Mixing models (advection/diffusion/ non-local exchange) and ^{210}Pb sediment profiles from a wide range of marine sediments

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Introduction

Particles settling from the water column may enter the sediment below by physical or biological activity. Because these transport processes play a role during early diagenesis (Aller, 1990), their understanding and quantification is crucial in the fate of many sediment bound particles reaching the seafloor. Theoretically sediment accumulation rates depends only in the variable or constant supply of particles. For many years sediment bound tracers have been used to estimate sediment accumulation rates, a commonly used one is concentration profiles of excess ^{210}Pb (Nittrouer *et al.*, 1983; DeMaster *et al.*, 1994). This radiotracer is strongly bound to particulate material, hence its redistribution depends mainly on the supply at the sediment-water interface, *in situ* production from ^{238}U via ^{226}Ra decay, sediment accumulation and physical (earthquake, waves) or biologiactivity concentration profiles. This fact is quite important because violate one of the prerequisite in using tracers as time clocks in sediments, that is, the immobilisation of the tracer upon arrival to the sediment-water interface (Kadlec and Robbins, 1984). Biological mixing in marine sediment has been estimated assuming that sedi-

result over time appears as diffusive and the activity can be quantify as biological diffusive mixing (Db) (Boudreau, 1986a; Mulsow and Boudreau, 1999). This coefficient is usually modelled from sediment-depth profiles of particle bound radioactive tracers. However, empirical data showed quite often-subsurface maximum (Smith *et al.*, 1986) that can not be accounted for as diffusive mixing. Alternative hypotheses are fluctuation in the input sources, burrows or tube's infilling or a mechanism that introduce surface (young) sediment at depth in the sediment column. This latter process is call non-local exchange (Boudreau, 1986b). Because of the complexity of such processes biological-mixing effect on ^{210}Pb sediment profiles is often ignored and not accounted for. One of the reasons is the lack of systematic models that could account for the main biological mixing activities in marine sediments. Soetaert *et al.* (1996) presented a family of bioturbation models including diffusive and non-local exchange processes and demonstrated its applicability and limitaments. At this station the sediment was collected using a gravity corer. The sediment was sliced on board and freeze-dried. An aliquot of 100-200 mg of sediment was digested in a mixture of $HF+HCL+HNO_3$ in a Teflon bomb and microwave. The activity of ^{210}Pb was measured by alpha counting of its daughter ^{210}Po considered here as in secular equilibrium. ^{208}Po or ^{209}Po were used as chemical yield. Standard sediment sample as well as blanks were used with each batch of samples analysed. ^{210}Po were spontaneously deposited on silver discs. Bulk density and porosity were determined from the difference in wet and dried weight after correction for salinity content. The activity concentration of ^{210}Pb was expressed in dpm ml^{-1} of total activity in order to satisfy the model's requirement used here. The supported production is calculated as a parameter in the models.

Models

Basically, we used the models proposed by Soetaert *et al.* (1996) These authors proposed a family of models with increasing complexity (number of parameters added) of diffusive and non-local exchange mixing processes included in the models. The models require only a known sedimentation rate and total activity of the tracer profile. In our study we used the most close sedimentation rate from the literature for each one of the sites and ranged from 1-10 $cm.kyr^{1}$. For details in the models see Soetaert, *et al.* (1996).

Results and discussion

The sediment cores studied come from a wide range of marine environments. Some stations are from coastal areas (Morocco, Kara Sea), others from intermediate depth water from the

Mediterranean Dyfamed and others from the Northwest Pacific and Arabian Sea deep-sea ocean (Table 1). The water depths ranged from 10 to > 4000 meter. In all instances the sediments were carefully collected and handled. The radiometric measurements were done at IAEA-MEL.

