COMMENT

What controls the mixed-layer depth in deep-sea sediments? The importance of particulate organic carbon flux

Smith and Rabouille (2002; hereafter SR02) have examined the relationships between the mixed-layer depth in deep-sea sediments, *L,* as based on ^{210}Pb and ^{14}C profiles, and a set of environmental variables that include particulate organic carbon (POC) flux, oxygen penetration depth, and oceanographic depth. They have established the existence of a strong nonlinear correlation between their operationally defined mixed-layer depth, *L,* and the POC flux. Such a correlation is useful for predictive purposes, potentially suggests a cause and effect relationship, and satisfies the expectations of benthic biologists and geochemists, including this commentator.

However, SR02 further attempted an evaluation of the model offered by Boudreau (1998; hereafter B98) for the relationship between the *mean* mixed-layer depth, the intensity of bioturbation, and the reactivity of the organic matter; in this latter matter the analysis in SR02 is in error, a judgment shared by two independent reviewers of this comment and the senior author of SR02. It is the aim of this note to explain that error and illustrate the correct implementation of the resource-feedback model contained in B98. In addition, this comment unreservedly acknowledges a notational shortcoming in B98 that contributed significantly to SR02's misinterpretation of B98; specifically, B98 used the symbol *L* for both the site-specific and mean mixed-layer depths, with the result that SR02 used formulas for the calculation of site-specific mixed depths, *L,* that are only valid for the (interenvironmental) mean mixed depth, *L̄.*

Before the discussion can begin, we need a means to avoid confusion about the numbering of equations, since equations appear in SR02, B98, and this comment. Thus, equations found in B98 will be designated Eq. B98 #, those referred to in SR02 will be noted as Eq. SR02 #, and equations in this comment will simply be given as Eq. #; Table 1 summarizes the equivalences between equations in the different papers.

The resource-feedback model addresses the prevalent criticism that the amount (*G*) and lability (*k*) of the infaunal food resource and the intensity (D_B) and the site-specific depth (*L*) of mixing in the widely used constant-coefficient diffusion model of bioturbation (largely a construct of geochemists) are all independent (unrelated) quantities. B98 argued that this independence was unlikely and that the intensity of mixing, as characterized by D_B, should be a function of the amount of food at a given depth, at least for some types of mixing. In the absence of any data, B98 assumed a linear function between mixing intensity and the food resource,

$$D_B(x) = D^*(G) \tag{1}$$

where *x* is depth into the sediment and *D** is a new mixing (intensity) coefficient with units of length squared per unit time and unit concentration of food, e.g., $cm^5\ s^{-1}\ gG^{-1}$ if *G* is in units of grams of food per cubic centimeter, as when food is measured by carbon concentration. Because *G(x)* is a function of its lability, Eq. 1 also implies that the mixing is a function of *k.* Furthermore, B98's solution of the resource-feedback model, i.e., Eqs. B98 4 and 5,

$$G(x) = G_0\left(1 - \frac{x}{L}\right)^2 \tag{2}$$

with

$$L = 4\left(\frac{3D^*G_0}{8k}\right)^{1/2} \tag{3}$$

where $G_0 = G(0)$, indicates that the depth of mixing, *L,* can no longer be set arbitrarily; *L* is now also a function of the amount of mixing and the decay constant for the food. In fact, *L* is the depth where $D_B = 0$ because $G = 0$ at that depth. All the parameters become interrelated and functions of what the biology is doing in the sediments, and they are no longer mere mathematical free parameters. There are obvious limitations to Eq. 1; for example, some types of mixing result from activities other than trying to find food. In addition, Eq. 1 says there is only one type of food. Thus, Eqs. 1–3 are idealizations, but at least they recognize the biology and the potentially important influence of resource availability for the first time and in a simple mathematical formula!

Next, B98 used Eq. 3 to predict the *mean* mixed depth of sediments, *L̄.* This is based on the data in Fig. 1 (i.e., fig. 2 of B98), which plots observed mixed-layer depths, *L,* versus water depth. This figure contains some 160 data points from marine sites with water depths ranging from 1 to 5600 m. What is observed in this figure is data characterized by a mean (the dotted line) of 9.8 cm with considerable variance, both in shallow and deep waters. A linear regression on this data has an r^2 of much less than 0.05, and visually the data over the entire range appear to be uncorrelated. It is possible to find more significant correlations if subsets of the data are considered, but B98 wanted to see if a universal explanation could be obtained for the observed mean. Unfortunately, B98 also introduced a flaw in his notation, designating both the specific and the mean mixed depths as *L;* this had the unintentional effect of confusing some readers, including SR02, into believing that some equations in B98 held for

Table 1. Formula equivalences between Boudreau (1998), Smith and Rabouille (2002), and this comment.

