Sediment accumulation, rather than mixing, controls the temporal resolution of the sedimentological record

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Abstract

Sedimentary particles such as organismal remains carry information on the Earth's past. As a result of mixing in surface sediments, particles of different ages can be found at the same depth (time-averaging), and particles of identical ages can be found at different stratigraphic positions (stratigraphic disorder). This results in simultaneous stratigraphic and temporal blurring of the recorded signal, thus reducing the resolution of the sedimentological record.

Here, we draw on a set of observations from modern marine sediments in which the three principal properties of the surface mixed layer (sediment accumulation, mixing depth, and bioturbation intensity) have been measured together, allowing us to disentangle their relative contributions to time-averaging and stratigraphic disorder. We find that sediment accumulation has the strongest influence on time-averaging in modern marine environments. Time-averaging increases with water depth, and a sediment layer in deep sea environments may represent more than 10 kyr of time. In contrast, stratigraphic disorder is controlled by mixing depth. Surprisingly, particle mixing due to bioturbation has only a weak effect on stratigraphic disorder and time-averaging, as the majority of modern sediments are already thoroughly mixed.

Our results highlight that age-reversals are a common feature of the sedimentological record when sampling below decimeter scale and that the physical processes of sediment mixing and accumulation rather than analytical errors provide an upper limit on the temporal resolution achievable in Holocene marine records. Time-averaging and stratigraphic disorder are the result of the same mixing process in the surface mixed layer, and high temporal and stratigraphic resolution can only be achieved when sediment accumulation is high. Secular increases in mixing depth could have led to a 10-fold decrease in the temporal resolution of the sedimentological record across the Phanerozoic.

Introduction

Sedimentary particles, among them fossils, are the building blocks of the geological record. In reading it, we generally assume superposition: younger sediment is found on top of older sediment (Steno 1916). Before entering historical records, particles are mixed as they transition the sediment surface mixed layer (SML), leading to particles of different ages being buried together. This reduces the temporal resolution, which propagates into all downstream analyses of the original signal, including paleoenvironmental or evolutionary reconstructions, chemostratigraphy, age-depth models, and diversity and disparity analyses (Dolman et al. 2021; Hülse et al. 2022; Tomašových et al. 2023).

Particle mixing results in two distinct, but related effects that necessitate each other: time-averaging, where particles of different ages are found in the same sediment layer (Kowalewski 1996; Tomašových et al. 2022), and stratigraphic disorder, where particles of the same age are found at different stratigraphic positions (Berger and Heath 1968; Cutler and Flessa 1990; Flessa et al. 1993). Dating individual shells in Holocene marine environments (e.g., via radiocarbon or amino acid racemization dating) has shown that both effects are common, with values of time-averaging of thousands of years, and shells of similar ages multiple decimeters apart (Flessa and Kowalewski 1994; Kosnik et al. 2007, 2009; Dominguez et al. 2016; Tomašových et al. 2018, 2022; Berensmeier et al. 2023). For example, in the Po river prodelta (Northern Adriatic Sea), Tomašových et al. (2018) observed shells younger than 25 years both at the sediment surface and buried below 1 m, with values of time-averaging of 50 years (Figure 1 A).

Time-averaging and stratigraphic disorder have a profound influence on our interpretation of the geological record: Time-averaging acts as a low-pass filter on paleo-time series (Kidwell 2013). Stratigraphic disorder implies that the law of superposition, a crucial model

63 assumption for establishing the order of geological events and for age-depth modelling
64 (Haslett and Parnell 2008; Hohmann et al. 2025), breaks down below a certain physical scale.

65 Estimating time-averaging and stratigraphic disorder by means of dating individual particles
66 in a sedimentary layer is labor-intensive and limited to the resolution of radiocarbon dating.
67 As a result, researchers lack methods to easily assess the resolution of their records,
68 particularly in the pre-Quarternary. Here we refer to resolution as the depositional resolution
69 of an unbedded sedimentological record, i.e. not the stratigraphic resolution that is the
70 property of a bedded (discrete) record (sensu Kowalewski and Bambach (2003)). Particle
71 mixing in the SML is controlled by sedimentological and ecological parameters such as
72 mixing depth, bioturbation intensity, and sediment accumulation rate. Values of SML
73 parameters are characteristic for specific depositional environments, and their change
74 throughout the Phanerozoic has been documented (Tarhan 2018; Zhang et al. 2024; Tarhan et
75 al. 2025). Here we use a diffusion-advection model to predict time-averaging and
76 stratigraphic disorder from SML parameters. This opens the opportunity to estimate the
77 resolution of the sedimentological record from extrinsic, empirically traceable factors.

