Organic matter reaction kinetics in bioturbated sediments

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Abstract

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Keypoints:

- Age-dependent organic matter kinetics is coupled to a Lagranian particle tracking model
- Organic carbon concentrations, reactivities and degradation rates in the bioturbated zone are presented
- A simple first-order (one-G) model suffices for well-mixed sediments and sediments receiving pre-processed organic matter
Abstract

Most organic matter delivered to the seafloor is degraded within the bioturbated layer. Theory and empirical evidence have shown that organic matter reactivity relates to the age of a particle. However, due to particle mixing, the age-depth linear relation induced by sediment accretion is obfuscated. Here we combine a Lagrangian particle tracking model that resolves the age distribution of particles in the bioturbated zone and couple it to age-dependent organic matter degradation. Depth profiles for organic carbon concentration, reactivity and degradation rate are presented for sediments receiving low-quality and high-quality organic matter in coastal, continental slope and deep-sea environments. Our results show that a simple first-order kinetics model suffices for well-mixed sediments and systems receiving pre-processed materials. A reactive continuum approach is needed for poorly-mixed sediments receiving high-quality organic matter and for sediments below the bioturbated layer.

Plain Language Summary

Animals inhabiting marine sediments mix particles and impact the degradation kinetics and rate of organic matter degradation. Experiments and theory have shown that age-dependent kinetics is needed to accurately describe sediment organic matter degradation. However, most studies employ a simple first-order model. Here we couple an individual particle mixing model with age-dependent kinetics and show that a first-order model is adequate for well-mixed sediments and for sediments receiving pre-processed organic matter. A continuum degradation model is needed for poorly mixed sediments receiving labile organic matter.
1. Introduction
Sediments are the ultimate sink for organic matter produced in or delivered to the ocean. The surface layer of marine sediments serves as a habitat for animals that live on the organic matter deposited at the seafloor. These animals physically mix the sediments as they search for food, hide from predators, or create structures for ventilation. This bioturbation often leads to a layer that is intensively mixed by the activity of the animals (Boudreau 1998) and has major consequences for sediment texture, dispersal of solid particles and microbial activity (Richter 1952; Meysman et al., 2006). The bioturbated layer of marine sediments represents a break in time scale from week to months in the overlying water to century to million years in the underlying sediments. As such it is a key interface in System Earth because it governs whether deposited materials are recycled within the biosphere (short-term cycle) or become eventually buried and enter the geosphere (long-term cycle) (Middelburg 2018).

Particle transport within the bioturbated layer is a consequence of many discrete displacement events over a variety of length and time scales, and can often be well described by a simple diffusive model (Meysman et al., 2010). This dominance of diffusive over advective transport distinguishes the bioturbated layer from the overlying water in which particles settle by gravitation and the underlying sediments in which particles move downward relative to the sediment-water interface through sediment accretion. In these advection systems, there is a one-to-one relationship between time
and water or sediment depth: i.e., time = depth/(advection rate). The reshuffling of particles in the bioturbated layer complicates the relations between depth in sediment and time since deposition, i.e., age, of a sediment particle. Moreover, each sediment layer now contains a whole assemblage of particles with a broad distribution of particle ages (Meile & Van Cappellen 2005; Kuderer, 2022; Rooze et al., 2023).

This shift in time scale and particle transport mode has major consequences for biogenic particles arriving at the seafloor characterized by a range of reactivities such as organic matter (Middelburg 1989, Boudreau & Ruddick 1991, Arndt et al. 2013; Pika et al., 2023; Rothman, 2024). Recently settled organic particles show a large range (orders of magnitude) in their susceptibility to degradation. This initial wide range and the preferential consumption of labile organic matter by consumers results in a decrease in quantity and quality as organic matter degradation progresses (Westrich and Berner 1984, Middelburg 1989). This change in reactivity with reaction progress is difficult to trace in the bioturbated zone because of convoluted age-depth relationships.

Here we combine a particle tracking model that resolves the age distribution of particles in the bioturbated zone and then couple this to continuum organic matter degradation kinetics that links organic matter reactivity directly to age (Middelburg, 1989; Rothman, 2024). This allows the calculation of the organic matter reactivity and distribution in the bioturbated zone. We will report depth profiles of organic matter concentration ($C$), reactivity ($k$) and the reaction rate ($R$), and how they depend on the sediment accumulation rates $\omega$,
mixing intensity \( (D_b) \) and the initial age/reactivity \( (a) \) of the organic matter.

