

1 **The effect of bioturbation in pelagic sediments: Lessons from radioactive**  
2 **tracers and planktonic foraminifera in the Gulf of Aqaba, Red Sea**

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10

## 11 **Abstract**

12 Studies of recent environmental perturbations often rely on data derived from marine  
13 sedimentary records. These records are known to imperfectly inscribe the true sequence of  
14 events, yet there is large uncertainty regarding the corrections that should be employed to  
15 accurately describe the sedimentary history. Here we show in recent records from the Gulf of  
16 Aqaba, Red Sea, how events of the abrupt disappearance of the planktonic foraminifer  
17 *Globigerinoides sacculifer*, and episodic deposition of the artificial radionuclide  $^{137}\text{Cs}$ , are  
18 significantly altered in the sedimentary record compared to their known past timing. Instead of  
19 the abrupt disappearance of the foraminifera, we observe a prolonged decline beginning at core  
20 depth equivalent to  $\sim 30$  y prior to its actual disappearance and continuing for decades past the  
21 event. We further observe asymmetric smoothing of the radionuclide peak. Utilization of  
22 advection-diffusion-reaction models to reconstruct the original fluxes based on the known  
23 absolute timing of the events reveal that it is imperative to use a continuous function to describe  
24 bioturbation. Discretization of bioturbation into mixed and unmixed layers significantly shifts  
25 the location of the modeled event. When bioturbation is described as a continuously decreasing  
26 function of depth, the peak of a very short term event smears asymmetrically but remains in  
27 the right depth. When sudden events repeat while the first spike is still mixed with the upper  
28 sediment layer, bioturbation unifies adjacent peaks. The united peak appears at an intermediate  
29 depth that does not necessarily correlate with the timing of the individual events. In a third  
30 case, a long lasting sedimentary event affected by bioturbation, the resulting peak is rather  
31 weak compared to the actual event and appears deeper in the sediment column than expected  
32 based on the termination of the event. The model clearly shows that abrupt changes can only  
33 endure in the record if a thick sediment layer settled on the sediment-water interface at once or  
34 if bioturbation rates decreased to very low values for a prolonged period of time. In any other  
35 case smearing by bioturbation makes an abrupt event appear to have started shortly before the  
36 real timing and end long after its true termination.

## 37 **Keywords:**

38  $^{137}\text{Cs}$ ,  $^{210}\text{Pb}$ , recent sediments, *Globigerinoides sacculifer*, event deconvolution, advection  
39 diffusion reaction model

## 40 **1. Introduction**

41           The sedimentary record is an imperfect archive of the past and is known to be strongly  
42 influenced by numerous processes such as: organic matter remineralization, sediment mixing  
43 by burrowing organisms, physical sediment transport processes and variations in sediment  
44 accumulation rates (Aller, 2014; Berner, 1980). Among these processes, mixing of marine  
45 sediments by burrowing benthic organisms (bioturbation) is often the most deceiving process  
46 for environmental change reconstructions since it smoothes and displaces events in the  
47 sedimentary record in ways that are not always intuitive. For example, in the practical  
48 application of pollution spikes for dating and stratigraphic correlation purposes, it is often  
49 considered that diffusion and bioturbation had smeared the sedimentary peaks but assumed that  
50 it did not shift peak locations. This assumption was challenged in several studies that compared  
51 sedimentary records with documented fluxes (Klaminder et al., 2012; Kramer et al., 1991) or  
52 stable isotope composition of contemporaneous organisms (Bard et al., 1987; Löwemark et al.,  
53 2008). It is thus clear that unwrapping the distorting effect bioturbation has on sedimentary  
54 records is key to obtaining accurate age determinations. Yet, despite the obvious importance  
55 of this practice and the availability of numerical procedures for its solution, its implementation  
56 in paleoceanographic studies remains rather sparse due to difficulties in producing reliable  
57 reconstructions (Bard et al., 1987; Berger et al., 1977; Schiffelbein, 1985; Trauth, 2013).