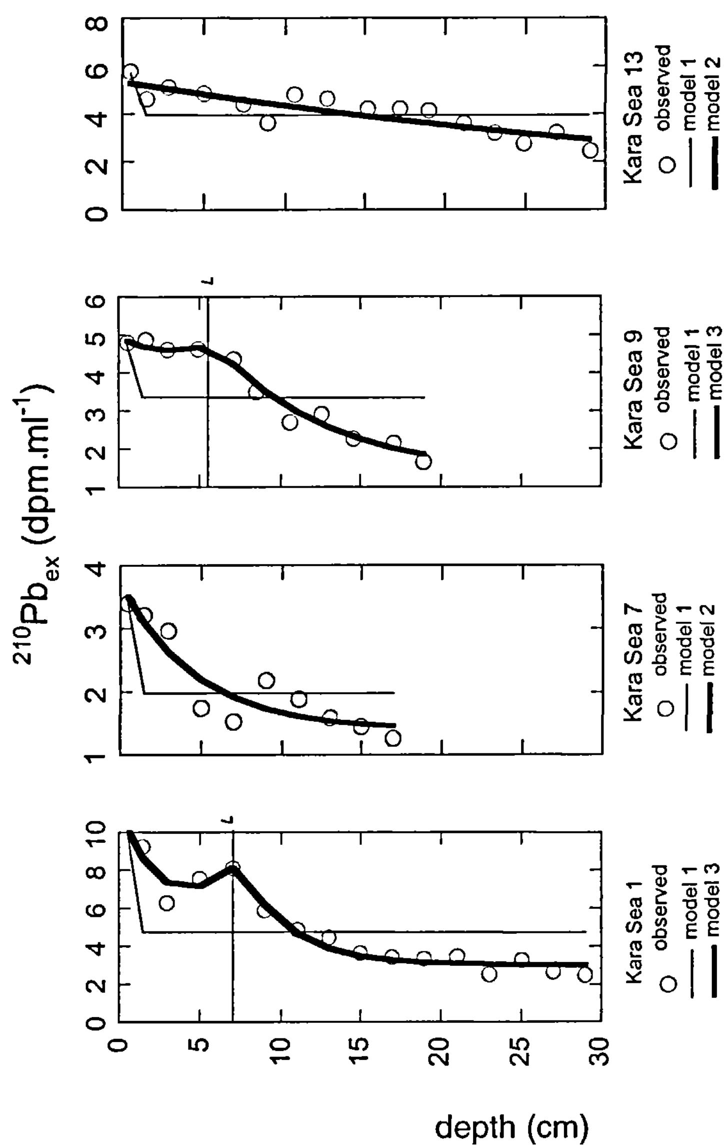
Station	depth	latitude	longitude	H_0: 1/ 2	H_0: 2/ 3	H_0: 3/ 4a	best fit
South Med.	900	35° 48N	9° 55E	***	ns		Model 2
Dyfamed	2300			**	**	ns	Model 3
Geosecs 413	2830	13° 21.8N	53° 15E	***	***	**	Model 4a
Kara Sea 1	195	69° 57.6N	61° 52E	***	**	ns	Model 3
Kara Sea 7	27	72° 59.9N	72°.58E	**	ns		Model 2
Kara Sea 9	30	73° 58.9N	73° 17E	***	*		Model 2
Kara Sea 13	17	72° 25.9N	80°.39E	***	ns		Model 2
NW Pacific 6	4577	11° 28.3N	164° 52E	***	**	ns	Model 2
NW Pacific 8	5390	15° 30.2N	159° 30E	***	ns		Model 2
NW Pacific 9	5002	22° 22.1N	152° 40E	***	ns		Model 3

Table 1
Name of the stations and statistical results of the F-test comparison among the models. *** p>0.9999; ** p 0.99-0.999 and * p 0.95-0.99.

