

Letter Section

## STATISTICAL RE-ANALYSIS FOR SIZE DEPENDENCY IN DEEP-SEA MIXING

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### Abstract

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Using the data of Ruddiman et al., we tested the implicit assumption that biogenic mixing intensity ( $D_b/SL_n$ ) within a deposit is independent of particle size. A conservative Friedman rank sums test and the multiple comparison test for it were used to compare the downcore dispersion of several size fractions (11-500  $\mu\text{m}$ ) of volcanic ash. In three of the seven cores analyzed, the null hypothesis of size-independent mixing was rejected. Fisher's method of compounding independent probabilities forced rejection of the hypothesis of size-independent mixing overall ( $P < 0.001$ ), i.e., when all the data for the seven cores were considered together. Mixing is size dependent, with finer fractions being more intensely mixed. The likely cause is size-selective feeding by infauna. The importance of the observed differences in stratigraphy among size fractions must be evaluated against the resolution required to address the problem at hand.

### Introduction

Displacement of particles by benthic organisms is an important and nearly ubiquitous process in aquatic environments. Only in areas characterized by very low dissolved oxygen levels or very high sedimentation rates are sediment-stirring animals precluded. Thus, a thorough understanding of the driving mechanisms, styles, and rates of bioturbation is germane to many fields of study. At present, bioturbation is most often modeled as a one-dimensional (vertical), diffusive process (Guinasso and Schink, 1975; Boudreau, 1986a); although models that take into account nonlocal, advective mixing also exist (Boudreau, 1986b). Implicit in each of these models are

several necessary assumptions that must be met before tenable conclusions can be drawn. Of primary importance in the context of the present letter is the question of whether particle size-dependent mixing occurs. If mixing is size dependent then estimations of mixed-layer thicknesses and mixing rates made from one size class may not apply to other size classes, and mean mixing rates may be poorly applicable to particles of a given size range (Officer and Lynch, 1983).

An explicit examination of the assumption of size-independent mixing was made by Ruddiman et al. (1980). They tabulated the vertical spread of different size fractions of pulsed tracers (volcanic ash and microtektites) in cores and compared them graphically with each

other and with theoretical curves (Guinasso and Schink, 1975). No statistical tests for size selectivity were performed. Based upon these authors' visual comparisons their implicit null hypothesis of non-selective mixing failed to be rejected. They concluded that bioturbation is not a strongly size-dependent process in deep-sea sediments, although they cautioned that in some cores there were minor tendencies toward greater mixing of the fine fraction. Despite the original authors' due caution, however, their paper is now widely cited (e.g., DeMaster and Cochran, 1982; Stordal et al., 1985; Cochran, 1985) as evidence that size-selective mixing does not occur.

Failure to reject a null hypothesis gives no support to its verity without an analysis of statistical power (beta or type-II error) (Sokal and Rohlf, 1969; Conover, 1980). Further, our visual inspection of the same data suggests that size-dependent mixing does exist. DeMaster and Cochran (1982), Stordal et al. (1985) and Cochran (1985) have gone to great lengths to find explanations other than size-selective mixing for observations that are most parsimoniously explained by size dependence. In light of the importance that the study by Ruddiman et al. (1980) has acquired through such citations, a more objective analysis of their data is in order. Robust nonparametric statistical tests in fact demonstrate that the null hypothesis must be rejected; smaller particles are more extensively mixed than coarser ones to a degree that can not be explained by chance or sampling error.

The specific goals of this letter are two: to discuss reasons why size-dependent mixing is expected, and to re-analyze the data of Ruddiman et al. (1980) showing that a conclusion opposite to that which has been widely quoted is the more defensible.

### **Background**

If, as seems likely, deposit feeding is the most important animal activity in terms of net par-

ticle displacement (Aller, 1977; Thayer, 1983), consideration of the distribution of food items in sediments is crucial to an evaluation of size-dependent mixing. The long-standing observation that deposit-feeder standing stock increases with decreasing particle size of the deposit suggests that more food is to be found in finer elements (Purdy, 1964; Longbottom, 1970). With decreasing particle size the ratio of grain-surface area to grain volume increases, providing the potential for more food per unit volume (assuming that a component of the food is surface associated). Quantitative measures of the relationship between sediment surface area and microbial abundance and organic carbon (DeFlaun and Mayer, 1983; Yamamoto and Lopez, 1985) support this explanation at least down to grain diameters of about 10  $\mu\text{m}$ . The above observations were put into an optimal foraging context by Taghon et al. (1978) who predicted that deposit feeders should under most conditions preferentially ingest small particles.