2 Methods

2.1 Particle tracking model

Particle mixing is described using a diffusion approximation because our interest is on the longer timescales (Meysman et al. 2010). On the macroscopic level the tracer concentration is governed by the 1D Advection-Diffusion-Reaction equation (Berner 1980, Boudreau 1997)

\[
\frac{\partial C(z,t)}{\partial t} = \frac{\partial}{\partial z} \left( D_b(z) \frac{\partial C(z,t)}{\partial z} \right) - \frac{\partial}{\partial z} (\omega C(z,t)) - R(z,t) \quad (Eq \ 1)
\]

\( C(z,t) \) is the organic matter concentration, normalized to the concentration at steady state, \( D_b \) is the bioturbation mixing intensity in \([\text{cm}^2/\text{kyr}]\), \( \omega \) is the sediment accumulation rate \([\text{cm}/\text{kyr}]\), \( z \) is the depth below the sediment-water interface in \([\text{cm}]\) and \( t \) is the time in \([\text{kyrs}]\).

The upper boundary (at \( z = 0 \)) is a prescribed flux, Robin boundary, i.e., a constant flux of particles enters via the sediment-water interface, but particles cannot return to the water column and are thus reflected. The domain extends to \( z \to \infty \), where the concentration gradient vanishes. The model is spun up until a steady state has been reached, i.e., the concentration is uniform and stationary. The spin up time is an order of magnitude larger than the mean mixed-layer residence time and can be readily determined by the age of the oldest particle in the mixed layer.
The shape of mixing intensity $D_b(z)$ cannot be determined experimentally (Boudreau, 1986) as it is a poorly constrained quantity due to the diffusive nature of the process, i.e., the entropy of the system is increasing and information is lost. Therefore, certain assumptions for the function $D_b(z)$ have to be made. Here $D_b(z)$ is assumed to be a smooth, continuously decreasing function. Following Hull et al. (2011), this study employs a hyperbolic tangent function to describe the depth dependency of the mixing intensity and the depth of the bioturbated zone.

$$D_b(z) = \frac{D_{b,0}}{2} \left(1 - \tanh\left(\frac{z-z_0}{z_s}\right)\right) \quad \text{(Eq 2)}$$

The tanh function is versatile and by decreasing the scaling parameter $z_s$ and increasing $D_{b,0}$ it can also be used to approximate the classical box model from Berger & Heath (1968). $D_{b,0}$ is the mixing intensity at the sediment-water interface $D_b(z = 0)$. Throughout this study, the scaling length ($z_s$) is 2 cm and the inflection point ($z_0$) is 10 cm, to approximate the global average mixed-layer depth (Boudreau, 1998). $z_0$ is the defining characteristic length scale. However, a large parameter $D_{b,0}$ allows particles to penetrate deeper into the sediment than $z_0$. As the $D_b(z)$ is smooth, the depth gradient $\frac{\partial D_b}{\partial z}$ remains bounded, that means there is a finite chance that a particle is mixed below the inflection point, i.e., the mean mixed-layer depth. This has the effect that the transition between the mixed layer and the sedimentary record is continuous and gradual.

On the microscopic ‘particle’ level, the description of the physical mixing of bioturbation translates to a sequence of discrete particle
displacements, i.e., a random walk, where the step length is a
function of the mixing intensity \( D_b \) and the direction of the movement
('up' or 'down' in one dimension) is stochastic in nature:

\[
\frac{\partial p(z,t)}{\partial t} = - \frac{\partial}{\partial z} \left( \alpha(z,t) \ p(x,t) \right) + \frac{1}{2} \frac{\partial^2}{\partial z^2} \left( \beta(z,t)^2 \ p(z,t) \right) \tag{Eq 3}
\]

which include a drift term \( \alpha = \frac{\partial D_b(z,t)}{\partial z} + \omega \) and a diffusion term
\( \beta = \sqrt{2D_b(z,t)} \). Hence, Eq 3 can be interpreted as a Fokker-Planck
equation, which describes the temporal evolution of the probability
density function \( p(x,t) \) of a single particle. By inserting the factors \( \alpha \)
and \( \beta \) into the Fokker-Planck equation and invoking the law of large
numbers, Eq 1 (without the reaction term) is retrieved again.