78 We establish the connection between time-averaging, stratigraphic disorder, and SML
79 parameters (mixing depth, bioturbation intensity, and sediment accumulation). Surprisingly,
80 we find that sediment accumulation, not bioturbation intensity, is the dominant control of the
81 temporal resolution in modern marine sediments. Sediment accumulation is a predictor of
82 temporal resolution in environments for periods where direct assessments of time-averaging
83 are impossible. Stratigraphic disorder and time-averaging are equivalent expressions of
84 mixing in the SML, and records having both high temporal resolution (low time-averaging)
85 and high stratigraphic resolution (low stratigraphic disorder) require high accumulation
86 settings. In deep time, our model predicts a 10-fold decrease in temporal resolution over the
87 Phanerozoic due to secular increases in mixing depth with progressive infaunalization.

Methods

We model the joint distribution of particle ages and depths via the diffusion-advection equation

$$\frac{\partial}{\partial a}u(a,d)=\frac{\partial}{\partial d}\left(D_b(d)\frac{\partial}{\partial d}u(a,d)\text{-}Su(a,d)\right) (Eq.\,1)$$

where a is particle age, d is depth below the sediment-water interface, $u(a,d)$ is the density of particles of age a at depth d, S is sediment accumulation rate, and D_b is the depth-dependent biodiffusion coefficient (Figure 1 B). This model is based on the classic Guinasso and Schink (1975) model, see Hohmann (2024) for the model derivation and Terry and Novak (2015) for a similar model in cave environments. It assumes particles are abundant and sediment mixing due to bioturbation can be approximated as biodiffusion (Meysman et al. 2010; Kuderer 2022). For the boundary conditions, we assume particles of age 0 are introduced at the sediment surface, mixed and advected in the surface mixed layer (SML), do not exit at the sediment-water interface, and are eventually exported into historical sediment layers below the SML (maturation depth sensu Sadler (1993)) (see Supplementary Information).

To inform the model using compilations of SML parameters from modern marine environments, we assume biodiffusion D_b is constant within a SML of thickness L and drops to 0 below (Hohmann 2022). To reduce the parameter space and facilitate numeric stability, we re-scale the system using mixing depth L as characteristic length unit and L/S (transit time of particles through the SML due to sediment accumulation) as characteristic time unit. The re-scaled system is fully characterized by the dimensionless mixing intensity (inverse Péclet number)

110 $$G=\frac{D_b}{L \cdot S}\ (Eq.2)$$

111 (Guinasso and Schink 1975), which represents the importance of mixing relative to
112 (advective) burial in particle transport. We measure time-averaging $tavg$ and stratigraphic
113 disorder $disord$ using the interquartile range of particle ages and depths, respectively
114 (Tomašových et al. 2018; Berensmeier et al. 2023). Let F_{mix}(G) be time-averaging in the
115 rescaled system as a function of mixing intensity. Reversing the scaling, we get

116 $$tavg=F_{mix}(G) \cdot \frac{L}{S} \quad and \quad disord=F_{mix}(G) \cdot L \quad (Eq.\ 3)$$

117 for time-averaging and stratigraphic disorder, yielding the relation

118 $$tavg \cdot S=disord\ (Eq.4)$$

119 between the two (see Supplementary Information, Supplementary Figure 1). Values of F_{mix}
120 were calculated using Matlab (MATLAB R2025b) for values of G between 10^{-3} and 10^{5}
121 (Figure 2), all other analyses were performed in the R language version 4.5.3 (R Core Team
122 2026), see Supplementary Information and Code for details.

123 We calculate time-averaging and stratigraphic disorder for locations in the SMLBase, a global
124 compilation of 287 simultaneous co-located measurements of D_b, S, and L in modern marine
125 sediments based on tracer profiles (Hohmann (2022), Supplementary Figure 2). We consider
126 an environment to be saturated with respect to mixing when F_{mix} is within 90 % of the
127 maximum F_{mix} achievable, i.e., when $F_{mix} > 0.989$ (Figure 2, Supplementary Figure 2 D).
128 We use two generalized linear models (GLMs) with identity linkage function to examine the
129 relationship between D_b, S, and L (independent variables) and time-averaging and
130 stratigraphic disorder (dependent variables). For the GLMs, we determine partial R^2, where a
131 large value indicates a strong relationship, and the regression and standardized regression

coefficients, where a high value reflects that a change in the independent variable results in a large change in the dependent variable (Figure 3, Supplementary Tables 1 and 2, Supplementary Figure 3). In addition, we examine how time-averaging and stratigraphic disorder change along a water depth gradient (Figure 4).

Results

We find that sediment accumulation rate is the dominant control on the temporal resolution of the sedimentological record (regression coefficient -1.057, standardized reg. coefficient -0.991, partial R^2 0.995, Figure 3 A-C, Supplementary Table 1, Supplementary Figure 3). Halving the sediment accumulation rate roughly doubles the temporal resolution of the sedimentological record, as measured by time-averaging (interquartile range of particle ages found within the same sediment layer (Tomašových et al. 2018)). Time-averaging reaches values as high as 10 kyr in deep-sea settings (Figure 4 A, Supplementary Table 3).

