

LATTICE-AUTOMATON MODELLING OF BIOTURBATION: IMPLICATIONS FOR SHORT-LIVED AND EARLY TRANSIENT TRACERS

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The activities of infauna have a profound influence on the fabric and composition of sediments. For example, sediment fabric and structure are modified and biogenic heterogeneities are created that change the acoustic response and geotechnical properties; contaminants at the sediment-water interface can be removed to depth far more rapidly than by burial alone, whereas "capped" pollutants can be transported back to the surface and re-introduced to the environment; the preserved geological/geochemical record can be fundamentally altered in terms of both timing and intensity of events, clouding our understanding of climate and palaeoceanography; finally, geochemical reactions can be instigated or significantly promoted, such as the dissolution of carbonates or redox reactions.

Most models of bioturbation adopt a continuum representation in the form of diffusion or non-local mixing models. These representations are comparable to diffusive models of turbulence, i. e., very good at fitting data and marginally successful at making actual predictions, but extremely limited in providing mechanistic understanding of the link between real animal activities and sediment mixing. This final failure constitutes a major problem to further progress in this field.

The authors are addressing this challenge with a new type of model (BOUDREAU *et al.*, 2001; CHOI *et al.*, 2002). Biologically active sediment is represented as a random collection of solid and water "particles" on a lattice with individually assigned chemical, biological and physical properties, e. g. food *versus* inert material. Particles can be added to the model by sedimentation and removed by burial and compaction, guaranteeing the existence of a sediment-water interface and the disintegration of some biologically generated features. Model benthic organisms move through the lattice as programmable entities, i. e. automata, by displacing or ingesting-defecating particles. Each automaton obeys a set of rules, both deterministic and stochastic, designed to mimic real infaunal behavior. The initial version of our model, known as LABS (Lattice-Automaton Bioturbation Simulator), has only one functional type of organism, i. e. a small deposit feeder, similar to some Capitellid worms.

Mixing can be studied with LABS by introducing radioactive tracers (so-called steady state tracers) or labels (transient tracers) as a particle property. The resulting 2D distributions can be integrated laterally to produce equivalent 1D profiles which can then be modelled via 1D mixing models to obtain traditional measures of mixing, e. g. D_B . Thus, the link between actual animal activities (feeding rate, locomotion rate etc.) and population characteristics (animal numbers/density etc.) and the bulk mixing parameters can be studied. This paper focuses on two aspects of the results from our tracer work: 1) Will different radiochemical tracers suggest the same mixing intensities for identical animal behaviours? 2) What is the behaviour of transient tracers in the model and what does this reveal about the nature of mixing in our model (and by extension about natural sediments)?

Fig. 1a illustrates the steady-state D_B calculated from various isotopes as a function of time over a 50 year period (starting 500 years into a model simulation), assuming constant input of the tracers at the sediment-water interface and sampling once a year. Notice that the longer-lived isotopes (^{228}Th , ^{210}Pb , ^{32}Si) do not vary significantly with time, whereas the shorter-lived isotopes (^7Be , ^{234}Th) display significant temporal variance. The shorter-lived isotopes are,

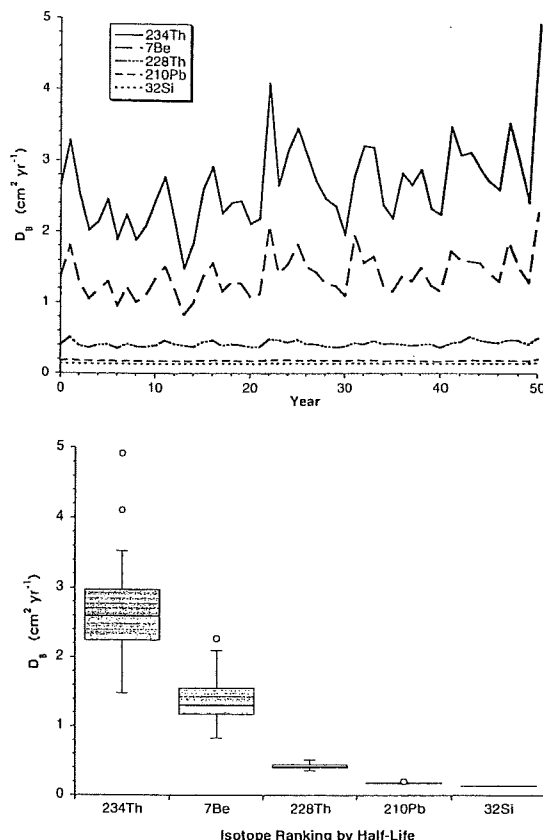


Fig. 1. a (top). Time series (1x per year sampling) of the calculated D_B value for various decaying isotopes subject to the same mode and frequency of mixing. b (bottom). Box diagram of the value of D_B for the isotope records in a). The box is one standard deviation whereas the bar in the box is the median; the second smaller bar is the second standard deviation. The larger D_B of the short-lived isotopes is due to the violation of the scale criterion for diffusive mixing, and their large variance is due to the violation of the frequency criterion.

thus, sensitive to the stochastic nature of the mixing in the model. In addition, calculated D_B correlates with the half-life of the isotope (Fig. 1b). Mixing of shorter-lived isotopes violates two criteria for diffusive mixing, and thus generates noisy time series and anomalously high D_B values. The mixing distance for these isotopes is comparable to the spatial scale of their profiles. This means they are mixed more deeply than expected because mixing is not "small scale"; the result is a large apparent D_B value. Secondly, these short-lived tracers have decay times comparable to the times between mixing events. Thus, their depth profiles become very sensitive to the timing of mixing events relative to the mixing event. These facts argue that shorter-lived isotopes cannot be interpreted with a classic diffusion model (MEYSMAN *et al.*, in press).