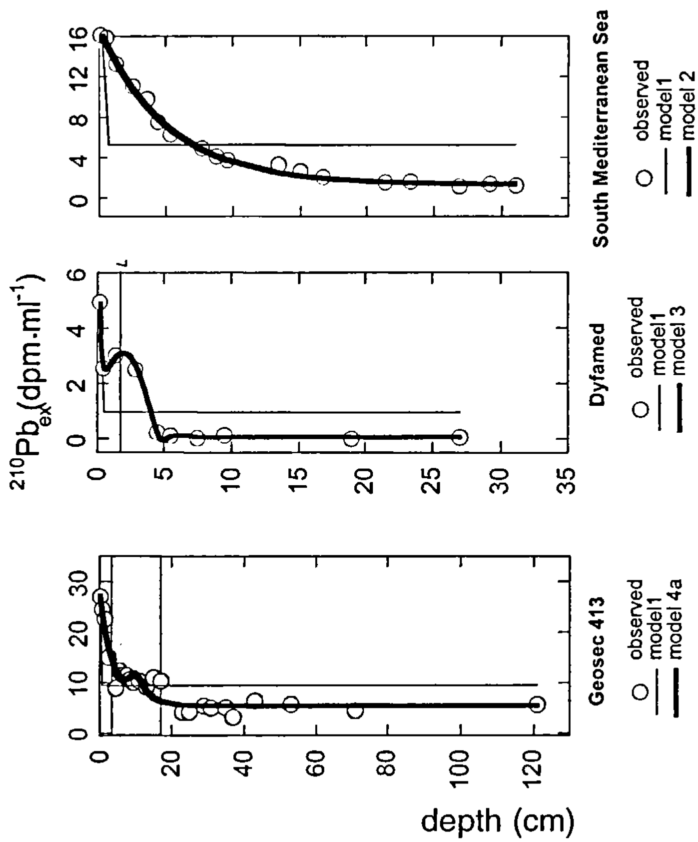
None of the 10 cores measured for ^{210}Pb-concentration profiles could be interpreted as the result of only decay and sedimentation rate (Table 2; Figures 1-3). In 50 % of the cases a simple diffusion-like mixing coefficient addition was enough to better reproduce the observed data points. In 4 cores the addition of a non-local exchange parameter, injection of particles from the surface layer to a depth L, was necessary to improve the fitting of the observed activity profile. In only one instance, a more complex model was required to explain the observed data point (Arabian Sea Core: Geosec 413; table 2). In this latter case a subsurface layer is depicted of certain thickness $L \pm \delta x$, for the modeller this may suggest the result of homogeneously egested sediment by benthic organisms at this depth. This sediment core was collected using a gravity core of (10 cm OD). As it is shown in its porosity profile (Figure 4b) one can see that this particular core may have been

Station	best fit	$Sup.Flux_{mod3}$	Db_{mod3}	$Flux1_{mod3}$	$Flux2_{mod3}$	L_{mod3}	Db_{mod2}
South Med	Model 2	0.04	0.73	0.00	2.40	0.54	0.80
Dyfamed	Model 3	0.11	0.04	1.15	0.94	3.31	0.17
Geosecs 413	Model 4a	0.07	0.12	0.50	1.36	9.81	0.83
kara Sea 1	Model 3	0.05	0.03	0.20	1.43	3.20	2.44
kara Sea 7	Model 2	0.02	0.02	0.06	0.13	2.20	0.63
kara Sea 9	Model 2	0.00	1.39	0.34	0.96	5.79	4.32
kara Sea 13	Model 2	0.00	19.94	2.02	1.26	10.00	27.44
NW Pacific 6	Model 3	0.00	1.36	0.00	34.10	2.71	2.32
NW Pacific 8	Model 2	3.69	0.74	28.57	32.97	9.44	17.74

Table 2
Parameters calculated from the best-fitted models compared to the less complex model for each run. Supported.produtcion in $dpm.cm^{-3}.yr^{-1}$, Flux 1 and Flux 2 in $dpm.cm^{-2}.yr^{-1}$, Db in $cm^{-2}.yr^{-1}$, L in cm. Shaded area corresponds to best-fitted model's values.