Below decimeter resolution, the law of superposition begins to break down due to stratigraphic disorder, with mixing depth being the major determinant of disorder (regression coefficient 0.931, standardized reg. coefficient 0.949, partial R^2 0.981, Figure 3 D-F, Supplementary Table 2, Supplementary Figure 3). When sampling below this resolution, recovery of true age reversals (finding older particles stratigraphically higher than younger ones) will be common, and reducing sampling resolution further will not improve the temporal resolution of the recovered record.

Counterintuitively, bioturbation intensity as expressed by the biodiffusion coefficient has only a weak effect on time-averaging and stratigraphic disorder (time-averaging: regression coefficient 0.063, standardized reg. coefficient 0.078, partial R^2 0.569, stratigraphic disorder:

154 regression coefficient 0.063, standardized reg. coefficient 0.227, partial R^2 0.569, Figure 3 B,
155 E, Supplementary Tables 1 and 2, Supplementary Figure 3).

156 We found that environments with mixing intensity G larger than 1.56 (Péclet number below
157 0.64) are saturated with respect to mixing (Figure 2). In these environments, time-averaging
158 and stratigraphic disorder are dominated by the physical dimensions of the surface mixed
159 layer (mixing depth and transit time due to sediment accumulation) rather than variations in
160 mixing (Equation 3). Of the 287 modern sediments included in the analysis, 79 % are
161 saturated with respect to mixing (Figure 2, Supplementary Figure 2 D). This explains the
162 results of our regression analysis (see above), where time-averaging and stratigraphic
163 disorder are controlled by sediment accumulation rate or mixing depth rather than the
164 biodiffusion coefficient.

165 Time-averaging and stratigraphic disorder are related through the sediment accumulation rate
166 (Equation 4), demonstrating that both parameters are equivalent manifestations of particle
167 mixing in the surface sediments. Records having both high temporal and stratigraphic
168 resolution (low stratigraphic disorder and time-averaging) can only be achieved in high
169 sediment-accumulation settings.

170 Discussion

171 As first-order approximation, we found that time-averaging in modern marine sediments is
172 approximately equal to the particle residence time in the surface mixed layer (SML)

173 $$tavg \approx \frac{L}{S} \ (Eq. 5)$$

174 (compare Delhez and Deleersnijder (2012)) and stratigraphic disorder is approximately equal
175 to the mixing depth:

176 $$disord \approx L\ (Eq. 6).$$

177 These approximations hold because most modern environments (79 %) are thoroughly mixed,
178 and minor variations in mixing intensity will, accordingly, not impact time-averaging and
179 stratigraphic disorder (Figure 2, Equation 3). Commonly, systems with mixing intensity G
180 larger than 10 (Péclet number Pe below 0.1) are considered dominated by mixing
181 (Wheatcroft 1990; Kuderer and Middelburg 2024). Our study identifies environments with a
182 mixing intensity G larger than 1.56 (or, equivalent, $Pe < 0.64$) as thoroughly mixed based
183 on a comparison with the maximum achievable time-averaging and disorder. This shows that
184 even moderate biodiffusion values are sufficient to result in a mixing-dominated SML, in
185 which increases in mixing do not result in more time-averaging or stratigraphic disorder.

186 On a global average, mixing depth is approximately 10 cm in modern sediments (Boudreau
187 1994, 1998) and correlates positively with measures of food availability, such as seafloor
188 organic carbon availability and macrofauna biomass, but not water depth or sediment
189 accumulation rate (Teal et al. 2010; Zhang et al. 2024). Stratigraphic disorder of
190 approximately 10 cm should thus be the null expectation for modern sediments. Nonetheless,
191 significant local deviations from this prediction are possible. Hypoxic conditions can reduce
192 both bioturbation depth and intensity (Smith et al. 2000; Sturdivant et al. 2012). While
193 reduced mixing depth will improve the resolution of sedimentary records of sediment
194 underlying low-oxygen bottom waters, the total effect depends on how the decreases of
195 bioturbation and mixing depth balance out in G. Similar considerations hold for
196 extrapolations into deep time or into the future. Humans modify the seafloor in a plethora of
197 ways, which can change mixing depth, sediment accumulation rate, and biodiffusion - and, as
198 a result, time-averaging and stratigraphic disorder - in all directions (Tomašových et al. 2018;
199 Berensmeier et al. 2023; Nawrot et al. 2024).
200 While infaunalization emerged early in the Paleozoic, the development of a well-mixed

sediment surface layer lagged, and mixing depths only gradually increased (Seilacher et al. 2005; Tarhan et al. 2015; Tarhan 2018). This suggests that time-averaging and stratigraphic disorder increased throughout the Paleozoic in parallel with the rise of bioturbators (Kidwell 1997; Tomašových et al. 2024). Inference of paleo-mixing depths is challenging and associated with large uncertainties (Buatois et al. 2025). Quantitatively, our Equation 3 predicts that the 10-fold increase in mixing depth across the Phanerozoic reported by Tarhan et al. (2015) would result in an increase of time-averaging and stratigraphic disorder by an order of magnitude (given the SML remained well-mixed).