The corresponding stochastic differential equation is then interpreted
in the Ïto sense (Øksendal 2003; Spivakovskaya et al. 2007; Kuderer,
2022):

\[
dz = \alpha \ dt + \beta \ dW \tag{Eq 4}
\]

\[
dz = \left( \frac{\partial D_b}{\partial z} + \omega \right) dt + \sqrt{2D_b} \ dW \tag{Eq 5}
\]

where \( W \) is a so-called Wiener process, which describes Brownian
motion. \( W \) has a mean of 0 and its variance increases linearly with
time. The diffusion gradient \( \frac{\partial D_b}{\partial z} \) is a correction term, which accounts
for the depth dependency of the diffusivity term. The correction term
prevents the unphysical accumulation of particles in areas of low
diffusivity (Visser 1997, Ross & Sharples 2004). The stochastic
differential equation was solved numerically, see Kuderer (2022) for
details and code.
2.2 Organic matter degradation model

Organic matter arriving at the ocean floor is a complex mixture of thousands of organic compounds that may originate from various organisms, come from different environments and have experienced a different degradation history. Organic matter degradation is traditionally modelled using a one-G model (Berner 1964) involving first-order reaction kinetics for bulk organic matter. However, actual rate measurements (Jørgensen 1978), experimental studies (Westrich & Berner 1984), and theory (Rothman, 2024) showed that the reactivity of organic matter decreases upon degradation. Multiple studies have shown that the evolution of organic matter degradability can be expressed as (Middelburg, 1989; Boudreau & Ruddick 1991, Arndt et al. 2013):

\[ k(t) = v \cdot (a + t)^{-1} \] (Eq 6)

where \( v \) is a shape parameter, \( a \) is the apparent initial age of the particle and \( t \) is time. Based on empirical data of sediments below the bioturbation zone and experimental degradation studies Middelburg (1989) reported a \( v \) value of 0.16 and an exponent near \(-1\), which are close to the theoretical values (Rothman, 2024) and these will be used here.

2.3 Coupled model

In advection dominated systems, depth and time are directly linked and it is straightforward to apply age-dependent kinetics. The relation between depth and time is convoluted in the bioturbated zone, where mixing dominates over advection and individual particles have to be considered. Lagrangian particle tracking allows to follow the tracer particles within the model domain and simultaneously keep
track of the particle ages. The reactive continuum description (Eq. 6) can then be applied to each of the simulated particles. Particle mixing combines particles with age differences and thus also differences in reactivity into the same sediment layer, which results in a potentially broad distribution of reactivities in a single sediment layer.

In contrast to Meile & Van Cappellen (2005), who used a stochastic implementation of the reaction term $R(z, t)$, we employ a deterministic formulation of the reaction using the time dependent formulation $k(t)$. The tracer particles all have one unit of weight when they enter the model domain via the sediment-water interface and their assigned organic matter content decreases each time step according to the age dependent reaction rate. The concentration $C(t)$ can be solved numerically:

$$\delta C = C(t + \delta t) - C(t) = -R \cdot \delta t = -k(t) C(t) \delta t \quad \text{(Eq. 7)}$$

$$=> C(t + \delta t) = C(t) \cdot [1 - k(t) \delta t] \quad \text{(Eq. 8)}$$

Initialization of the coupled model involved model spin up till it reaches steady state and tracer particle concentrations are uniform. Therefore, the mean of the organic matter concentration distribution is proportional to the total concentration within a sediment layer. The same is true for the total rate $R$.

2.4 Model parameter selection
To illustrate the impact of age-dependent kinetics on organic carbon ($C$), its degradation rate ($R$) and its reactivity ($k$) in the mixed layer, we explore a coastal, continental slope and a deep-sea environment, characterized by sediment accumulation rates ($\omega$) of 100, 10 and 1 cm/kyr, respectively. The mixing intensity at the sediment water
interface $D_{b,0}$ will be varied over 5 orders of magnitude to cover low 
($D_{b,0} = 1 \text{ cm}^2/\text{kyr}$) to high mixing ($D_{b,0} = 10,000 \text{ cm}^2/\text{kyr} = 
10 \text{ cm}^2/\text{yr}$). This range is consistent with observations in modern 
ocean margin sediments (Middelburg et al. 1997; Solan 2018). To 
explore the importance of the nature of the incoming organic matter, 
simulations with two initial reactivity constants $a$ will be presented: 
$a = 10 \text{ yrs}$ and $a = 10,000 \text{ yrs}$ for input of labile and refractory 
organic matter, respectively. This range of initial reactivity values $a$
covers most sediments (Pika et al., 2023) and this combination of 
mixing intensities and organic matter reactivities is consistent with 
the adopted mixed-layer depth ($z_0 \approx 4.6 \sqrt{D_{b,0}}$; Middelburg, 2019).

