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# *Vertical Mixing in Pelagic Sediments*<sup>1</sup>

Wolfgang H. Berger and G. Ross Heath

*Scripps Institution of Oceanography  
La Jolla, California*

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## ABSTRACT

Vertical mixing in sediments can be quantitatively described if it is assumed that: (i) upon deposition, detrital particles are mixed uniformly to a depth,  $m$ , below the sediment-water interface at a rate that is much faster than the sedimentation rate, (ii) the species,  $z$ , whose vertical distribution is to be described, appears or disappears abruptly, and (iii)  $z$ , throughout its time-range, forms a constant proportion of the sediment that settles to the sea floor. Upon appearance, the concentration of  $z$  increases rapidly from a first occurrence of  $m$  units below the contemporaneous ocean floor. Upon extinction, the concentration decreases gradually, with significant (0.1%) upward contamination extending about six mixed-layer thicknesses above the extinction level. Within certain limits, the model is applicable to pelagic sediments. Marked stratigraphic errors can appear if the layers representing time ranges are similar in thickness to the mixed layer, as may be the case in many Quaternary sediments.

Deep-sea stratigraphy (other than magnetic stratigraphy) is based on the concentrations of chemical, mineralogical, and biological species at various levels in deep-sea sediment cores. Several workers have recognized that mixing by benthonic animals or mechanical agents near the sediment-water interface is important in changing the original concentration of such components (Arrhenius 1952, Bramlette and Bradley 1940, Emiliani and Flint 1963, Goldberg and Koide 1962). Riedel (1967) has used the presence of pre-Quaternary Radiolaria in Quaternary sediments to infer the distribution of Tertiary rocks. McIntyre et al. (1967) have noted an exponential decrease in the concentration of nanofossils above the Plio-Pleistocene boundary; they ascribed this decrease to vertical mixing. For similar studies, it may be useful to quantify the concept of vertical mixing of microfossils and other detrital components in sediments.

Fig. 1 is a diagram of a simple mixing model. Shelled microplankton or other particles rain down onto the sediment-water interface, where they become thoroughly mixed with older deposits in the homogeneous layer.

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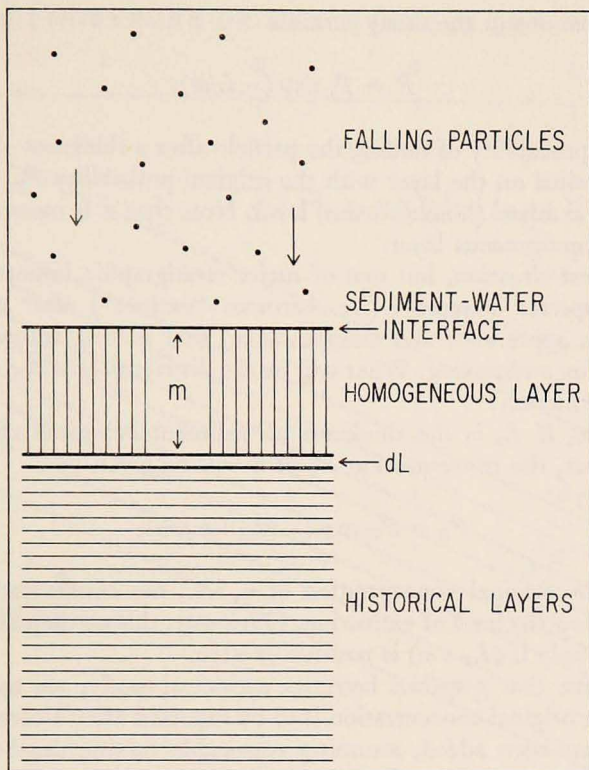


Figure 1. Simple conceptual model of detrital deep-sea sedimentation. Detrital particles rain upon the sediment-water interface and are quickly incorporated into the homogeneous layer of thickness  $m$ . The rate of deposition determines the rate at which a thin basal slice of the homogeneous layer of thickness  $dL$  is incorporated into the historical layer.