58           Bioturbation is a nearly ubiquitous phenomenon in marine sediments underlying  
59 oxygenated bottom waters but its intensity can vary over several orders of magnitude  
60 (Boudreau, 1994; Tromp et al., 1995). The immediate effect of bioturbation is that it tends to  
61 erase short term events from the sedimentary record under a continuous sedimentation regime  
62 hence limiting the possibility to extract high resolution data from the sedimentary record  
63 (Bentley et al., 2006; Wheatcroft and Drake, 2003). On a first glance the effect of bioturbation  
64 may seem somewhat arbitrary yet faunal mixing rates seem to be correlated with the organic  
65 carbon flux and sediment accumulation rates and have fairly constant depth dependence  
66 (Boudreau, 1994; Middelburg et al., 1997; Müller and Suess, 1979; Suess, 1980; Trauth et al.,  
67 1997; Tromp et al., 1995); this means that in most cases its effect should be predictable to a  
68 certain degree. Early attempts to quantitatively assess the effect of bioturbation on pelagic  
69 sediments assumed that the upper sediment layer is homogeneously mixed at an infinite rate  
70 (Berger and Heath, 1968). Later versions of this model introduced a biodiffusion coefficient  
71 which was assumed to mix the sediments of the upper layer at a constant rate (Guinasso and  
72 Schink, 1975; Peng et al., 1979). This model is still widely used and seems to fit radioisotope

73 data very well in many cases (Boer et al., 2006; Maire et al., 2008). The use of a diffusion  
74 coefficient to describe such complex processes is conceptually problematic but appears to be  
75 valid as long as the mixing process is random and faunal activity is fast compared to the studied  
76 timescale (Meysman et al., 2010). A bigger problem with the two layer model is the  
77 discontinuous description of bioturbation which is not supported by the observation that the  
78 decrease in sediment macrofauna abundance with depth is normally gradual (Flach and Heip,  
79 1996; Hines and Comtois, 1985). Because of the problem of discontinuity, diagenetic models  
80 that try to explain several parameters with a single code generally shifted to describe  
81 bioturbation as a decreasing function with depth (Cai et al., 2010; Krumins et al., 2013).

82 In the present contribution we calculate the sedimentation rates in the Gulf of Aqaba,  
83 Red Sea, and analyze the application of mathematical modeling for high resolution  
84 environmental change studies from sedimentary records. This was done by reconstructing the  
85 sedimentary record development over time for the artificial radioisotope  $^{137}\text{Cs}$  and the  
86 disappearance of a common planktonic foraminifera species based on their known water  
87 column fluxes using advection-diffusion-reaction models. These reconstructions were  
88 compared with the actual sedimentary records to lend insight into the way punctuated events  
89 are recorded in marine sediments and illustrate the effect of the mathematical model and flux  
90 variations on the resulting sedimentary records and particularly on the location and shape of  
91 the recorded peaks.

## 92 **2. Study site**

93 The Gulf of Aqaba (GOA) is a long (~180 km), narrow (15-25 km) and deep (1830 m  
94 maximal depth) northward extension of the Red Sea (Ben Avraham et al., 1979). The regional  
95 climate is hyper arid with scarce fresh water sources. The main sediment source to GOA comes  
96 from infrequent flash floods that deliver high sediment loads with very little water (Katz et al.,  
97 2015). Additional sediment sources are precipitation of the shells of marine organisms (Reiss  
98 and Hottinger, 1984; Steiner et al., 2014) and dust (Chen et al., 2007). The only significant  
99 water source to GOA is Red Sea surface waters entering through the Straits of Tiran. Driven  
100 by a density gradient, this water flows northward mainly during April-September. In the  
101 process, Red Sea surface water subducts the GOA intermediate water as its density increases  
102 due to evaporation (Biton and Gildor, 2011). Deepwater forms within GOA mostly during  
103 December-March and generally flow southward toward the strait and into the depth of the Red  
104 Sea.

