

## NOTES

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### Mean mixed depth of sediments: The wherefore and the why

**Abstract**—The activities and consequently the bioturbation effects of deposit-feeding organisms are largely restricted to a narrow surficial zone of marine sediments with a worldwide, environmentally invariant mean of 9.8 cm with a standard deviation of 4.5 cm. Currently available theories of infaunal behavior cannot predict quantitatively this observation. A new simple model that accounts for the feedback between resource (food) abundance, its reactivity, and the intensity of bioturbation leads to a quantitative estimate of 9.7 cm. This model constitutes a fundamental advance in our understanding of bioturbation.

Bioturbation is the mixing of surficial sediments as a result of the activity of macrofauna, largely deposit feeders (Jumars et al. 1990). Bioturbation is pervasive in marine and lacustrine environments, and its impact cannot be overstated, e.g. profound modification of the structure, texture, composition, and other sedimentary properties (Rhoads 1974; Berner 1980; Aller 1982; McCall and Tevesz 1982; Rhoads and Boyer 1982). The fate of particle-bound pollutants also depends largely on bioturbation (Bosworth and Thibodeaux 1990; Jumars et al. 1990; Thomann et al. 1993). At the same time, bioturbation results from a complex and imperfectly understood infaunal foraging-survival strategy (Jumars et al. 1990); therefore, compelling reasons exist for benthic ecologists to arrive at a better comprehension of this behavior.

Time-averaged bioturbation is usually treated mathematically as a diffusive process (Berner 1980; Boudreau 1986; Guinasso and Schink 1975); as such, bioturbation is characterized numerically by both an intensity coefficient,  $D_B$ , and a depth over which it occurs,  $L$ , i.e. the so-called mixed depth (Guinasso and Schink 1975). In particular, the steady-state distribution of a solid species subject to first-order decay (e.g. a radionuclide) in a constant porosity sediment with negligible advection is governed by the conservation equation

$$D_B \frac{d^2 C}{dx^2} - \lambda C = 0, \quad (1)$$

where  $x$  is depth,  $C$  is concentration of the species in the solid phase,  $D_B$  is the mixing or biodiffusion coefficient ( $\text{length}^2 \text{time}^{-1}$ ), and  $\lambda$  is a rate (decay) constant ( $\text{time}^{-1}$ ).

Eq. 1 has proven to be remarkably good at fitting data, but is extremely limited in providing any mechanistic understanding or prediction about the bioturbation process, notwithstanding the efforts of Boudreau (1986), Wheatcroft et al. (1990), and Smith (1992). In particular, it is necessary to specify independently the (mean) mixed depth,  $L$ , over

which Eq. 1 is valid, even if  $D_B$  is modified to be a prescribed function of depth (Boudreau 1986).

A large database of  $D_B$  and  $L$  values has accumulated over the past 20 years. Analyses of these data show that  $D_B$  is a relatively strong function of sediment accumulation rate (Boudreau 1994; Tromp et al. 1995) or water column depth (Middelburg et al. 1997). This variation in  $D_B$  has been attributed to decreasing food resource with water depth. Conversely, the mixed depth, as based on radio-isotope profiles, appears to be largely independent of water depth (Fig. 1) and sedimentation rate (Boudreau 1994), with a worldwide mean of  $9.8 \pm 4.5$  cm ( $1-\sigma$  error). The mixed depth then corresponds to the zone that contains the dominant biomass of macrobenthos; however, current models of infaunal behavior (e.g. Jumars and Wheatcroft 1989) cannot quantitatively predict this result nor easily explain its observed environmental constancy. A new paradigm is clearly needed to advance our understanding of bioturbation.

The divorce between mixing intensity and mixed depth in Eq. 1 is artificial, as both characteristics result from the same activities of deposit feeders (Jumars and Wheatcroft 1989; Smith 1992). Furthermore, the separation is not necessary; specifically, if the intensity of biodiffusion is related to the depth distribution of the reactive/labile organic matter (food), then the essential invariance of  $L$  becomes a natural and predictable result. To arrive at this conclusion, one can argue that  $D_B$  is not a constant as in Eq. 1, but depends on the availability of labile organic matter,  $G$ , with depth in a sediment, i.e.

$$D_B(G) = D^*G, \quad (2)$$

where  $D^*$  is a new constant with units of  $\text{length}^2 \text{concn}^{-1} \text{time}^{-1}$ . This relationship has strong conceptual appeal, and, in the absence of any data, is favored by the application of Occam's Razor; nevertheless, other functionalities, such as a power law, would produce similar results.