Once incorporated into the historical layer, the particles come to rest. We assume that the rate of mixing in the homogeneous layer is great compared with the sedimentation rate; this seems reasonable for most pelagic sediment. A particle just deposited, therefore, can be thought of as residing with equal probability at any depth within the homogeneous layer. The rate at which the sediments are deposited on the interface determines the rate at which a bottom slice of this layer is incorporated into the motionless sediment below. Thus, there is a certain probability that a given particle will disappear into the historical layer. The probability of finding that particle in the homogeneous layer decreases accordingly. For a small subtraction of sediment, the ratio of the probability of coming to rest to the probability of being found in the homogeneous layer is equal to the ratio of the thickness of the subtracted sediment to the thickness of the mixed layer:

$$dP/P = -dL/m. \quad (1)$$

Integrating, we obtain the decay formula

$$P = P_0 \exp(-L/m); \quad (2)$$

here  $P$  is the probability of finding the particle after a thickness  $L$  of sediment has been deposited on the layer with the original probability  $P_0$ , and  $m$  is the thickness of the mixed (homogeneous) layer. Note that  $L$  is measured from the base of the homogeneous layer.

The simplest situation, but one of major stratigraphic importance, is that in which a species disappears (i.e. becomes "extinct") after a "life-span" (time between appearance and disappearance) that is long compared to rates of sedimentation and mixing. What will be the distribution of the species above its level of extinction?

In this case, if  $L_e$  is the thickness of sediment deposited after species  $z$  becomes extinct, the concentration  $P_z$  of  $z$  will be given by

$$P_z = P_{sz} \exp(-(L_e + m)/m); \quad (3)$$

here  $P_{sz}$  is the original concentration of  $z$ , i.e., the concentration at a distance of  $m$  below the level of extinction. Obviously, this mathematical relationship is useful only if  $(L_e + m)$  is positive or zero.

If we assume that a species becomes extinct abruptly, we may ask what fraction of the original concentration is to be expected after a certain thickness of sediment has been added, assuming reasonable mixing depths. Depths of from 2 to 5 cm are usually given in the literature (Arrhenius 1952, 1963, Blackman 1966, Ericson et al. 1961). By specifying reasonable contamination levels, it is possible to calculate the stratigraphic resolution of deep-sea cores under the assumptions of this model.

Fig. 2 shows the relationships between mixed layers of various thicknesses and the lengths of core sections in which the percentage of an extinct fossil will fall to a certain proportion of its original value. For example, if the thickness of the homogeneous layer is 4 cm and the permissible contaminant level is 10% (i.e. upward mixed particles shall not exceed 10% of the original concentration), it can be seen in Fig. 2 that the original site of deposition could have been as much as 9 cm deeper in the core. If 10% is considered to be a reasonable value for the definition of 'extinct,' then stratigraphic resolution based on this concept would be about 9000 years for sedimentation rates of 1 cm per thousand years and about 2250 years for rates of 4 cm per thousand years. For an extinction value of 1%, these time-spans must be doubled. The exact level corresponding to extinction can be obtained by determining the position at which the concentration of the species is  $1/e$  or 0.37 times its maximum concentration below. This concentration level is completely independent of the thickness of the mixed layer.