Sediment accumulation rate negatively correlates with water depth, and has an indirect influence on biodiffusion intensity by delivering organic matter (Middelburg et al. 1997; Zhang et al. 2024). Combined, this suggests that both water depth and sediment accumulation rates can be used as an (external) taphonomic clock to estimate the temporal resolution of depositional environments for which no direct estimates of time-averaging are available (Kidwell 1997; Immenhauser 2009; Tomašových et al. 2017). In the rock record, estimates of accumulation rate decrease with the period of observation (Sadler 1981) and in sections without good age control it will be often impossible to calculate this rate at the timescale comparable to the transit time of a particle through the SML. However, when short-term accumulation rates are available, they correlate negatively with time-averaging, providing an empirical support to our model results (Meldahl et al. 1997).

It is well-established that sediment mixing acts as a low-pass filter on pre-diagenetic geological signals, smoothing out signals below a certain frequency via time-averaging (Olszewski 1999; Kanzaki et al. 2021; Hülse et al. 2022; Kuderer 2022). This can both remove a signal of interest (e.g., precession, Hülse et al. (2022)) or help focus on long-term baselines by removing noise below the timescale of interest (Kowalewski et al. 1998; Kidwell 2013). Depositional environments are characterized by a range of typical sediment

accumulation rates, and, as a result, can be assigned characteristic values of time-averaging and an associated cutoff frequency of a low-pass filter. This connection can serve as a heuristic to determine depositional environments suitable to record a signal of interest. For example, intermediate accumulation rate settings are more suitable for establishing pre-anthropogenic baselines for conservation paleobiology, while settings with rapid accumulation are more suitable to study deep-time analogues for climate change in high resolution. However, high sediment accumulation rate environments are usually near-shore and thus prone to erosion (Sommerfield 2006), indicating that there might be a fundamental trade-off between stratigraphic completeness and the maximum achievable temporal resolution.

We find a strong connection between time-averaging and stratigraphic disorder, as they can be transformed into each other by multiplication with the sediment accumulation rate (Equation 4). This is a direct consequence of purely advective particle transport below the mixed layer (Supplementary Figure 1, Supplementary Equations 5 to 7). As such, it is independent of how the SML is modeled and will similarly hold for complex, multimodal distributions of particle ages. Equation 4 makes the suspected connection between time-averaging and disorder (e.g., Kowalewski (1996)) explicit and allows to estimate disorder by means of time-averaging and sediment accumulation rate, data that is more easily traceable empirically (e.g., Tomašových et al. (2018)). A well-ordered record with high temporal resolution (low values of both time-averaging and stratigraphic disorder) is highly desirable for any study relying on paleorecords. Our results formalize why these records are most likely found in high-sedimentation environments.

The law of superposition is a core principle of geology, frequently used as model assumption in geochronology or to establish ordering of events in the absence of age constraints. Age-depth modeling methods assume the age of a sediment layer can be known exactly given

sufficient high-resolution data, and they typically enforce the law of superposition when faced with age-reversals (Haslett and Parnell 2008; Hohmann et al. 2025). Our results highlight that, below the physical scale of stratigraphic disorder and time-averaging, sediment layers do not have a single, well-defined age. On this scale, the physical processes of sediment deposition and mixing introduce irreducible uncertainty into age-depth relationships that cannot be resolved with the addition of more, high-resolution data. Palaeoecological studies frequently report time-averaging above 1000 years (Flessa and Kowalewski 1994; Scarponi et al. 2017; Tomašových et al. 2018; Berensmeier et al. 2023), an order of magnitude larger than the age-uncertainty of dating individual particles (e.g., via radiocarbon or amino acid racemization dating (Hajdas et al. 2021)) and stratigraphic disorder on the decimeter scale (Flessa et al. 1993; Kosnik et al. 2007, 2009; Dominguez et al. 2016; Tomašových et al. 2018). Not dating precision, but age uncertainty introduced by time-averaging will be the limiting factor for age-depth modelling in low-accumulation (sediment accumulation below 0.01 cm/y) Holocene environments (Kowalewski et al. 1998; Dolman et al. 2021).

Our model assumptions of constant sediment accumulation, biodiffusion, and mixing depth reflect data availability from compilations of empirical measurements and the standard approaches used to estimate SML parameters from tracer profiles. While there are multiple global compilations of individual SML parameters available (e.g., Song et al. (2022); Solan et al. (2019)), we use a compilation containing all three parameters of interest measured at the same location to avoid propagation of extrapolation effects into our results (Hohmann 2022). We hypothesize that episodic sediment accumulation will reduce time-averaging and disorder by removing particles from the SML faster, thus reducing their exposure to mixing (Sadler 1993). Deep mixing below the recognized mixing depth will, however, increase time-averaging (Tomašových et al. 2023) and, as a result, stratigraphic disorder.