3 Results
The organic carbon concentration declines with increasing 
depth in the sediment, both within and below the mixed layer (Fig. 1).
Organic carbon with higher initial reactivity (Fig. 1a-c) degrades 
shallower and more extensively than more refractory organic matter 
(Fig. 1d-f). Particle mixing lowers organic carbon concentration in the 
near surface and increases labile but not refractory organic carbon 
concentrations at depth. Increasing mixing intensity turns quasi-
exponential concentration versus depth profiles into vertically uniform 
distributions. Organic carbon concentrations at depth are higher in 
coastal sediments with high accumulation rates than in deep-sea 
settings.

The average degradation rate constant decreases with depth 
for all scenarios but in different ways (Fig. 2). Evidently, the initial 
reactivity of the delivered material plays a major role in degradability
of sedimentary organic matter (compare Fig. 2a-c with 2d-f). For sediments receiving low-quality \((a = 10,000 \text{ yrs})\) organic matter, depth gradients in reactivity are very limited (i.e., less than a factor 2), particularly in strongly bioturbated and/or rapidly accumulating sediments. In contrast, sediments receiving high quality organic matter \((a = 10 \text{ yrs})\) show larger vertical gradients in reactivity, particularly in the upper few \(\text{cm}\)s and under low mixing conditions. For very low mixing conditions, average reactivities vary up to factors of 18, 30 and 11 for coastal, slope and deep-sea sediment respectively, while reactivities are depth uniform for high mixing activities. Particle mixing decreases the average reactivity of organic matter in the surface layer, because older particles with lower reactivity are transported upwards. Conversely, bioturbation increases the average reactivity of organic matter at depth because young particles are mixed downwards. Intense mixing results in quasi-uniform degradation rate constants in the mixed layer. Another important factor is the sediment accumulation rate because it governs the residence time \((\tau)\) of particles in the mixed layer and thus average degradation rate constant (Eq 6). Coastal sediments receiving high quality organic matter \((a = 10 \text{ yrs})\) have an average degradation rate constant about 100 times higher than those of deep-sea sediments receiving the same material because of a factor 100 difference in particle residence times.

The degradation rate \((R)\), i.e., the quantity of organic matter degraded per unit of time, is the product of the normalized concentration \((C, \text{Fig. 1})\) and the reactivity \((k, \text{Fig. 2})\). Consequently, it generally decreases with depth as well (Fig. 3). In the case of
highly reactive particles (low $a$, 3a-c), most organic matter is degraded in the topmost layer of the sediment and an increase in mixing (causing transport of reactive particles downwards) attenuates the depth gradient in mineralization rates. High mixing intensity eventually results in quasi-uniform distribution of organic matter degradation rates in the mixed layer, in particular when initial reactivity is low.

Figure 4 shows the distribution of organic matter reactivity constants at a depth layer of $10 - 11 \text{ cm}$ for a continental slope and deep-sea sediment subject to very low ($D_b = 1 \text{ cm}^2/\text{kyr}$) to moderate ($D_b = 1000 \text{ cm}^2/\text{kyr} = 1 \text{ cm}^2/\text{yr}$) mixing and receiving labile ($a = 10 \text{ yrs}$) or refractory ($a = 10,000 \text{ yrs}$). For the low mixing scenario, the distribution of reactivity constants has a small range, is approximately symmetric and the mean and median reactivity coincide. Moderate mixing causes a wide spread in the reactivity constant within a single layer, and the mean and median are different because the distribution is asymmetric. This range and asymmetry is larger for labile organic matter ($a = 10 \text{ yrs}$) than for refractory organic matter ($a = 10000 \text{ yrs}$) because the latter distribution is limited to the right by $k(t = 0) = 0.16 \cdot 10^{-4}/\text{year}$, which is determined by the choice of the initial age $a$.