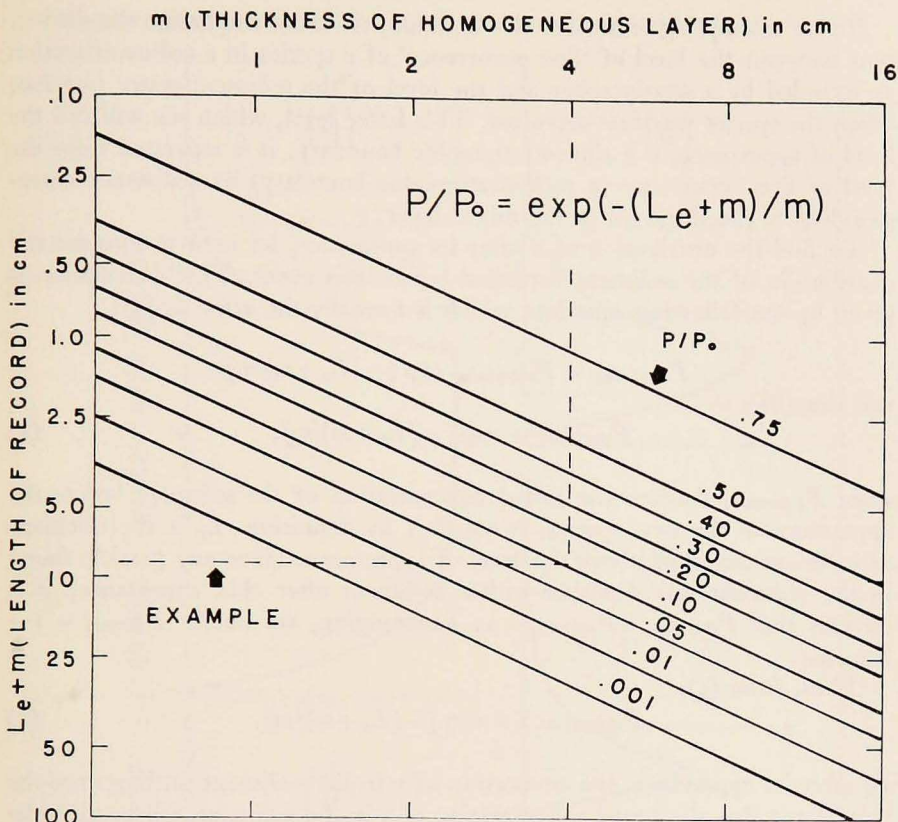


Figure 2. Proportion of the original concentration of a species ( $P/P_0$ ) that is found in the sediment at a distance of  $L_e$  above its level of disappearance. For example, if the thickness of the homogeneous layer is 4 cm and the distance through which upward mixing has taken place is 9 cm, the concentration of the assemblage undergoing mixing has fallen to one tenth of its original value.

What is the chance of finding a Tertiary fossil mixed into a Recent assemblage, based on upward mixing alone? If the thickness of the sediment that separates the Tertiary level of deposition from the Recent level is as little as 1 m, then, for a mixed layer of a few centimeters, the concentration will have decreased to about one millionth of its original value. Erosional processes and the resultant lateral transport of sediment are therefore probably the dominant factor in admixing older assemblages into younger pelagic sediments. Thus, in mapping such contaminants, Riedel (1967) probably mapped the influence of nearby outcrops of older rocks.

Another stratigraphically important situation is one in which a new species,  $z$ , suddenly appears in an area. What is the vertical distribution of  $z$  in the sediment section in the vicinity of its level of appearance?

Before attempting to answer this question, we must emphasize the distinction between the level of 'first occurrence' of a species in a sediment section as recorded by a stratigrapher and the level of the sediment-water interface when the species was first deposited. This latter level, which we will call the level of appearance, is a time-stratigraphic boundary; it is separated from the level of first occurrence (a rock-stratigraphic boundary) by a distance corresponding to the thickness of the mixed layer.

To find the distribution of  $z$  after its appearance, let us first consider the distribution of the sediment deposited before this event. This distribution is given by the following equation, which is formally the same as (3):

$$P_{(\text{before})} = P_{s(\text{before})} \exp [-(L_a + m)/m];$$

this simplifies to

$$P_{(\text{before})} = \exp [-(L_a + m)/m], \quad (4)$$

since  $P_{s(\text{before})}$  denotes the initial concentration of the sediment before the appearance of the new species; it equals 1 by definition.  $L_a$  is the thickness of sediment deposited above the level of appearance. Since any particle found in the sediment was deposited either before or after this 'appearance,' it is obvious that  $P_{(\text{before})} + P_{(\text{after})} = 1$ . Rearranging, we obtain  $P_{(\text{after})} = 1 - P_{(\text{before})}$ .

Thus, from (4),

$$P_{(\text{after})} = 1 - \exp [-(L_a + m)/m]. \quad (5)$$

If, after its appearance, the proportion of  $z$  in the sediment settling onto the interface is  $P_{oz}$ , the actual concentration of  $z$  in the sediment will be given by  $P_z = P_{oz} \times P_{(\text{after})}$ ; by substitution from (5),

$$P_z = P_{oz} (1 - \exp [-(L_a + m)/m]). \quad (6)$$

Again  $(L_a + m)$  must be positive or zero to be physically useful.

For this case, the level of appearance of  $z$  will correspond to the level at which its concentration in the historical layer reaches  $(1 - 1/e)$  or 0.63 times its maximum concentration in the overlying sediment. This value also is independent of the thickness of the mixed layer.

Fig. 3a depicts the two cases that have been considered above. The gradual decrease in the concentration of a species upon 'extinction' is shown in the upper part of the illustration, the gradual increase in concentration upon appearance in the lower part.