Eq. 1 for the labile organic matter with first-order decay (Berner 1980; Westrich and Berner 1984) becomes

$$\frac{d}{dx} \left( D^*G \frac{dG}{dx} \right) - kG = 0, \quad (3)$$

where  $k$  is the decay constant that characterizes the lability of the organic matter (i.e.  $\lambda = k$ ). Examination of this equation indicates a feedback between mixing and the organic carbon resource. Bioturbation mixes  $G$  downward, but  $G$  decays during this movement; consequently, the intensity of mixing decreases with depth and decay becomes more efficient at removing  $G$  as compared to its downward mixing, and this feedback strengthens with depth. In fact, a depth

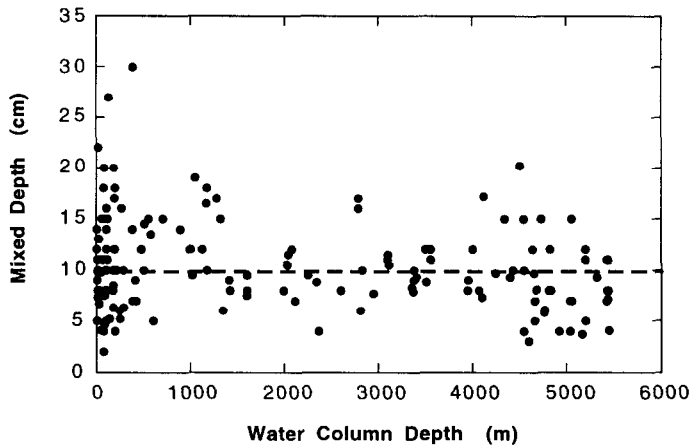


Fig. 1. Plot of the tracer-identified mixed-layer thickness,  $L$ , of marine sediments as a function of overlying water-column depth (160 data points). Although there is considerable scatter, there is no apparent dependence of  $L$  of the water depth, as confirmed by a linear regression, which explains  $<10\%$  of the variance. The dashed line is the worldwide mean value of  $9.8 \pm 4.5$  cm (1 SD). Sources for this data can be found in Boudreau (1994). Note that deep mixing at shallow depths may be influenced by physical processes.

exists below which mixing disappears because all available  $G$  has decayed. This is the mixed depth,  $L$ , but unlike Eq. 1, the value of  $L$  is not known a priori, but is instead part of the solution to the problem.

The explicit solution of Eq. 3 for both  $G$  and  $L$  is (Boudreau 1997)

$$G = G_o \left(1 - \frac{x}{L}\right)^2, \quad (4)$$

where

$$L = 4 \sqrt{\frac{3D^*G_o}{8k}} \quad (5)$$

and where  $G_o$  is the organic matter concentration at  $x$  of 0. This solution can be verified by direct substitution. Eq. 5 argues that the mixed depth,  $L$ , is not an independent parameter, but is rather a function of the initial intensity of mixing,  $D^*G_o$ , and the lability of the organic matter,  $k$ .

While this last result is intellectually satisfying, it would be of limited value if it could not confirm the environmental invariance of  $L$ . This calculation requires the input of measured values of  $D^*G_o$ , and these are not available. Fortunately, the parameter  $D_B$  in Eq. 1 can be thought of as the average value of  $D^*G$  over the mixed layer, i.e. 0 to  $L$ . If Eq. 4 and 5 are substituted into Eq. 2, and the result is averaged over the mixed layer, one obtains

$$D^*G_o = 3D_B. \quad (6)$$

The value in this result is that the variability of  $D_B$  across marine environments, ranging from the deep sea to shallow coastal areas, is reasonably well understood and quantified; specifically, from Boudreau (1994)

$$D_B = 15.7w^{0.6}, \quad (7)$$

where  $w$  is the sedimentation velocity in  $\text{cm yr}^{-1}$  and  $D_B$  is in  $\text{cm}^2 \text{yr}^{-1}$ . Over the same wide range of marine environments,  $k$  ( $\text{yr}^{-1}$ ) has also been related to  $w$  (Tromp et al. 1995),