Many models of particle mixing and its effect on earth science signals are available in the scientific literature, allowing for modeling of complex depth- and time-dependent dynamics (see e.g., Meysman et al. (2010)). The majority of SML parameters are estimated by fitting tracer profiles predicted by the Guinasso and Schink (1975) model to empirical observations (e.g., DeMaster and Cochran (1982)). As the diffusion-advection model used here is also derived from the Guinasso and Schink model, it minimizes discrepancies between inference and prediction models while remaining simple enough to provide analytical insights into the connection between particle age and depth (e.g., Equations 3 and 4).

Biodiffusion can be anisotropic (Wheatcroft 1991), spatially heterogeneous (Zuhr et al. 2022) and size-dependent (Wheatcroft and Jumars 1987; Shull and Yasuda 2001; Hupp et al. 2019; Hupp and Kelly 2020) due to ecological preferences of bioturbators and physical effects such as granular convection (Savranskaia et al. 2022). Higher biodiffusion coefficients have been observed in the fine particle fraction (Wheatcroft and Jumars 1987), suggesting that time-averaging and disorder might be reduced for large particles. However, it is common to observe high values of stratigraphic disorder and age-homogenization across multiple decimeters for large shells (fraction > 4 mm) (Kosnik et al. 2007, 2009; Dominguez et al. 2016; Tomašových et al. 2018). This suggests that while mixing intensity of large particles is high enough for our results to be valid for large size fractions, the exact values of time-averaging and stratigraphic disorder might vary across size fractions.

Destruction of particles in the taphonomic active zone (Davies et al. 1989) reduces time-averaging (Kowalewski 1996; Olszewski 2004; Kowalewski et al. 2017), and, as a result, stratigraphic disorder. Our model does not incorporate particle destruction, as the taphonomic half-life of particles encapsulates age- and taxon-dependent dissolution of (bio)minerals, sequestration, and loss of taxonomically identifiable features and is accordingly difficult to constrain (Davies et al. 1989; Meldahl et al. 1997; Kidwell et al. 2005; Tomašových et al.

2014; Kowalewski et al. 2017; Nawrot et al. 2022). Our estimates are applicable to particles with a taphonomic half-life longer than the particle residence time in the taphonomically active zone (Delhez and Deleersnijder 2012). Especially in deep-sea environments with very high predicted values of time-averaging, taphonomic half-life will become a limiting factor (Kuderer and Middelburg 2024). Particle destruction will also reduce sample size, increasing the effects of random fluctuations (Olszewski 2004). However, the interquartile range is robust to outliers, reducing the effect of small sample sizes and reworking of exceptionally old particles.

Conclusions

Informing a model of the surface mixed layer with parameters measured in modern environments, we found sediment accumulation has the strongest effect on the temporal resolution of the sedimentary record as expressed by time-averaging of particles, attaining values higher than 10 kyr in deep-sea settings. The law of superposition breaks down below decimeter scale due to stratigraphic disorder, which is controlled by mixing depth. Secular increases in mixing depth might have resulted in a 10-fold decrease in temporal resolution throughout the Phanerozoic.

Code and data availability

All code required to reproduce the results is available under https://doi.org/10.5281/zenodo.20813310 (Hohmann 2026), supplementary information is archived under https://doi.org/10.5281/zenodo.20813575 (Hohmann and Jarochowska 2026).

Author contributions

NH: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing (original draft, review and editing). JM: Writing (review and editing). EJ: Conceptualization, Funding acquisition, Validation, Supervision, Writing (review and editing).