This comment	Boudreau (1998)	Smith and Rabouille (2002)
(1)	(2)	DNA*
(2)	(4)	DNA
(3)	(5)	DNA
(4)	(6)	DNA
(5)	DNA	(3)

* DNA = did not appear.

the site-specific mixed depth, *L,* when these equations only applied to the mean, $\bar{L}$.

To explain $\bar{L}$ with Eq. 3, B98 introduced some necessary assumptions, specifically Eqs. B98 6–8, that robbed the resource-feedback model of its ability to deal with local variability, i.e., specificity. The trade-off for this loss of specificity was the ability to employ parameter values from the constant-D_B model of bioturbation. In the context of this comment, the crucial assumption is that the mean of the mixing intensity in the resource-feedback model can be equated to a traditional constant D_B

$$\frac{D^*G_0}{3} \approx (D_B)_{constant} \qquad (4)$$

Eq. 4 equates parameters from models that are mathematically incompatible, i.e., the food/organic carbon distribution cannot obey both the resource-feedback and constant-D_B models; therefore, Eq. 4 can only hold true where means are taken of large data sets and errors cancel. That was the hope in B98, and one that appears to have been fulfilled, since B98 predicted the mean in Fig. 1. With Eq. 4, Eq. 3 becomes

$$\bar{L} \approx \left(\frac{9D_B}{8k}\right)^{1/2} \qquad (5)$$

which is the equation employed by SR02, i.e., Eq. SR02 3. From the above discussion, it is clear that Eq. 5 as used by SR02 is only valid for the mean $\bar{L}$, yet SR02 have mistakenly applied it to calculate site-specific *L* values, and they have consequently, but incorrectly, found the resource-feedback model wanting.

If the resource-feedback model in B98 is a reasonable representation of nature, then it should be valid in specific situations and not just in describing the mean of the data distribution. This, in fact, is the case, but definitely not in the manner implemented in SR02. In order to illustrate a correct application of the resource-feedback model, let us consider a specific example. The B98 model is for organic matter, and SR02 examine deep-sea examples; therefore, let us consider the organic matter profile at MANOP (magnanese nodule project) site H (core BC-16) reported by Emerson et al. (1985)—fig. 2. The profile is monotonic and meets the assumptions of steady-state and mixing-decay balance. To test the resource-feedback model, one does not now apply Eq. 5 to this data, but Eq. 2, which does not contain any cross-model assumptions, i.e., it does not contain Eq. 4. If Eq. 2 is fit to the data in Fig. 2, one finds that $L \approx 2.3$
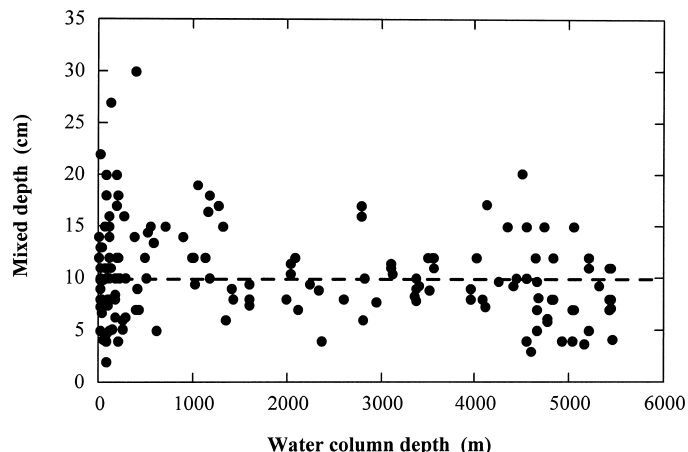

Fig. 1. Plot of the tracer-identified mixed-layer thickness, *L,* of marine sediments as a function of overlying water-column depth (160 data points). The dashed line is the worldwide mean value of 9.8 ± 4.5 cm (1 SD), designated $\bar{L}$. Sources for this data can be found in Boudreau (1994). Reproduced from Boudreau (1998).

± 0.3 cm. ^{210}Pb is available from an adjacent core (MBC 15), and it indicates a mixed-layer *L* that must be less than 4 cm. All in all, this is a consistent picture.