105 GOA's region was very scarcely populated until the middle of the 20<sup>th</sup> century. The  
106 independence of Jordan and Israel at 1946 and 1948, respectively, turned it to a major  
107 commercial and oil port of these countries and initiated the rapid development of the cities Eilat  
108 and Aqaba on the northern coast. This development increased the nutrient input to the highly  
109 oligotrophic water from the phosphate docks and raw sewage spillage. Untreated sewage from  
110 Aqaba and Eilat was directly released to sea until 1985 and 1995, respectively. An even larger  
111 source of nutrients was commercial fish cages that operated in northern GOA between 1989-  
112 2008 (Black et al., 2012; Lazar et al., 2008; Oron et al., 2014).

### 113 **3. Materials and Methods**

#### 114 **3.1 Sampling**

115 Short sediment cores were retrieved at various locations in northern GOA at a water  
116 depth range of 400-720 m (Fig. 1) using a four barrel MC-400 multicorer (Ocean Instruments,  
117 San Diego) with sample tube length of 60 cm and inner diameter of 9.5 cm. The cores were  
118 sectioned at a vertical resolution of 0.5-2 cm. An aliquot of 10 gr of each sample was wet sieved  
119 through a 250  $\mu$ m mesh for foraminifera picking. The remaining sample was weighed, dried at  
120 60°C for one week, weighed again for porosity determination (see supplementary material) and  
121 crushed to powder. 1 gr of the powdered sample was processed for <sup>210</sup>Pb determination by  
122 alpha spectroscopy; the activity of <sup>137</sup>Cs as well as <sup>40</sup>K, <sup>238</sup>U and <sup>232</sup>Th was measured in the  
123 remaining sample by gamma spectroscopy.

#### 124 **3.2 Alpha spectroscopy**

125 <sup>210</sup>Pb activity (half life=22.2 y; Basunia, 2014) was measured indirectly by measuring  
126 the activity of its decay product <sup>210</sup>Po using an Octete Plus alpha spectrometer (ORTEC, Oak  
127 Ridge) equipped with 450 mm<sup>2</sup> silicon dioxide-passivated, ion-implanted detectors. Each  
128 sample was counted for 74-90 hours. Samples were prepared for <sup>210</sup>Po counting 12-24 months  
129 after retrieval of the cores to ensure secular equilibrium with <sup>210</sup>Pb (<sup>210</sup>Po half life=138 d;  
130 Basunia, 2014). Excess <sup>210</sup>Pb (<sup>210</sup>Pb<sub>ex</sub>) in the cores was calculated by subtracting the steady  
131 state activity measured at the bottom of the core from all samples and correcting for  
132 disintegrations during the time elapsed since sampling.

133 Sample preparation for alpha counting was as follows: 450-500 mg of dry crushed  
134 sediments were weighed in a polypropylene centrifuge tube, wetted with 1 ml double distilled  
135 water and acidified with 5 ml concentrated HCl (37%). The samples were vortexed, and then

136 heated to 85°C for 6.5 hours while shaking at 50 rpm. The acid was separated from the solids  
137 by centrifugation and decanted to a flat bottom polyethylene bottle. 40 ml double distilled water  
138 was then added to the sediment tube, centrifuged and decanted to the acid containing bottle  
139 with additional 4 ml of 40 gr/L ascorbic acid. After 30 min, a thin silver disc covered on the  
140 bottom side with an electrical tape (and washed with ethanol and water) was added to the flat  
141 bottom bottle. <sup>210</sup>Po spontaneously adsorbed onto the silver disc during 17 hours of heating to  
142 60°C (Flynn, 1968). All samples from each core were prepared simultaneously with a sediment  
143 sample that served as a repeating internal standard. The measured difference in activity  
144 between duplicates and the internal standard was always lower than 10%. This assured that  
145 measured <sup>210</sup>Pb profiles are consistent and well calibrated against each other. Absolute activity  
146 calibrations were done by adding a spike of <sup>209</sup>Po with known activity into selected samples  
147 from each core at the beginning of the acid leaching.