$$k = 3.0w^{0.6}, \quad (8)$$

when rounded to one significant figure as in Eq. 7. The organic matter characterized by Eq. 8 is the labile material found in the upper part of sediments and used by most deposit feeders. Eq. 7 and 8 argue that  $D_B$  and  $k$  are strongly correlated, and the seasons for such correlations are discussed in Boudreau (1994) and Tromp et al. (1995), and they are not repeated here. At the same time, there is nothing in the original bioturbation model, Eq. 1, that would suggest the existence of this correlation. In contrast, Eq. 2 predicts that the mixing intensity should be closely correlated with the decay of the organic matter.

If now Eq. 6–8 are introduced into Eq. 5, one obtains an environmentally invariant estimate that the mean mixed depth is  $L$  of 9.7 cm, which is statistically identical to the observed mean in Fig. 1, even if large errors must be associated with both estimates. The speculation that the invariance of the mixed depth is a result of the feedback between the food dependence of bioturbation and the decay of that resource appears to be true or at least consistent with observations.

Jumars and Wheatcroft (1989) advanced the proposition that the mixed depth is limited by the increasing energy costs of deeper burrowing as the sedimentary overburden increases. As stated by these authors, this is a difficult hypothesis to verify. In contrast, resource-feedback theory of this paper is easily quantified, as demonstrated above. In fairness, however, the present theory could be considered to be, in some ways, a highly derived version of the earlier theory.

The above results were obtained from  $D_B$  and  $k$  correlations derived from data taken in the marine realm. Similar relations may hold in lacustrine environments, but these are not presently known; furthermore, physical mixing is likely to be more common in lakes, and this will compromise any attempt to find such equations. Nevertheless, no obvious reason exists that would argue that Eq. 5 would not be true for diffusive bioturbation in lacustrine sediments.

Eq. 3 will probably not supplant the use of Eq. 1 in describing isotope/tracer profiles in sediments. The reason is of a rather practical nature. Specifically, advective transport normally must also be included, so that the diagenetic equation for a tracer with the mixing functionality implied by Eq. 3 and 4 reads as

$$\frac{d}{dx} \left[ D^*G_o \left(1 - \frac{x}{L}\right)^2 \frac{dC}{dx} \right] - w \frac{dC}{dx} - \lambda C = 0. \quad (9)$$

This equation has been considered previously by this author (Boudreau 1986), and no convenient analytical solution presently exists. Numerical methods can be used fairly easily (Boudreau 1987), but many investigators will not choose this path voluntarily. Therefore, the importance of Eq. 3 may lie primarily in providing a theoretical explanation for the mean mixing depth and not in revolutionizing diagenetic modeling of organic matter and tracer profiles.

In conclusion, the resource (food)-feedback model of bioturbation, Eq. 3, not only predicts the existence of a finite-depth bioturbated zone in sediments, but substitution of currently available parameter values into this model indicates that the mean mixing depth should be a worldwide constant of 9.7 cm, independent of water depth or sedimentation rate. This result agrees with the data compilations in Fig. 1 and in Boudreau (1994). If this paper had dealt with a problem of physics or chemistry where predictive theories are the norm, then the model and calculations presented here would be valuable, but not overly remarkable; however, the natural sciences, and particularly geochemistry and ecology, are singularly lacking in successful quantitative theories. The complexities of the phenomena studied in these fields is thought to preclude simple and predictive explanations. This paper also illustrates the fallacy of such a belief.

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## Determination of dissolved vanadium in natural waters by flow injection analysis with colorimetric detection

**Abstract**—A flow injection technique for the determination of dissolved vanadium in natural waters has been developed. The technique utilizes the vanadium-catalyzed oxidation of Bindschedler's green leuco base by bromate with tiron and tartrate as reaction activators. The reaction product is quantified colorimetrically. A chelator column of immobilized 8-hy-

droxyquinoline reduces matrix effects but can be eliminated if samples with a constant matrix are being analyzed. By using the chelator column, 1 ml of sample can be analyzed in <10 min with a detection limit of 0.2 nM. The method has been used successfully for the determination of dissolved vanadium in river and estuarine waters.