Now, for comparison, let us treat the same case following the logic applied by SR02. Cochran (1984) and Emerson et
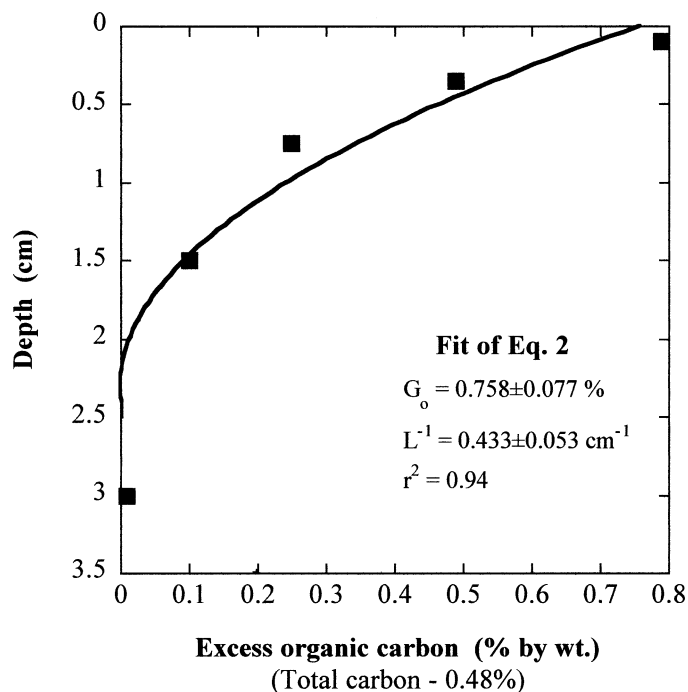

Fit of Eq. 2

$G_o = 0.758 \pm 0.077$ %

$L^{-1} = 0.433 \pm 0.053$ cm^{-1}

$r^2 = 0.94$

Fig. 2. Plot of the excess organic carbon at MANOP site H (*see* Emerson et al. 1985). Excess carbon is defined as the total organic carbon minus the assumed asymptotic value (0.48%). The curve is the best fit of Eq. 2 of the text, i.e., the resource-feedback model presented in Boudreau (1998). G_0 is the initial amount of food, assumed to be the excess (reactive) carbon, at $x = 0$, while *L* is the site-specific mixed-layer depth, which is also where the food *G* disappears ($G = 0$), as a result of Eq. 1.

al. (1985) have employed the constant biodiffusion model and a porewater O_2 model to the data at this station to obtain $D_B = 0.6–2.8 \times 10^{-9}$ cm^2 s^{-1} and $k = 0.5–1.0 \times 10^{-9}$ s^{-1}, respectively. If we now substitute those values into Eq. 5, i.e., Eq. SR02 3, then one obtains $L = 3.2–10.0$ cm, values in a range much greater than the observed value or that derived by direct application of the resource-feedback model. One cannot expect that Eq. SR02 3 will provide reasonable predictions of L; that it does in 50% of the cases examined by SR02 is, in my opinion, remarkably high for an unintended application.

Smith and Rabouille (2002) have not presented us with a test of Boudreau (1998). Moreover, the resource-feedback model, i.e., Eqs. 2 and 3 above, does not say that the site-specific mixing depth, L, cannot depend on the local POC flux (unlike $\bar{L}$); in fact, the resource-feedback model demands such a dependence. Specifically, G_0 in Eq. 2 must be a function of the POC flux, i.e., the amount of carbon at the surface of sediment depends directly on its incoming flux; in turn, both $D_B(G)$ and L, which both depend on G_0, are themselves functions of the local POC flux. Contrast this prediction of a definite POC dependence in the resource-feedback model with the constant-D_B model, which treats D_B and L as independent parameters. The constant-D_B model in no way suggests that D_B and L should depend on the POC flux, and this can only be discovered by supratheoretical data correlations, e.g., those done by SR02. Should not a realistic theory suggest its own dependencies?

Finally, should we seek the increased realism and increased complexity of the resource-feedback model over the mathematical simplicity of the constant-D_B biodiffusion model? This commentator would argue yes, and strongly so. The objective of science is to explain nature. Finding correlations provides a guide in science, but mechanistic modeling of data is the route to fundamental understanding. Even if the resource-feedback model is ultimately found to be wanting, it is certainly a far step better in this direction than the constant-D_B model to which we all cling like a security blanket.

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