There have been numerous empirical studies of particle selection (summarized by Jumars et al., 1982), as well as a priori tests of size selectivity (Taghon, 1982). The most frequent finding is of preferential selection for smaller particles, although exceptions do exist. The carefully examined and well-documented exceptions appear to correspond with locally elevated food abundances on particles of large size (Whitlatch, 1974). More recent experimental studies with glass beads of varying sizes and specific gravities and animals from several phyla further support the earlier findings of peak selectivity for small particles (10–20  $\mu\text{m}$ ) (Self and Jumars, in prep.).

Indirect evidence of particle size-dependent mixing comes from studies of trace metal and radionuclide distributions. Brown (1986) studied the distributions of Cd, Cu, Ni, and Zn in a Welsh estuary and found that fecal pellets of a gastropod and several bivalves were enriched by up to a factor of seven in these elements. Brown suggested that the preferential occurrence of

trace metals with finer-grained particles, and active selection on the part of the mollusks for these particles, explained her results. Particle size-dependent mixing has also been invoked by DeMaster and Cochran (1982) to explain disparities between  $^{210}\text{Pb}$ - and  $^{32}\text{Si}$ -derived mixing coefficients and by Stordal et al. (1985) to reconcile differences resulting from  $^{210}\text{Pb}$  and  $^{239,240}\text{Pu}$  profiles. In both cases the radionuclide that yielded the higher mixing values was inferred to be associated with finer particles. Cochran (1985) also found a disagreement between mixing coefficients calculated from the profiles of the artificial radioisotopes,  $^{137}\text{Cs}$  and  $^{239,240}\text{Pu}$ , and  $^{210}\text{Pb}$ . He suggested differential mixing of different sized particles, but also stated that chemical migration of the radionuclides could not be discounted. A further, independent line of evidence that suggests size-dependent mixing comes from studies of calcium carbonate ages in the mixed layer. Berger and Johnson (1978) hypothesized that discrepancies between  $^{14}\text{C}$  dates and oxygen isotope curves could be the result of greater mixing of the bulk carbonate fraction relative to the large foraminiferas from which the oxygen record is derived. All of these observations underscore the importance of close inspection of what is probably the best data set in existence for an explicit test of size-selective mixing.

## Methods

Ruddiman et al. (1980) examined in seven cores the vertical dispersion of silicic, volcanic shards and microtektites ranging in size from 11 to 500  $\mu\text{m}$ . Details of the techniques used to isolate, subdivide, and count the glass shards can be found in the original paper. By re-analyzing seven sub-samples from each core, fairly low ( $< \pm 12\%$ ) standard deviations in counting were obtained (Ruddiman et al., 1980). Downcore ash concentrations were area normalized following the technique of Guinasso and Schink (1975), thus minimizing visual distortions due to changes in the absolute concentra-

tion scale (Ruddiman and Glover, 1982). The data for our re-analysis thus consist of normalized (relative) ash abundances classified by size class and by depth stratum in the core.

We suspect that the reason for the absence of statistical analysis in the original treatment (Ruddiman et al., 1980) is that such analysis is not straightforward. Two modes of statistical analysis come to mind immediately but must be rejected on the basis of actual or potential failure of their assumptions. The first is parametric analysis of variance (ANOVA). While it is ideal in that all the cores can be combined readily in one analysis, the design is unbalanced (different numbers of strata in different cores). More importantly, the assumption of homoscedasticity is violated by the interaction of mixing intensity with the shape of the buried depth-frequency distribution. The second method is the Kolmogorov-Smirnov two-sample test for identity of distributions and its extension to multiple samples (Conover, 1980). Running these tests, however, would require the original data (to specify the number of particles) and, more critically, would violate the vital assumption of random sampling of individual particles (Venrick, 1986).