### 148 3.3 Gamma spectroscopy

149 Gamma ray emission by <sup>137</sup>Cs (half life=30.1 y; Browne and Tuli, 2007), <sup>40</sup>K, <sup>238</sup>U and  
150 <sup>232</sup>Th in the sediment samples was measured using a coaxial high purity germanium detector  
151 based gamma-ray spectrometer (EurisyS-Mesures, France). The detector was coupled with a  
152 4096 channels computer-based multi channel analyzer acquisition board (Gammafast) and  
153 calibrated with standard reference materials P37553 and M30593 (Amersham Int.). Spectrum  
154 acquisition, peak search and energy calibration were carried out using interwinner 4.0 software  
155 (EurisyS-Mesures, France). The background and sample activities of 16-52 gr dry weight  
156 samples were counted for 50,000 s in a Petri dish, using planar geometry, to minimize self-  
157 absorption and achieve higher detection efficiency. The efficiency and resolution of the system  
158 for <sup>137</sup>Cs (peak 661.6 keV) were 2.5% and 1.2keV respectively. <sup>137</sup>Cs activity was calculated  
159 with the equation:

$$160 \quad C = \frac{C_t - C_B}{m \cdot E_\gamma \cdot P_\gamma} \quad (1)$$

161 where m is the sample mass in kg, C<sub>t</sub> is the total counting rate (cps) of the 661 keV peak, C<sub>B</sub> is  
162 the counting rate (cps) of the background, E<sub>γ</sub> and P<sub>γ</sub> are the detection efficiencies and emission  
163 probability, respectively.

164 The gamma detector suffered significant instability during the analyses of core  
165 707Aug11. To correct this artifact, measured <sup>137</sup>Cs activities from core 707Aug11 were divided  
166 by measured <sup>40</sup>K activities. Validity of this correction was verified by the constant <sup>40</sup>K activities

167 with depth measured in core 400Aug11 and in six previously analyzed cores from the same  
168 region (Pittauerová et al., 2014).

### 169 **3.4 Foraminifera picking**

170 10 gr bulk sediment samples were wet sieved through a 250  $\mu\text{m}$  mesh. The  $>250\mu\text{m}$   
171 fraction was collected, dried at  $50^\circ\text{C}$  and used for picking and counting of planktonic  
172 foraminifera shells of the species: *Globigerinoides sacculifer*, *Globigerinoides ruber*,  
173 *Globigerinella siphonifera* and *Orbulina universa*. Species identification was done according  
174 to the handbook of Hottinger et al. (1993).

### 175 **4. A mass conservation model for a sedimentary profile**

176 The concentration of any component entrained in the sediment changes with time as a  
177 function of sedimentation rate, mixing by faunal activity (bioturbation), compaction, and by its  
178 generation/consumption rates. Mathematically, the burial of sediments can be described as  
179 advective transport, coupled to mixing processes that are often approximated as diffusive  
180 transport (Bernier, 1980; Boudreau, 1997; Burdige, 2006; Meysman et al., 2010).

181 Below we provide a mass conservation equation describing the vertical distribution of  
182 the foraminifer *G. sacculifer*, which disappeared from GOA in 1990 (see section 4.1), in order  
183 to evaluate the effect of bioturbation on its sedimentary record. The variable chosen to describe  
184 the distribution of *G. sacculifer* at any depth interval within the sediment was its relative  
185 abundance (the number of *G. sacculifer* individuals out of the total number of planktonic  
186 foraminifera). The relative abundance was used here for the following reasons: 1. It yielded a  
187 smooth vertical distribution as a result of filtering out abrupt variations in the absolute  
188 concentration of foraminifers; 2. The long-term ratio between the other main foraminifera  
189 species (*G. ruber* and *G. siphonifera*), show no change; and 3. The planktonic foraminifera  
190 counted in this study were all in a similar size range and had a pseudo-spherical structure,  
191 suggesting that the bioturbation coefficient is probably identical for all three species. Another  
192 simplification to Eq. 2 is exclusion of the reaction term. This was done since bottom water in  
193 the study area is highly supersaturated with respect to calcite and aragonite. Therefore,  
194 foraminiferal shells in the upper sediments of northern GOA are well-preserved, showing just  
195 mild dissolution patterns (Sultan, 2014). Accordingly, the 1-D mass conservation equation for  
196 vertical distribution of *G. sacculifer* in the upper sedimentary column only includes transport  
197 terms (sedimentation and bioturbation) (Bernier, 1980) :