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Figures

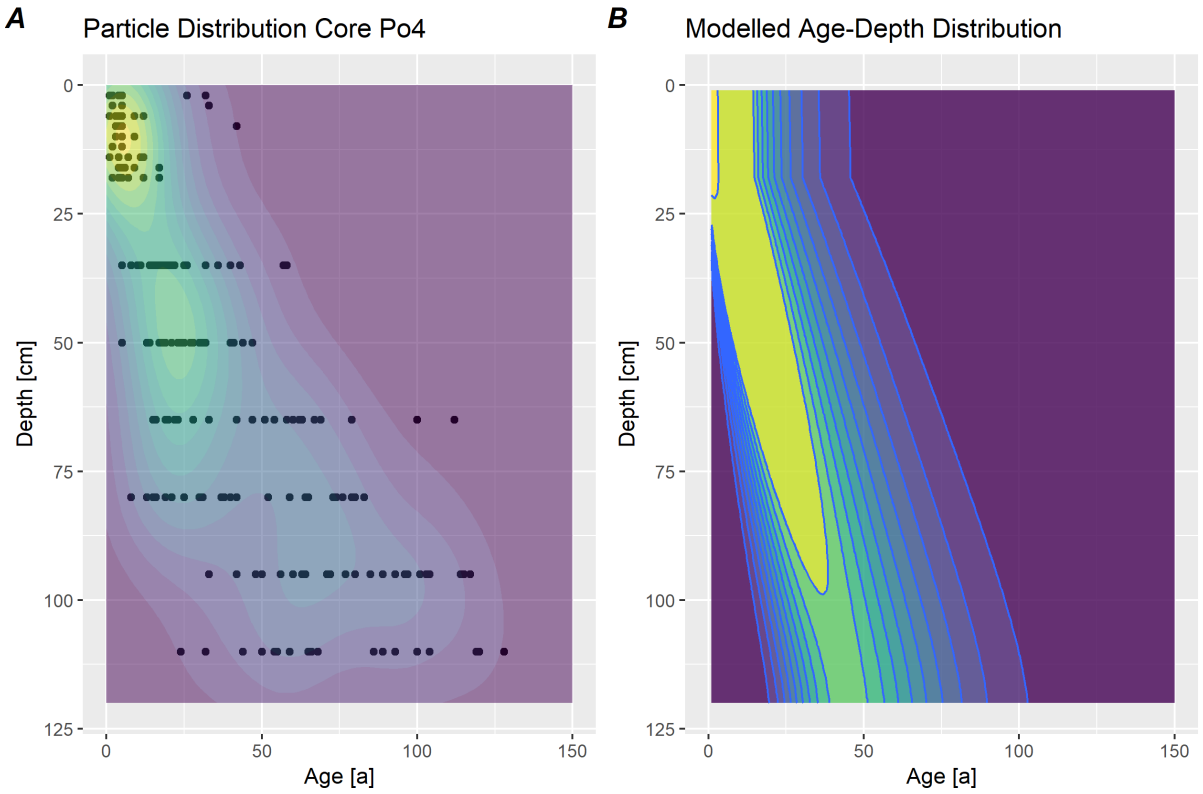
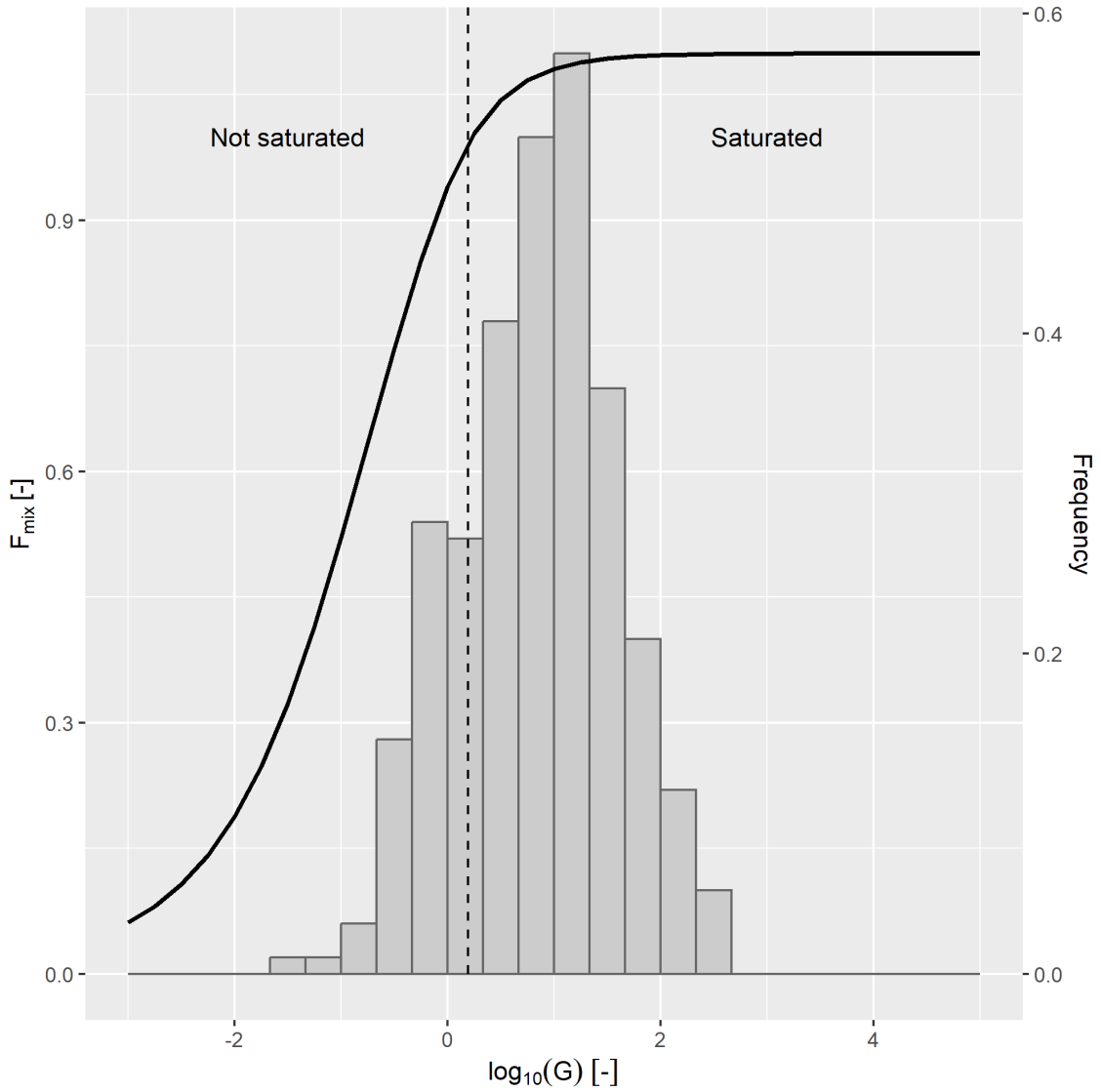