4 Discussion
4.1 A non-dimensional analysis
The distribution of organic matter and its reactivity depends on the relative importance of sediment accumulation, particle mixing and the reactivity of the organic matter delivered. It is instructive to discuss
our findings in the context of dimensionless numbers and particle residence times (Boudreau, 1997). The residence times of particles in the mixed layer \( \left( \tau = \frac{z_0}{\omega} \right) \) are 100, 1000 and 10,000 years for the coastal, continental slope and deep-sea settings, respectively, and this provides an upper limit to the reactivity of organic carbon leaving the mixed layer. The reactivity of labile organic matter at the seafloor decreases when particle reside in the mixed layer and this effect is strongest in slowly accumulating sediments and labile organic matter (Fig. 2a-c). As a consequence, there is relationship between the organic matter reactivity below the bioturbated zone and sediment accumulation rate, as reported by Müller & Mangini (1980), Reimers & Suess (1983), Aller & Mackin (1984) and Boudreau (1997). Sediment accumulation rate or residence time of particles in the mixed layer have little impact on refractory organic matter \( (a = 10,000 \text{ yrs}; \text{Fig. 2d-f}) \), consistent with observations by Emerson & Hedges (1988).

The Péclet number \( \text{Pe} = \frac{\omega z_0}{D_{b.0}} \) expresses the relative importance of particle transport via sediment accumulation and diffusive mixing. In simulations with \( \text{Pe} \ll 1 \), mixing dominates over sediment accretion. Sediments with low Péclet numbers are characterized by a quasi-uniform distribution of organic matter \( (\text{Pe} < 0.01; \text{Fig. 3.1}) \), organic matter reactivity \( (\text{Pe} < 0.1; \text{Fig. 3.2}) \) and organic matter degradation \( (\text{Pe} < 0.1; \text{Fig. 3.3}) \). Increasing mixing further (lower Pe) will not have a major impact on the depth profiles. Péclet number in marine sediments are typically \( < 0.1 \) (Tromp et al. 1995, Middelburg et al. 1997), indicating that the reactivity constant and degradation rates of organic matter are rather constant in the
mixed layer of most marine sediments. Hence, a one-G approach would be appropriate.

The Péclet number and particle residence time do not consider the reactivity of particles and the Second Damköhler number may be useful (Boudreau, 1986). The Second Damköhler number compares the rate of decay term over the advective time scale:

\[ \text{Da}(\text{II}) = k \tau \]

The advective time scale is the residence time of particle in the mixed layer and gives the mean particle age at the bottom of the mixed layer \( \tau = \frac{z_0}{\omega} \). If the initial age \( a \) is large compared to particle age at the bottom of the mixed layer, \( k(t) \) can be approximated by

\[ k \approx (a + \tau)^{-1} \approx a^{-1} \]

i.e., the reactivity is rather constant (Fig. 2d-f). However, if the initial age \( a \) is small compared to the particle age, \( k(t) \) can be approximated by

\[ k \approx (a + \tau)^{-1} \approx \tau^{-1} \]

In this case, the Second Damköhler number is independent of the sedimentation rate and around 1, implying that reactivity and advection are similarly important to organic carbon at the bottom of the bioturbated layer.

4.2 Implications

Our coupled particle tracking-reactive continuum model provides some useful insights. While it is well established that organic carbon concentrations, reactivity and degradation rates all decrease with depth below the bioturbated the zone (Middelburg, 1989; Beulig et al., 2018), our results show that it also applies for sediments with low mixing rates (e.g., those underlying low-oxygen bottom waters). However, the range in organic matter reactivities in
sediments receiving pre-processed organic matter (high $a$ values) is very limited (Fig. 2d-f) and these minor reactivity differences can be ignored given other uncertainties. Consequently, a simple exponential (or one G-model) model with constant $k$ then provides an adequate representation, particularly for rapidly accumulating sediments.

For well-mixed sediments ($Pe < 0.1$), organic matter reactivity is rather constant (blue lines in Fig 2a,d; blue and red lines in Fig 2b,e and blue, red and yellow lines in Fig. 2c,f), consistent with the common use of first-order kinetics in modelling organic matter degradation in marine sediments (Berner, 1980; Arndt et al. 2013). Concentrations of organic carbon can also become quasi-uniform in the mixed layer at high mixing rates or low initial reactivity (Fig. 1).

Accordingly, Berner’s one-G model based on a single, site-specific, depth-independent reactivity constant can be applied to sediments receiving extensively pre-processed organic matter (with high $a$ values) as well as sediments that are well-mixed (irrespective of initial reactivities). Our results also show that organic matter reactivity constants show large differences among sedimentary settings (i.e., the type of organic matter delivered and residence time of particles in the mixed layer), consistent with field observations (Emerson & Hedges, 1988; Middelburg, 1989; Arndt et al., 2013; Pika et al., 2023; Xu et al., 2023).