198 
$$\frac{\partial A}{\partial t} \varphi^s = \frac{\partial}{\partial x} \left[ \varphi^s D_B \frac{\partial A}{\partial x} \right] - \frac{\omega}{\rho^s} \frac{\partial A}{\partial x} \quad (2)$$

199 where A is the relative abundance of *G. sacculifer* (100·*G. sacculifer* shells/ total planktonic  
 200 foraminifera), t is time (years), x depth in the sediment (cm),  $\varphi^s$  the solid volume ( $\varphi^s$   
 201 =1-porosity) assuming steady state porosity (porosity changes only due to compaction),  $D_B$  is  
 202 a mixing coefficient which includes mixing by biological activity and physical processes  
 203 ( $\text{cm}^2 \cdot \text{y}^{-1}$ ),  $\omega$  rate of sediment accumulation ( $\text{gr} \cdot \text{cm}^{-2} \cdot \text{y}^{-1}$ ) and  $\rho^s$  is the solid density ( $=2.70 \pm 0.03$   
 204  $\text{gr} \cdot \text{cm}^{-3}$ , see supporting information for its calculation). The first term on the right hand side of  
 205 Eq. 2 describes the effect of biological and physical mixing as a diffusive process; the second  
 206 term describes the accumulation of new sediment on top of the old sediment surface and the  
 207 following downward compaction of the sediment. Upper boundary condition for the solution  
 208 is a constant flux (J) across the sediment-water interface ( $J_0 = -\varphi^s \cdot D_0 \cdot (\partial A / \partial x) + \varphi^s \cdot \omega \cdot A_0$ ,  
 209 subscript 0 marks the value at the sediment-water interface), lower boundary condition is  
 210  $\partial A / \partial x = 0$ .

211 The equation that describes  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$  activity in the sediment is similar to Eq. 2  
 212 with the addition of an expression which describes their radioactive decay (Meysman et al.,  
 213 2005):

214 
$$\frac{\partial C}{\partial t} \varphi^s = \frac{\partial}{\partial x} \left[ \varphi^s D_B \frac{\partial C}{\partial x} \right] - \frac{\omega}{\rho^s} \frac{\partial C}{\partial x} - \varphi^s \lambda C \quad (3)$$

215 here C is activity and  $\lambda$  the radioactive decay constant ( $\text{y}^{-1}$ ). The upper boundary condition is  
 216 a constant flux in the  $^{210}\text{Pb}_{\text{ex}}$  model and a variable input flux in the  $^{137}\text{Cs}$  model, the lower  
 217 boundary conditions for both radioisotopes are  $C=0$  and  $\partial C / \partial x = 0$ .  $^{210}\text{Pb}_{\text{ex}}$  flux to the sediment  
 218 surface was calculated from its inventory in the sediment by:

219 
$$J = \lambda \cdot \sum (C \varphi^s \rho^s dx) \quad (4)$$

220 where dx is the thickness of the sediment layer.

221 Porosity used for the calculation according to Eqns. 2-4 was fit to the measured porosity  
 222 profiles using the equation:

223 
$$\varphi = -a \cdot \ln(x) + b \quad (5)$$



224 where  $x$  is depth below the sediment-water interface,  $a$  and  $b$  are empirical parameters. The  
225 porosity profiles themselves along with the empirical fits are presented in the online supporting  
226 information. Mixing rates were assumed to decrease exponentially with depth (Cai et al., 2010):

$$227 \quad D_B(x) = D_0 \cdot e^{-x/D_x} \quad (6)$$

228 where  $D_0$  is the mixing coefficient at the sediment-water interface ( $x=0$ ), and  $D_x$  an attenuation  
229 coefficient of the mixing intensity with depth.