Figure 1: Age-depth distribution (A) of 221 individually dated shells of the bivalve Corbula gibba *from the Po prodelta, Northern Adriatic Sea (Tomašových et al. 2018) and their density estimate (B) approximated with the diffusion-advection equation used in this study (Equation 1, see Supplementary Information for details). Time-averaging of* C. gibba *at 95 cm is 49 years (interquartile range), shells younger than 25 years can be found both at the surface and buried below 1 m.*



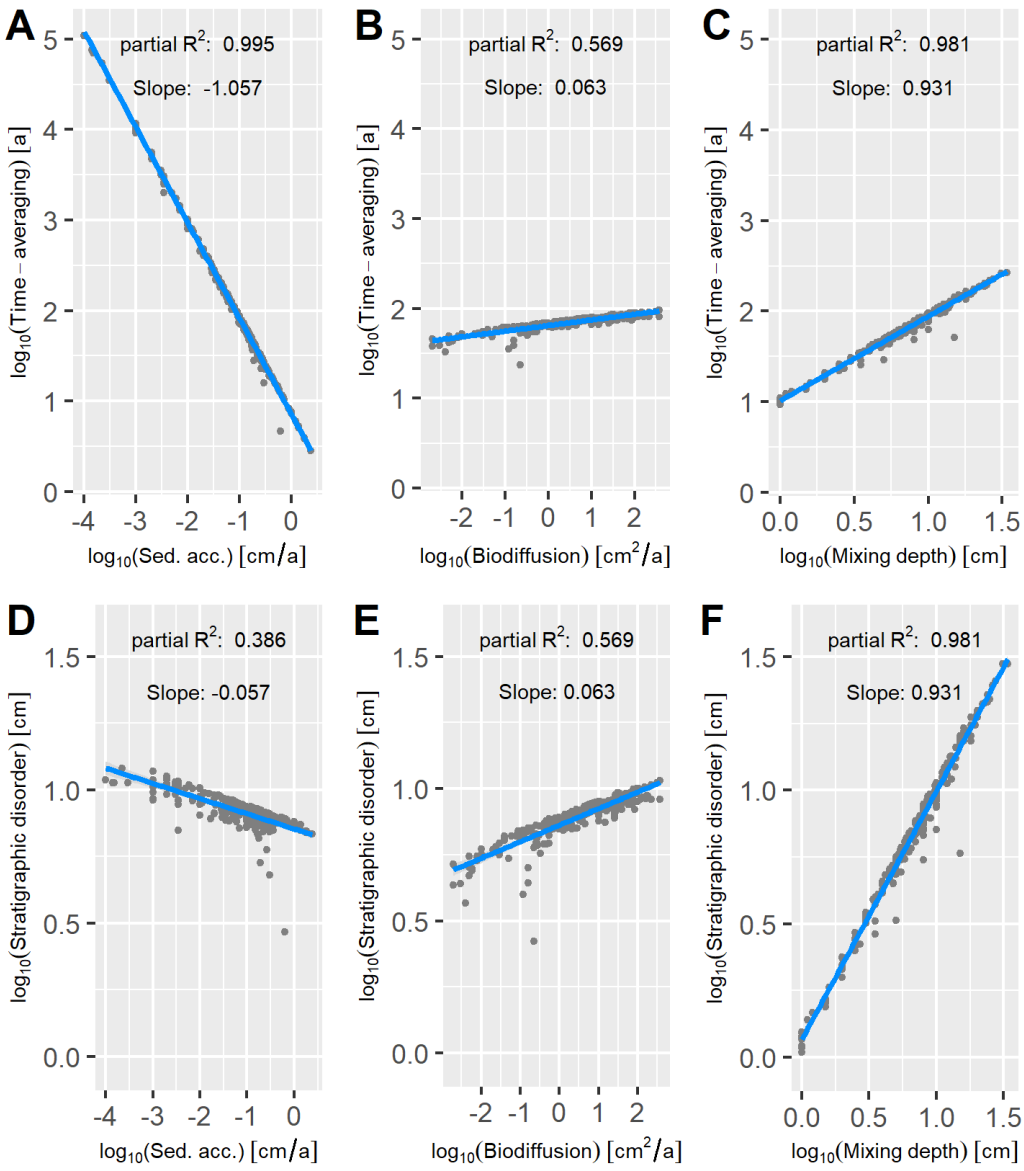
339

340 *Figure 2 Time-averaging F_{mix} in the rescaled system as a function of mixing intensity G*