The third and most complex situation involving a mixing model of the type under discussion occurs when the period between the appearance and disappearance of a species,  $z$ , is similar to the time necessary for the deposition of a bed of the same thickness as the mixed layer. Such a situation may occur

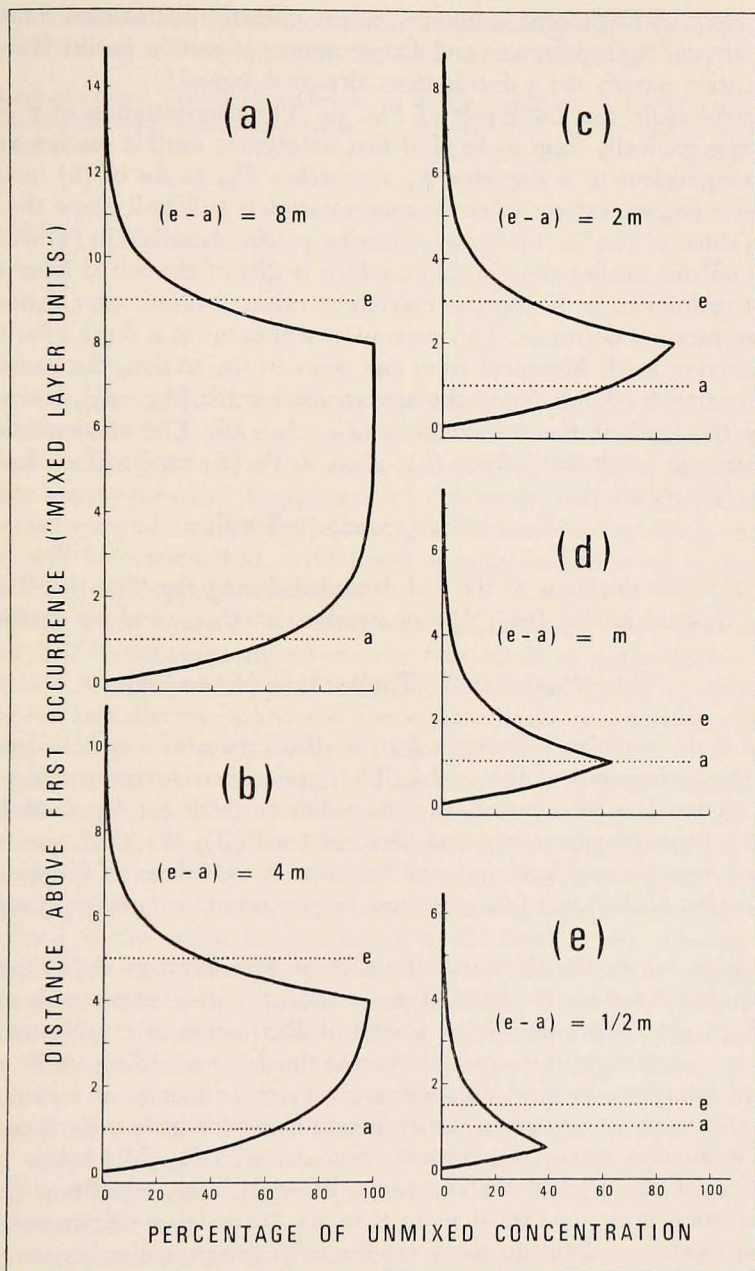


Figure 3. Distributions resulting from vertical mixing of a detrital component of a sediment.  $a$  and  $e$  mark levels of appearance and disappearance (extinction);  $m$  is the thickness of the mixed layer. Thickness and vertical distances are in multiples of  $m$ .

in the study of Pleistocene sediments, where climatic fluctuations frequently lead to alternating appearances and disappearances of certain fossils. How does this situation modify the  $z$  distributions already discussed?

Consider again the lower part of Fig. 3a. The concentration of  $z$  is seen to increase gradually from its level of first occurrence until it reaches 100%. This is equivalent to saying that  $P_z$  approaches  $P_{oz}$  as  $La$  of (6) increases. Now let  $z$  become extinct when its concentration is still well below the equilibrium value of 100%. The upward mixing process described in (3) will now operate on this smaller concentration, which is that of the mixed layer at the time of extinction. It is also the maximum value, because, after extinction, the concentration decreases. This maximum will occur at a depth of  $m$  below the extinction level. Measured from any point in the section, the position of the extinction level relative to the appearance level is  $(L_a - L_e)$ , and consequently the level of the maximum is  $(L_a - L_e - m)$ . The concentration at the maximum is obtained from (6):  $P_{\max} = P_{oz} (1 - \exp[-(L_a - L_e - m + m)/m])$ ; this reduces to

$$P_{\max} = P_{oz} [1 - \exp(-T/m)], \quad (7)$$

where  $T$  is the thickness of the bed deposited during the "life-time" of the species. Upward mixing [eq. (3)] now operates on  $P_{\max}$ , and we obtain

$$P_z = P_{oz}(1 - \exp(-T/m)) \cdot \exp(-(L_e + m)/m). \quad (8)$$

This is the complete expression for the distribution of a species deposited under the assumptions of the model. The species concentration at any level in the section is a function of only the sediment thickness deposited during the time between appearance and disappearance ( $T$ ), the thickness of the mixed or homogeneous layer ( $m$ ), and the distance to its level of disappearance or extinction ( $L_e$ ). Again  $(L_e + m)$  must be positive; if it is not, (5) must be used.