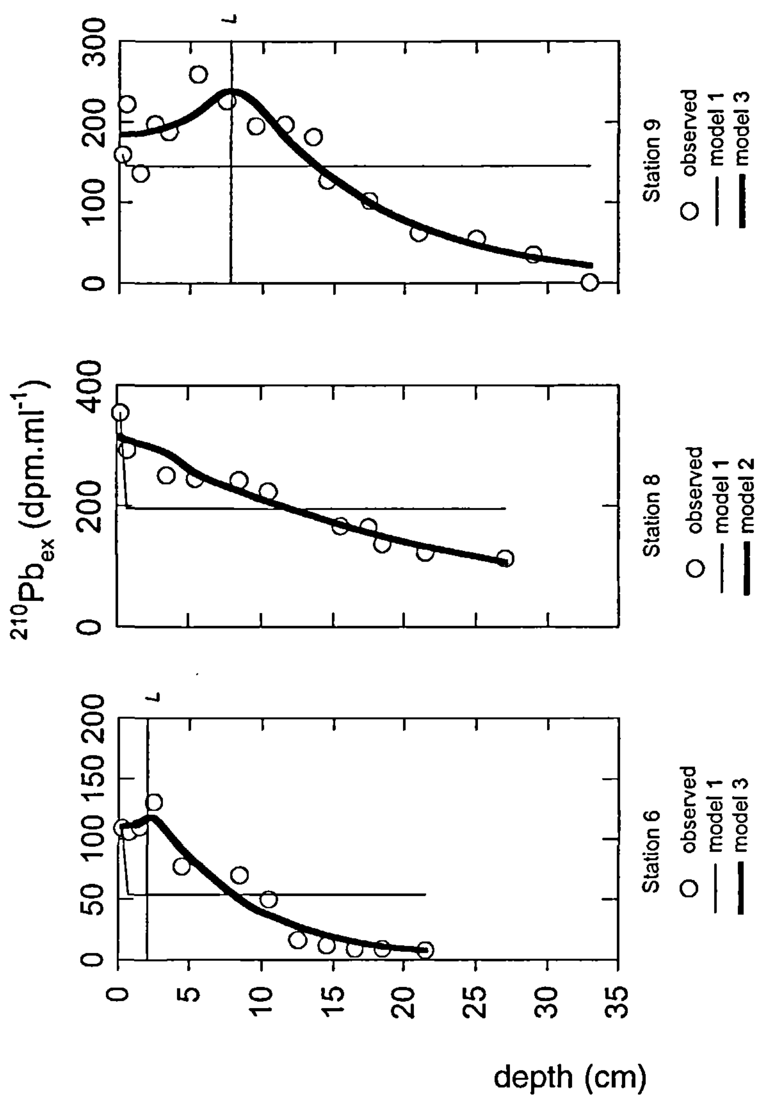


I Figure 1
^{210}Pb-depth profiles observed compared to data expected from advection and decay only (model 1) and with the addition of bioturbation. Model 2: advection + diffusive mixing and Model 3: advection + diffusive +non-local mixing processes.



I Figure 2
^{210}Pb-depth profiles observed compared to data expected from advection and decay only (model 1) and with the addition of bioturbation. Model 2 advection + diffusive mixing, Model 3: advection + diffusive +non-local mixing processes. Model 4a assumes that the flux injected is distributed homogeneously at depth (shaded area).

depth (Figure 5a). In general, the Db value decreased with depth as observed in other studies worldwide (Stoetaert *et al.*, 1996; Middelbourg *et al.*, 1997; Buffoni *et al.*, 1992). Although it is difficult to draw a conclusion with the few data point of this study, there is a clear tendency that the bioturbation influence decreases with



I Figure 3
^{210}Pb-depth profiles observed compared to data expected from advection and decay only (model 1) and with the addition of bioturbation. Model 2 advection + diffusive mixing and Model 3: advection + diffusive +non-local mixing processes

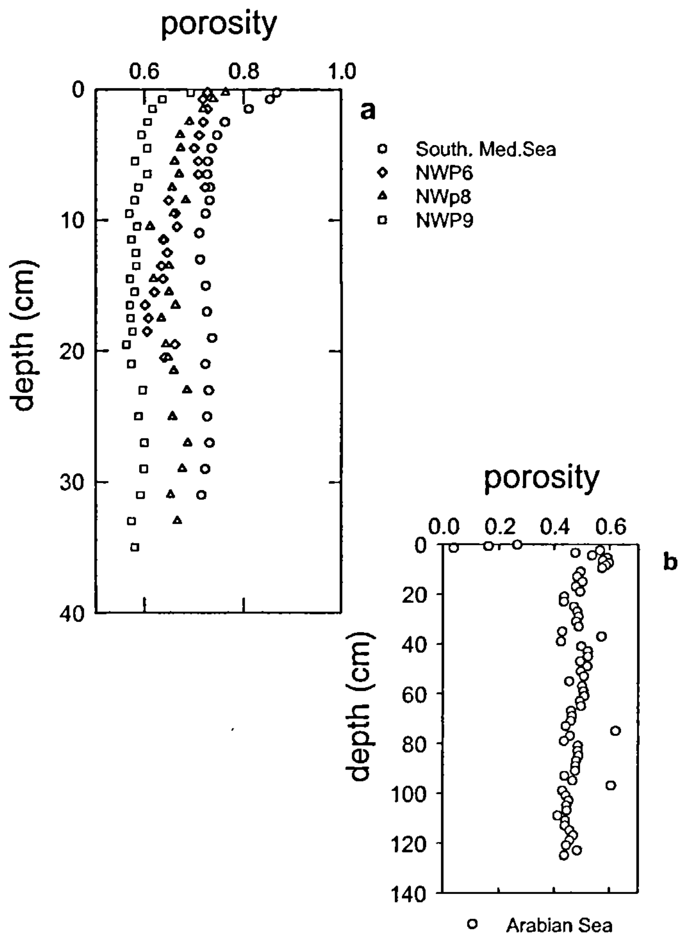


Figure 4
Sediment core porosity profiles. a) typical porosity-depth profiles observed in the studied sediments. b) Porosity profile of a sediment core collected with a gravity core.