341 *(black) and histogram of G in the SMLBase informing the regression analysis (Hohmann*

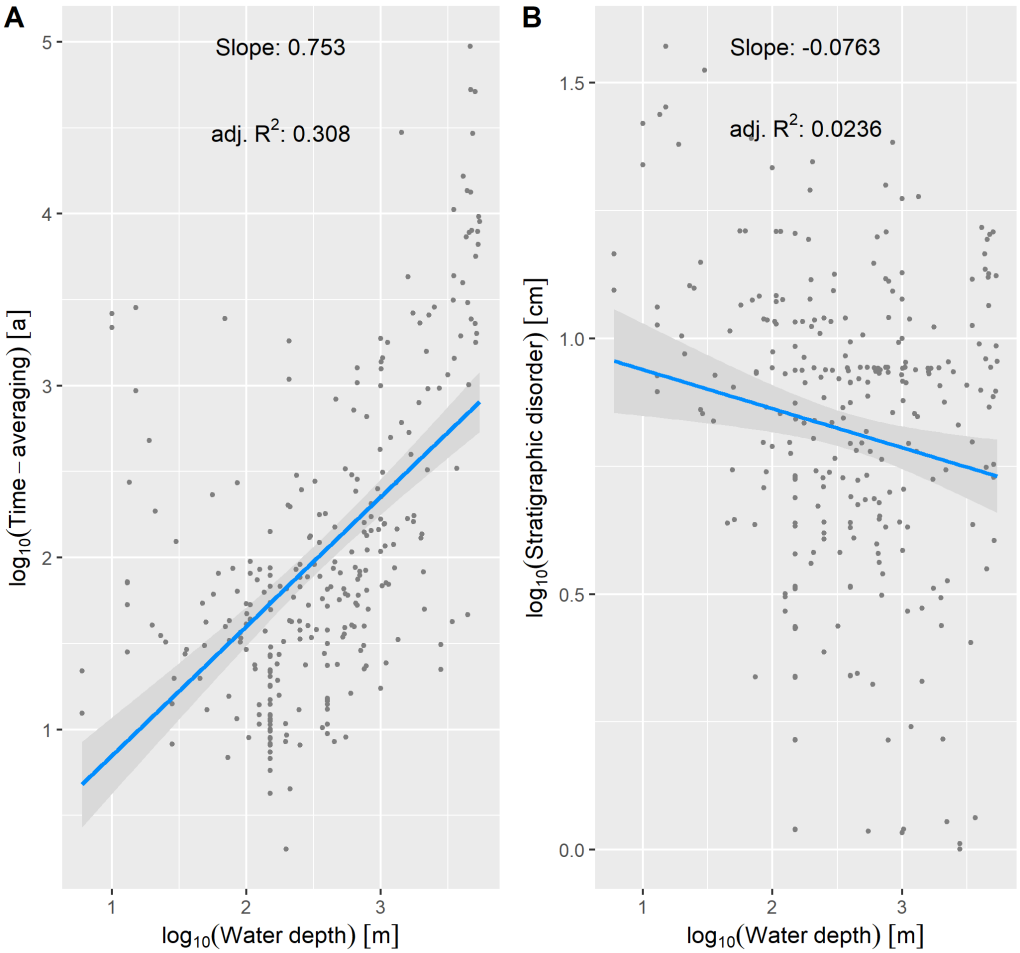
342 *2022). A total of 287 observations are included, the majority (79 %) are saturated with*

343 *respect to mixing (see also Supplementary Figure 2 D).*



344

345 *Figure 3: Time-averaging (top row) and stratigraphic disorder (bottom row) in dependence*
346 *of sediment accumulation rate S (A, D), mixing depth L (B, E) and biodiffusion D_b (C, F).*
347 *Sample size is n = 287, standard errors, p-values, and standardized regression coefficients*
348 *are reported in Supplementary Tables 1 and 2. Partial R^2 and slope of mixing depth and*
349 *biodiffusion are identical in both GLMs due to their analytical connection (Equation 4).*



350

351 *Figure 4: Water depth versus time-averaging (A) and stratigraphic disorder (B). Sample size*

352 *is n = 287, full results of the regression analysis are reported in Supplementary Table 3.*

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