For sediments receiving fresh organic matter (low $a$ values) and that are poorly mixed ($Pe > 0.1$), average organic matter degradation rate constants do vary with depth (Fig. 2), but less than reported by Stolpovsky et al. (2015). In their study of organic matter
kinetics in surface marine sediments, they imposed a power-law depth dependence of degradation rates, constrained these with porewater oxygen and nitrate data and then derived first-order rate constants as a function of depth. Their reactivity constants decrease over two orders magnitude with depth, whereas our results show less depth variation, i.e. about a factor 30 for low mixing activities and labile organic matter to no depth dependence for well mixed sediments (Fig. 2). Part of this difference may be due to differences in the bioturbation depth dependence imposed in our study and that of Stolpovsky et al. (2015), another part to a difference in the power exponent (−1 in our study and −2 to −3.7 in Stolpovsky et al. (2015)). Our individual particle based approach revealed an asymmetric distribution of reactivity in mixed sediments (Fig. 4) and this may have contributed to the difference as well.

Overall, it appears that organic matter reactivity in surface sediments is primarily governed by reactivity of the incoming material (as reflected in the apparent initial age) and by the residence of organic matter in the mixed layer (τ), which is governed by the sediment accumulation rate. Low particle mixing results in declining reactivities with depth, while high particle mixing rates redistribute old, hence refractory organic matter and young, reactive particle with the consequences that reactivity becomes rather uniform with depth and the spectrum of reactivities in any single layer increases. This spreading of organic matter reactivity classes may induce organic matter priming and consequently stimulate overall organic matter degradation (Zhu et al., 2024).
References


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Figure 1: Mean normalized concentration versus depth profiles.

Left column (a-c): Young, reactive particle with an (apparent) initial age \( a = 10 \) yrs. Right column (d-f): Old, refractory particles with an initial age \( a = 10,000 \) yrs. Upper row: Coastal station with a high sedimentation rate \( \omega = 100 \) cm/kyr. Middle row: Continental slope station with a sediment accumulation rate of \( \omega = 10 \) cm/kyr. Lower row: Deep sea station with a sediment accumulation rate of \( \omega = 1 \) cm/kyr.

The mixing intensities range from \( D_{b,0} = 1 \) cm\(^2\)/kyr to 10,000 cm\(^2\)/kyr. Blue: \( D_{b,0} = 10,000 \) cm\(^2\)/kyr, Red: \( D_{b,0} = 1,000 \) cm\(^2\)/kyr, Yellow: \( D_{b,0} = 100 \) cm\(^2\)/kyr, Purple: \( D_{b,0} = 10 \) cm\(^2\)/kyr, Green: \( D_{b,0} = 1 \) cm\(^2\)/kyr.
Figure 2: Depth distribution of the mean degradability $k$. Similar to Figure 1, panel a-c are for reactive particles ($a = 10 \text{ yrs}$) and panels d-f for aged particles ($a = 10,000 \text{ yrs}$) and upper, middle and lower rows are for coastal, continental slope and deep-sea accumulation rates (100, 10, 1 cm/kyr, respectively). Color schemes similar to Figure 1: mixing intensities increases from blue via red, yellow, purple to green.
Figure 3: Depth distribution of mean degradation rates. Similar to Figure 1, panel a-c are for reactive particles (a = 10 yrs) and panels d-f for aged particles (a = 10,000 yrs) and upper, middle and lower rows are for coastal, continental slope and deep-sea accumulation rates (100, 10, 1 cm/kyr, respectively). Color schemes similar to Figure 1: mixing intensities increases from blue via red, yellow, purple to green.
Fig: 4 Distribution of reactivity $k$ at depth layer $z = 10 - 11$ cm.

Blue lines for low mixing ($D_b = 1 \text{ cm}^2/\text{kyr}$) and purple lines for intermediate mixing ($D_b = 1,000 \text{ cm}^2/\text{kyr}$). Upper panels: low sediment accumulation rate: $\omega = 1 \text{ cm/kyr}$. Lower panels: high sediment accumulation rate: $\omega = 100 \text{ cm/kyr}$. Left panels: Sediment receiving reactive particles with initial age $a = 10$ yrs. Right panels: sediment receiving more refractory carbon with initial age $a = 10,000$ yrs. The mean and the median of the distributions are indicated by the plus and cross symbol. If median and cross coincide, plus and cross coalescence into an asterisk.
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Open science. The code is available on https://doi.org/10.33540/1544