We elected instead to run the Friedman rank sums test, the nonparametric analog of two-way ANOVA. It has the disadvantage relative to ANOVA that it can not resolve statistical interactions from treatment effects. Interactions can either masquerade as, or weaken, treatment effects. The test is conservative in this sense, since the interaction will not cause increased alpha error (rejection of a true null hypothesis). Our argument for using this test and our mode of application is as follows. Theoretically derived concentration curves for an instantaneously deposited tracer subject to a range of mixing and sediment accumulation rates are reproduced in Fig. 1. With increasing mixing rate relative to sedimentation rate the peak of the curve becomes broader and moves further down core, while the distribution is skewed increasingly upward. The greatest qualitative

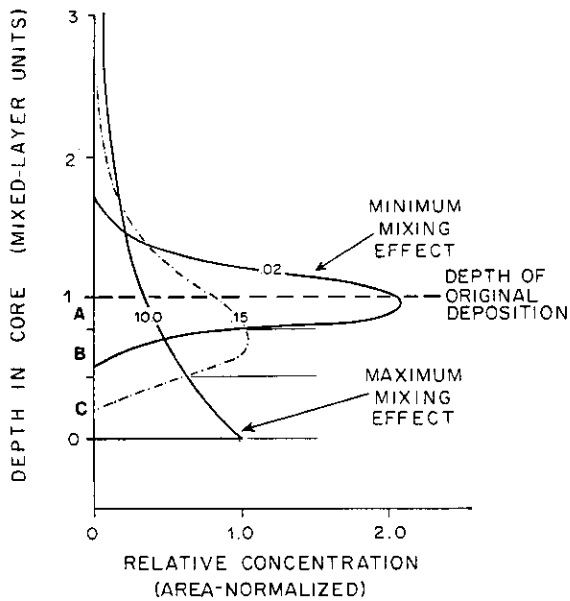


Fig. 1. Fig. 1. Relative concentration curves for instantaneously and simultaneously deposited tracers subjected to a range of mixing rates in the mixing layer before eventual burial (modified from Ruddiman et al., 1980). The plots are produced from a simple one-dimensional model of diffusive bioturbation in the nondimensionalized form suggested by Guinasso and Schink (1975), with their measure of mixing intensity ( $D_b/SL_b$ ) given on the respective curves. If finer particles are more intensely mixed, below the depth of original deposition they will have the highest rank in relative abundance over a comparatively greater vertical extent of the core (interval  $C > B > A$ ).

and quantitative differences among the curves occur below the depth of original deposition, so we limited our analysis to this region of predicted highest resolution. With increasing difference in mixing intensity, the depth interval over which the more intensely mixed particle type's abundance exceeds that of the less intensely mixed particles increases (Fig. 1). Thus, if finer particles are the more intensely mixed, their relative abundances should more often than not exceed those of coarser particles in strata below the depth of original deposition.

Under the null hypothesis of no size-selective mixing, the relative abundances of particles within any stratum should differ only by counting or sampling error, i.e., not systematically. We thus ran the Friedman rank sums tests using

depth strata below that showing the highest peak in the coarsest size fraction. In ANOVA terminology, the treatments are particle-size classes and the blocks are depth strata below the coarse-sediment peak. The explicit alternate hypothesis is that smaller particles should be more intensely mixed, giving rise to relatively higher abundance in more of these strata as particle size decreases. The ordinary Friedman test does not take into account the directional nature of this alternative hypothesis and thus is conservative in this sense as well. (More accurate alpha levels are approximately half of those presented in the results.)

Our test of the null hypothesis as phrased thus is not the most powerful possible. Hollander's modification for ordered alternatives (Hollander and Wolfe, 1973, p. 167) is more powerful, but we do not use it here because no multiple comparison tests have yet been tailored for it. We wished, if we found significant differences, to establish which size classes were significantly different from each other in mean rankings of relative abundance. We thus used the standard Friedman rank sums test and the multiple comparison test for it (Conover, 1980). Again both are conservative for the problem as posed here.

## Results and discussion

In three of the seven cores analyzed by Ruddiman et al. (1980), we were forced to reject the null hypothesis (Table 1), even with this admittedly weak test. In all of these cores the finest fraction yielded the highest rank sum, suggesting that it is most intensely mixed. In addition, in three out of the remaining four cores the trend was also toward more intense mixing of the fine fraction, although it is not statistically significant at our predetermined alpha level of 0.05. Only in core V29-39 is there a (very weak) trend in the opposite direction. A strong argument for monotonic dependence of mixing intensity on particle size is that all significant differences between size classes can be indi-

TABLE 1

Summary of results obtained from the Friedman test; shown in parentheses are the number used in each core. The numbers listed under sums of the rankings for each size fraction. U are those rank sums that do not differ significantly.