increasing depth. Since in 40 % of the cases the best fit was obtained using Model 3, a plot of percentage of the injected flux from the total input of the tracer with depth will give and indication on how important non-local exchange processes are in the study sediments. The relationship is not clearly defined due to, in one hand, the few

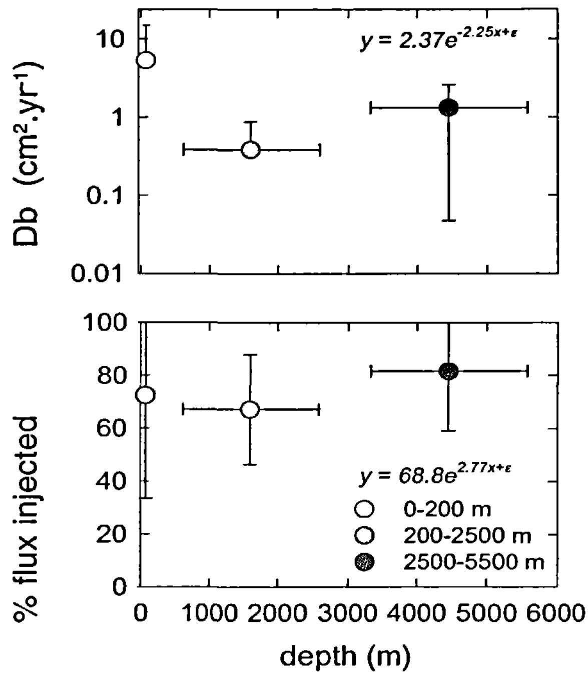


Figure 5
Estimated bioturbation coefficients and the percentage of the total flux which is directly injected into the sediments (flux 2), using model 3 parameters. The data were grouped by depth into shallow (white dot:10-200 m), mid depths (grey: 200-2800) and deep sea (dark grey: > 4000 m).

data available, and in other hand to perhaps a greater role of non-local exchange at those station from deep-sea, namely the Northwest Pacific's stations (Figure 5b). This may explain why in our study we found that the relation was opposite to bioturbation (Figure 5a). The sediment from the Northwest Pacific was very fine and in two stations, namely 8 and 9, they have an abundant cover of manganese nodules. Perhaps the turn over movement of nodules it is also a phenomenon that can increased the injection of younger sediment into the sediment column. In addition, at station 6, there was a two clearly distinctive facies with a contact at about 12 cm. The younger of them characterised by brown siliceous ooze and the older one by foraminifer ooze. We did not see any physical artefact based on porosity profiles measured at each one of the stations as shown in Figure 1. Station 6 is also relatively close to Marshal Island region, thus perhaps physical mixing may be also playing a role in this diagenetic parameters.

Conclusion

In summary, none of the ^{210}Pb-depth profiles were better fitted if sedimentation rate and radioactive decay of the tracer was considered. Our finding agree with those found in the literature. Soetaert *et al.* (1996) found in marginal sediment cores that the ^{210}Pb profiles were best fitted using Db and non-local exchange mixing like in our case. However, in their study they clearly showed that Db decreased with depth, it is worth to mention that these authors analysed 16 cores and many of them seasonally. Two major conclusions can be drawn from our study. One of them is that the use of ^{210}Pb in geochronology is increasingly doubtful

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if only one tracer is used and no attempts to study systematically the effect of bioturbation. Secondly, it appears that mixing of tracers and therefore any other sediment bound particle, reaching the sediment-water interface at deep-sea ocean sediments are perhaps more affected by mixing (diffusive/non-local exchange) as previously thought. Smith *et al.* (1986) showed that when non-local exchange is included in the analyses of determining bioturbation rates they could be overestimated. It is clear that bioturbation in marine sediments during early diagenesis do play a quantitative role in the fate of sediment bound contaminants. From our study it is also clear that geochronology based uniquely on ^{210}Pb-depth profiles is not suitable for obtaining sound accumulation rate values. Although the models can depicted mixing processes (diffusive/non-local mixing) taking place in the sediment columns, the lack of knowledge on the actors (benthos) who mix solute and found in our study. If this is possible then we can predict which

surface maxima peak often found on tracer-depth profiles and generally disregard as noise.

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