We also examined time-dependent stable tracers by labelling every particle in the model. This allows us to study the statistics of particle movement in the model, e.g., the time change of the mean-squared displacement. Fig. 2 displays the evolution of the mean-squared displacement, MSD (Δ^2), of all particles with time. Notice that for the type of mixing in this model, the MSD is not linear in time for the first 100 days, i. e. we expect that

$$\Delta^2 = 4 D_B t \quad (1)$$

where t is time; thus, D_B must be time dependent in the first 100 days of this experiment. This observation has implications for determining D_B values from short "salting" experiments.

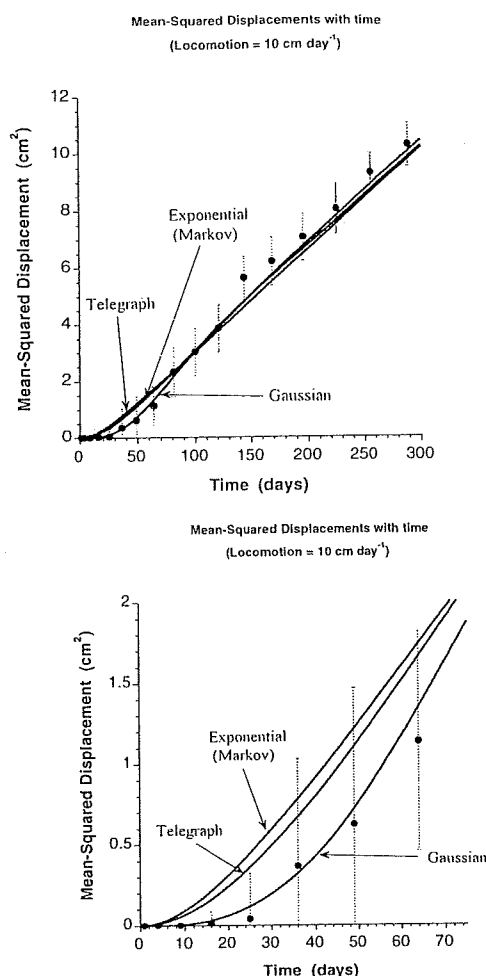


Fig. 2. a) (top). Time change of the MSD of particles in the LABS model; this indicates that D_B is a constant only for times greater than 100 days. The curve labeled Exponential is that expected for classical Markovian diffusion, whereas the "Telegraph" line is that expected for diffusion governed by the Telegraph equation (BOUDREAU, 1989). The data are better fit by a Gaussian time function. b) (bottom). Enlargement of a) for shorter times.

Time dependence of D_B is anticipated in the classic (Markovian) theory of diffusion, but what is expected in that case is a 2nd-order dependence at small times (Fig. 3). The data are better described by a 3rd-order power law at these times, and the 300 day record is better described by a Gaussian time dependence of D_B , rather than the classic exponential of Markov theory or even that for the Telegraph equation (BOUDREAU, 1989). Consequently, we see that more research is needed on the nature of the mixing found in the LABS model, even for a relatively simple organism.

In conclusion, LABS is already changing our understanding of mixing models and placing limits on our use of traditional mixing models, both for short-lived steady state tracers and for the early history of transient stable tracers. Specifically, "short"-lived isotopes usually violate both the scale and temporal conditions necessary for the popular bio-diffusive model, whereas transient tracers are subject to an appreciable period wherein the bio-diffusion coefficient is a function of time.

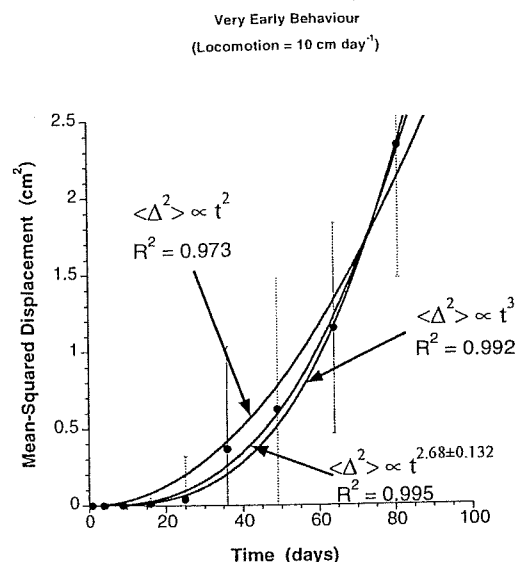


Fig. 3. Limiting early behaviour of the MSD. Classical diffusion and Telegraph-based diffusion both suggest t^2 limiting behaviour in the MSD for short times, whereas these data are much better described by a t^3 dependence which is suggested by the Gaussian curve in Fig. 2. The best fit to a power law is 2.68th-order, but statistically speaking, that is a bare improvement over a 3rd-order power.

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