For cases where the thickness of sediment equivalent to the "life-span" (life-span layer) and the thickness of the mixed layer are of comparable magnitude, Figs. 3b-d show the ultimate vertical distribution of a sediment component as a percentage of its concentration in the detritus settling on the water-sediment interface. Vertical distances are expressed in units of  $m$ , since the results then apply to any given values in centimeters or inches. Each curve in Fig. 3 terminates where the concentration ratio  $P_z/P_{oz}$  falls below 0.1%. Regardless of the original thickness of a life-span layer, significant (0.1%) contamination does not extend more than six mixed-layer thicknesses above its upper surface—about 20 to 30 cm for most pelagic sediments.

The interaction between downward and upward mixing becomes very important for those cases where the life-span layers are thinner than four times the thickness of  $m$ . In such cases, the maximum concentration never comes



Table I. Vertical distribution of fossils as percentages of the amounts deposited during a life-span.  $m$  is the thickness of the mixed layer.

Thickness of deposit equivalent to life-span (units of $m$ )	Fossils mixed below level of appearance (%)	Fossils remaining between levels of appearance and extinction (%)	Fossils mixed above level of extinction (%)
0.5 $m$	52	19	29
1 $m$	37	40	23
2 $m$	18	66	16
4 $m$	9	82	9
8 $m$	4.5	91	4.5

close to the true concentration in the sediment settling onto the ocean floor. In extreme cases (Fig. 3e) the maximum lies outside the life-span layer.

What distribution will result from a succession of fairly closely spaced alternate appearances and disappearances? Obviously, such an alternation will yield a sequence of maxima and minima, and the curve connecting these extremes will be saw-toothed, with lower boundaries appearing to be much more abrupt than upper boundaries.

Table I shows the ultimate distribution of fossils or other detrital components below, between, and above the true levels of appearance and disappearance. A large percentage of the particles delivered during the "life-span" will be lost to sediments below and above these levels in cases where the bed thickness is close to the mixed-layer thickness.

In order to arrive at the results summarized in Fig. 3 and Table I, we have made certain simplifying assumptions about detrital sedimentation on the ocean floor. First, we postulated instantaneous mixing throughout the homogeneous layer for all kinds of particles. As a corollary, a stratigrapher should find, in considering the section, that the influence of any event is first recorded at the base of the mixed layer, and not at the level of the sediment-water interface. This means that, in a deep-sea core, events will be recorded too early by as much as several thousand years if mixing is not taken into account in interpreting the sequence. This should be true for both detrital and magnetic events. The assumption of instantaneous mixing to a single depth, however, may not be true for all particles: the thickness of the mixed layer as well as the rate of mixing may differ for various species (McIntyre et al. 1967). In such a case, changes in the concentration of different particles and events deduced from them will appear separated in the sediment even though they were contemporaneous.

The second assumption that is basic to the model is the suddenness of appearance and disappearance of a species,  $z$ . An example of a sudden event is a single volcanic eruption that deposits ash. There are many observations that demonstrate a drastic change in the abundances of organisms over large areas

during relatively short time intervals (Elton 1958). Boundaries between different kinds of marine organisms usually are related to current systems (Johnson and Brinton 1963). In the course of climatic fluctuations, such boundaries may migrate (Phleger et al. 1953); or the currents inhabited by certain faunas may accelerate (Arrhenius 1952, Berger 1968), leading to pronounced changes in the kinds of fossils supplied to the ocean floor. Under certain circumstances, sediment above and below unconformities should ideally fit the postulates of the model for sudden appearance and disappearance. However, the sharp contacts in many cores suggest that burrowers do not always thrive in the older sediment; thus a mixed layer of the type we have postulated may not develop.

Many appearances and disappearances are quite gradual, especially during times of climatic stability. In such cases, changes in the concentration of a particular component in freshly deposited sediment may be expected to approximate an exponential function [i. e.,  $P_{oz}$  of equations (6)–(8) is no longer a constant or zero but is a function of  $L_a$  or  $L_e$ ]. The general mixing equation (8) of our model will then operate upon such a function. The resulting concentration curves are still exponential but are less steep than the corresponding curves shown in Fig. 3.

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