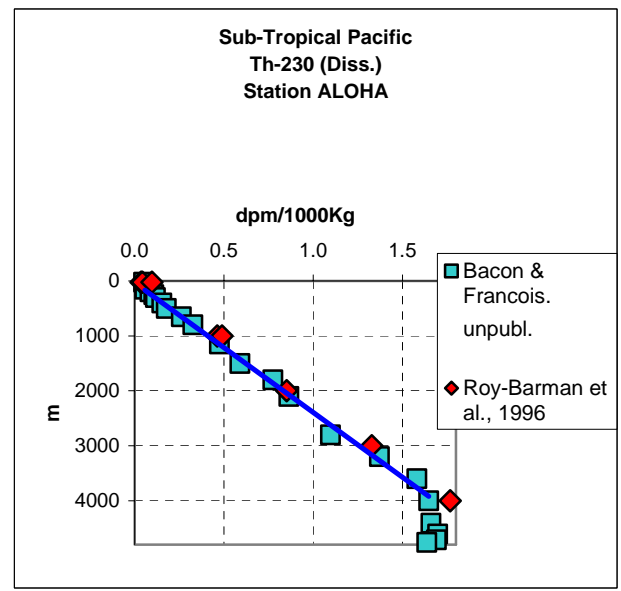


Figure 3d

3. Interpretation of sinking velocities based on ^{230}Th

The sinking velocity estimates given above, of 1-2 meters per day, are based on analysis of particles collected by filtration. They are much smaller than the estimates of 10-100 meters per day for the large aggregates that are caught in sediment traps and are believed to carry most of the downward flux of particulate material. This can be understood by postulating a small-particle, suspended reservoir and a large-particle sinking reservoir, between which material exchanges by a continuous cycle of aggregation and disaggregation, as illustrated schematically in Figure 4. The sinking velocity deduced from particulate ^{230}Th profiles can thus be interpreted as the average rate at which the particle pool works its way downward as the result of the aggregation/disaggregation cycle and the rapid sinking that occurs for the small percentage of the

time that the material resides in a large aggregate. For example, a small particle may have a negligible sinking velocity for 95% of its life but reside within an aggregate sinking at 40 meters per day for the other 5%. It would have an effective mean sinking velocity, as determined by particulate ^{230}Th profiling, of 2 meters per day.

We believe that filtration of suspended particles captures most of the particulate material that is undergoing remineralization and where uptake of ^{230}Th from seawater is occurring. This is because the concentration of the small, suspended particles is much higher than that of the large, sinking particles, and the surface area is very much larger. If this is so, then it follows that POC concentration profiles combined with particle sinking velocities based on particulate ^{230}Th profiles yield POC flux profiles from which remineralization rates can be determined. What would be missed in this analysis is the particle flux carried by robust aggregates originating in the surface layer that are not significantly reworked in mid-water but carry relatively unmodified material to the seafloor (Figure 4). Quantification of this will require analysis of the large-particle fraction, still to be carried out.

4. Application to POC profiles

As we have seen above, the effective mean sinking velocity of the particle pool appears to be remarkably invariant with depth. This implies that POC concentration profiles might be interpreted as relative flux profiles from which rates of loss with depth (rem mineralization) can be inferred. We have begun to examine JGOFS data with this idea in mind. Many of the JGOFS POC profiles do not go deep enough to be useful, but those from the Arabian Sea do. In Figure 5 we show some examples from the winter cruise (January 1995). We have applied a formula analogous to that of Martin et al. (1987):

$$[POC] = [POC]_{100} (z / 100)^b$$

Without particulate ^{230}Th profiles for these stations, we cannot convert these to flux profiles, but with the assumption of constant sinking velocity with depth, the POC concentration profile should give us the correct shape of the flux profile. Martin et al. obtained a best fit to VERTEX (eastern North Pacific) sediment trap POC flux data for $b = -0.858$. The b values for the Arabian Sea are systematically less negative than this, suggesting penetration of the POC flux to greater depth than in the eastern North Pacific. This difference is in a direction consistent with a “ballast” effect due to the higher carbonate fluxes in the Arabian Sea (cf. Francois et al., 2002).