#### 230 **4.1 Numerical solution**

231 Eqns. 2 and 3 were solved numerically with MATLAB in their differential form with a  
232 final difference scheme. For the solution the vertical axis was segmented into cells of variable  
233 size, each represents a layer that accumulated during 0.1 y. At each time step all cells shift one  
234 cell downward and a new sediment layer enters the top cell. The bottom cell leaves the solution  
235 scheme. All cells are then mixed with their neighbors. Since the model considers a decrease in  
236 porosity with depth due to compaction, the vertical scale of each cell decreases with depth.

237 The equations are solved iteratively at each time step using Gaussian elimination. The  
238 time derivative was approximated with a backward difference approximation (Hornberger and  
239 Wiberg, 2005). The second derivative in space was approximated by a central difference  
240 approximation and the first derivative in space by a backward difference approximation to  
241 avoid numerical instability as bioturbation approaches zero (Boudreau, 1996).

#### 242 **4.2 Profile formation following the arrival of a pollution spike**

243 As a preliminary assessment of the model predicting exponential decrease in  
244 bioturbation we calculated the process of profile formation following the arrival of a short term  
245 spike. This case examines a base assumption of dating utilizing iridium and cesium which is  
246 the claim that even if diffusion and bioturbation smeared the sedimentary peak, their location  
247 does not shift. This assumption can be analyzed using the mathematical description of diffusion  
248 by Fick's first law (Berner, 1980):

$$249 \quad F = -D \frac{\partial C}{\partial x} \quad (7)$$

250 Eq. 7 states that maximum net transfer of mass due to multiple random small movements  
251 (diffusion) will occur at the location of the maximum gradient in concentration as long as the  
252 diffusion coefficient is constant. In the specific case of bioturbation, the diffusion coefficient

253 is also varying with depth - it is normally high near the surface and declines with depth. The  
254 rapid decline of the bioturbation diffusion coefficient means that in addition to gradients in  
255 concentration, mixing rates will also be controlled by depth in the sediment as the concentration  
256 peak is advected downwards, and mass transfer due to bioturbation will be asymmetric (Fig.  
257 2).

258 A general case for  $^{137}\text{Cs}$ / iridium deposition in sediments may be described as a spike  
259 with very high activity that settles on the sediment-water interface. This spike is initially mixed  
260 downward by burrowing organisms; as more sediment settles on top the bioturbation process  
261 is shifted upward. As a result, the spike is mixed upward for a much longer period of time and  
262 upward mixing of mass is more important than downward mixing. Fig. 3 illustrates the profile  
263 formed should this process mix an inert tracer and the asymmetric nature of its final  
264 distribution. This process was previously shown to explain the shape of iridium anomalies (see  
265 Hull et al., 2011, for a detailed description of the effect varying sedimentation and mixing rates  
266 have on the final shape of the peak) and predict profile formation following pollution events  
267 (Fuller et al., 1999). An important outcome of this simulation is that in this case the peak  
268 position does not move and can be regarded as a reliable indicator of time.

#### 269 **4.3 Bioturbation in a two-layer model**

270 An alternative representation of the above case is assuming that within an upper  
271 “mixed” layer, bioturbation operates much faster than sedimentation. This condition holds if  
272  $\sqrt{D_B \cdot \Delta t} \gg \omega \cdot \Delta t$  for a given time interval,  $\Delta t$ . In this case the sediments within the upper  
273 mixed layer are homogenous; hence, the concentration of any inert solid variable in this layer  
274 is constant. This simple scenario can be expressed numerically to plot the present day  
275 sedimentary profile of any inert variable (that is supplied with the sediments settling on the sea  
276 floor) that underwent a square wave event, e.g., abrupt disappearance of a species from the  
277 water column and its recovery after a period. In this case the change in concentrations with  
278 time within the surface mixed layer is calculated using the following equation:

$$279 \quad C_{ML,i} = C_{ML,i-1} - \frac{C_{ML,i-1} - C_{S,i}}{n_{ML}} \quad (8)$$

280  $C_{ML}$  is the mixed layer concentration of the tracer,  $C_S$  is the concentration in the settling layer,  
281  $n_{ML}$  is the number of cells in the mixed layer,  $i$  stands for the current time step and  $i-1$  for the  
282 previous time step.