Core	Size fraction ( $\mu\text{m}$ )		
	500-250	250-125	125-62
V19-28 (8)	*	*	9
V19-29 (7)	*	13.5	14.5
V29-39 (6)	*	17.5	9.5
V29-40 (9)	*	20	24
RC17-126 (8)	*	18.5	15.5
E48-23 (7)	*	8	17
V27-19 (6)	14.5	13.5	19.5

\*indicates absence of data.

ated without ambiguity (T articles are arranged in order

To make an overall statement combined, we used Fisher's combined independent probability test (Rohlf, 1969). The actual core are simple and are based on  $-\ln P_i$  is chi-square distribution probability associated with independent tests). Thus by the negative natural logarithm probabilities and summed obtained for comparison under the appropriate (Table 2). In this case the value is highly significant 0.001. We again stress that could be devised. We do not apply these more specialized tests because the present analysis is perfectly adequate to reject the null hypothesis of size-independent mixing with a high degree of assurance. Furthermore the finer fractions are mixed more intensely, a result compatible with several other independent lines of evidence.

The implications of particle size-dependent mixing, whereby there is an inverse relationship between particle size and mixing rate, are

TABLE 2

Information used to combine the probabilities derived from individual cores (Table 1) in an overall test (bottom line) of the hypothesis of size-independent mixing intensity. The summed value of chi-square is compared to tabled values with the appropriate degrees of freedom (d.f.)

Core	P-level	$-\ln P$	d.f.
V19-28	0.0022	12.2386	2
V19-29	0.1500	3.7942	2
V29-39	0.2500	2.7726	2
V29-40	0.6200	0.9561	2
RC17-126	0.0096	9.2920	2
E48-23	0.0215	7.6794	2
V27-19	0.4150	1.7590	2
Overall	<0.001	38.4919	14

many. It means that the filtering effect that mixing has on paleoclimatic signals is not a simple one. Smaller microfossils (e.g., coccoliths) should be spread over greater vertical distances than larger ones, thus limiting the resolution of biostratigraphic information obtained from their distributions and complicating attempts to deconvolve mixing effects (Schiffelbein, 1985). This finding suggests that larger microfossils should be targeted in high resolution biostratigraphic studies, although there is evidence that enhanced upward movement of particles larger than about 2 mm can be effected by animals (I.N. McCave, pers. commun., 1986). The mechanism invoked by McCave, however, can operate only when the size fraction involved comprises a small volumetric fraction of the deposit.

Size-dependent selection might also increase the average age of surficial sediments by maintaining smaller particles in the surface mixed layer (Jumars et al., 1981). This effect would produce anomalously low apparent sediment accumulation rates and might potentially lead one to posit physical processes (e.g., winnowing or slumping) where none had occurred. The results of our re-analysis also suggest that further consideration be given to the details of radionuclide adsorption in the water column. Confusion persists regarding the removal of  $^{210}\text{Pb}$  and the various bomb-produced radioiso-

On page 161, TABLE 1 there is a printing error. Line 1 should read: V19-28(8) \* That is, each size class is statistically different in its dispersal.

ERRATUM !!!

$$\frac{9}{16} \frac{23}{0.0022}$$

topes ( $^{137}\text{Cs}$ ,  $^{239,240}\text{Pu}$ ) (Stordal et al., 1985). Until we know for individual radionuclide species the degree of association with respective size fractions and mode(s) of delivery to the bottom, the exact meaning of various radioisotope-derived biodiffusivity values will remain unclear. Studies that employ truly conservative tracers (e.g., glass beads or fluorescent pigments) are needed to provide controls to which radionuclide data can be compared.

Our analysis, based on conservative particles, documents unequivocally that size-dependent mixing is the rule in Ruddiman et al.'s (1980) data set. We have not established the magnitude of this effect or its applicability to other deep-sea and shallow-water areas. Whether it is quantitatively important in a given application will depend on the composition and activity of the infauna and on the degree of resolution required for the question at hand.

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