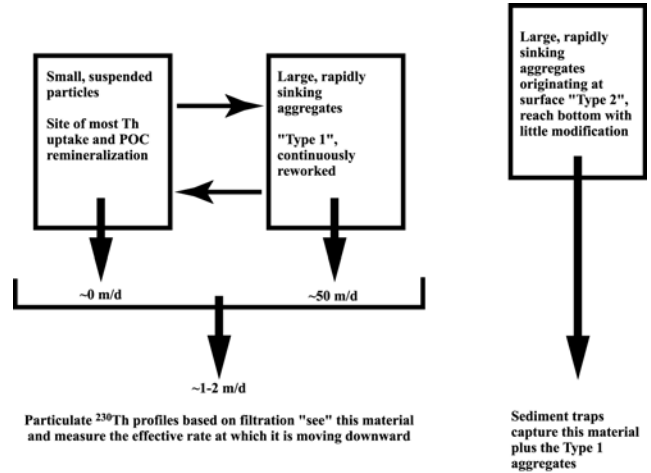


Figure 4

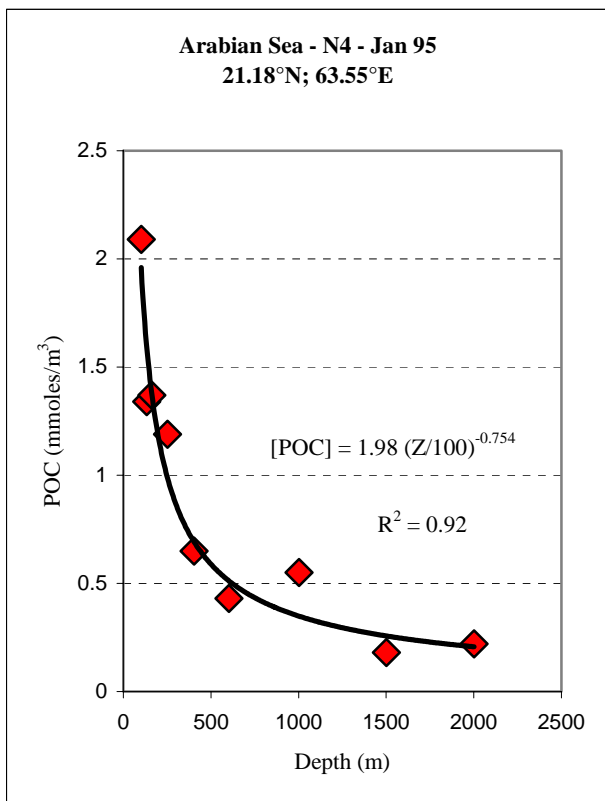


Figure 5a

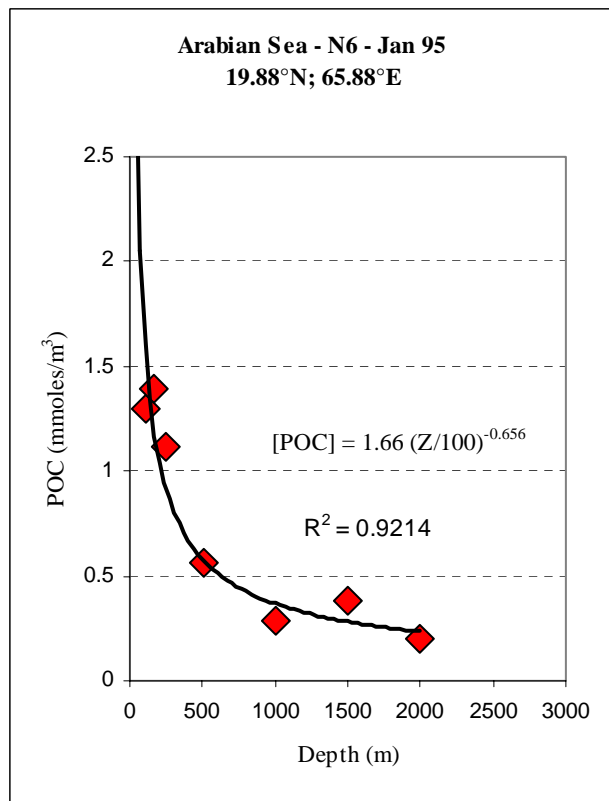


Figure 5b

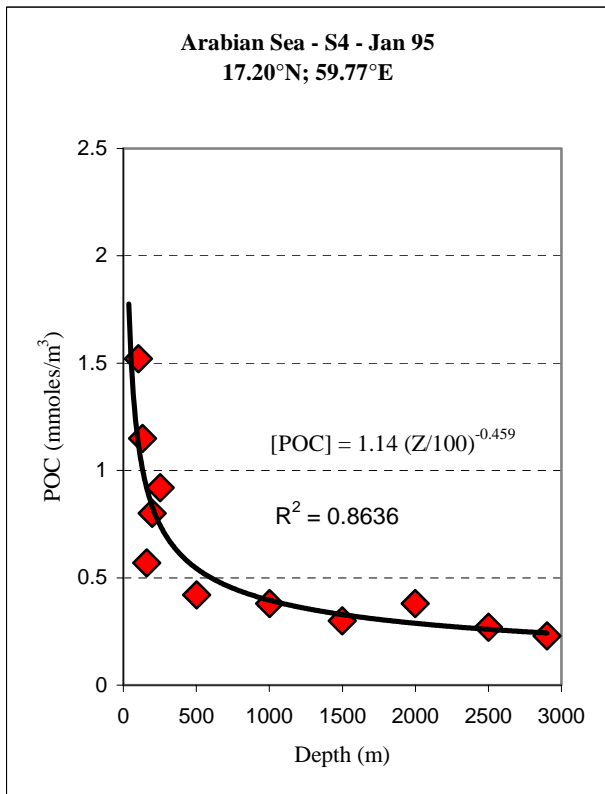


Figure 5c

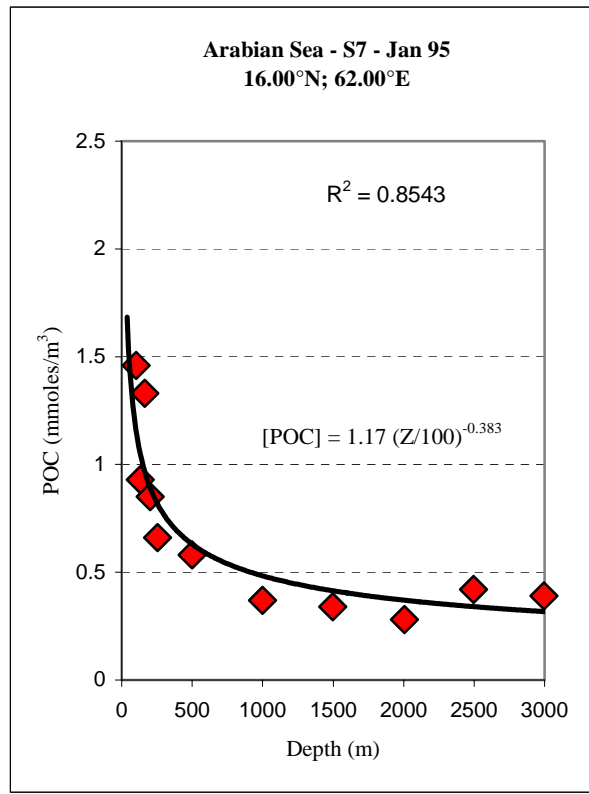


Figure 5d

5. Publications

The following papers were written with support from this project:

Bacon M. P. (in press) Reactive radionuclides as tracers of oceanic particle flux. In *Radioactivity in the Oceans* (ed. H. D. Livingston). Elsevier Science.

Francois R., Honjo S., Krishfield R. and Manganini S. (2002) Factors controlling the flux of organic carbon to the bathypelagic zone of the ocean. *Global Biogeochemical Cycles*, 16, 1087, doi:10.1029/2001GB001722.

Turekian K. K. and Bacon M. P. (2003) Geochronometry of marine deposits. In *Treatise on Geochemistry*, v. 6: *The Oceans and Marine Geochemistry* (ed. H. Elderfield). Elsevier Science, pp. 321-341.

In addition, results were presented in September 2003 at the Goldschmidt Conference in Kurashiki (Japan).

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