283           The two layer model produces large anomalies in the location of the peak (Fig. 4). In  
284 this case, every new sediment layer instantaneously mixes with the layers below it to form a  
285 uniform mixed layer profile. If an event is short termed (lasts only 1 dt) the next layer after the  
286 spike will again contain background concentrations. The bottom part of the former mixed layer  
287 will now stay below the mixed layer and preserve the mixed spike signal while the new  
288 sediment layer mixes with the entire mixed layer and brings its concentration closer to the  
289 background values (Fig. 4a). This means that the spike will appear a few cm too deep (the shift  
290 will equal the depth of the mixed layer - Trauth, 2013). If an event lasts for a longer period of  
291 time, the concentration in the mixed layer gradually approaches the flux to the sediment  
292 surface. As a result, at each time step, the concentration in the last layer that left the mixing  
293 zone will be closer to the event signal than the concentration in the layers below it. At the time  
294 of recovery the peak will therefore always be found in the same depth relative to the surface  
295 (just below the bottom of the mixed layer) and will gradually shift upward relative to the layer  
296 that represents the beginning of the event. The outcome of this calculation is that in the two  
297 layer model the peak location marks the base of the mixed layer at the time of recovery.

298           Guinasso and Schink (1975) modeled the effect of varying mixing to sedimentation  
299 ratios in a two layer model and showed that the degree of peak shifting decreases as  $D_B/\omega$   
300 decreases. As long as there is bioturbation, the two-layer model will always predict that the  
301 peak of a spike will be shifted downward. These anomalies as well as concentration flattening  
302 in the mixed layer do not appear in our data. Therefore, in this manuscript we consider only  
303 the model predicting exponential decrease in bioturbation and do not fit our data using the two-  
304 layer model.

## 305 **5. Results**

### 306 **5.1 *Globigerinoides sacculifer* abundance**

307           *G. sacculifer* comprised over 50% of the planktonic foraminifera in GOA during the  
308 majority of the Holocene and until the mid 1980's based on sediment cores (Reiss et al., 1980),  
309 sediment core tops (Reiss et al., 1974; Siccha et al., 2009), and plankton net tows (Almogi-  
310 Labin, 1984; Bijma et al., 1990; Erez et al., 1991). The last published observation of *G.*  
311 *sacculifer* in GOA by Russell et al. (1994) stated that its proportion from total planktonic  
312 foraminifera was ~5% in 1990. *G. sacculifer* was not found in plankton net tows during a 1992  
313 sampling campaign (Hastings et al., 1996) and was not observed since in the water column  
314 (numerous observation by J. Erez). Its shells are still abundant in sediment core tops. It was

315 assumed for the calculation that *G. sacculifer* distribution with depth in the sediment was  
316 constant until 1990 when it abruptly disappeared from the water column. The field data  
317 constrained this event to 1986-1992 and suggested that it may have been gradual; hence there  
318 is a ~10% uncertainty in calculated sedimentation rates based on this assumption.

319 The recorded disappearance of *G. sacculifer* from GOA's water column provides a well  
320 constrained anchor for sedimentation rate calculations. The sedimentary profile (Fig. 5)  
321 confirms that prior to its disappearance the abundance of *G. sacculifer* compared to the other  
322 large planktonic foraminifera was stable for a long period. It is also clear from this record just  
323 how different the actual event was from the observed sedimentary profile: In contrast to the  
324 rather abrupt disappearance from the water column, the sedimentary record shows a very  
325 gradual decline that started prior to the disappearance of the organism from the water column.  
326 At present *G. sacculifer* shells are still found in the top cores but their abundance declined to  
327 10-50% of its previous steady state abundance (Fig 5).

## 328 **5.2 <sup>137</sup>Cs activity**

329 The artificial radionuclide <sup>137</sup>Cs started to accumulate in the atmosphere in 1952 as a  
330 result of nuclear weapon tests. The atmospheric concentrations of <sup>137</sup>Cs peaked around 1963  
331 and started to decline afterwards (Pennington et al., 1973). Additional spikes of <sup>137</sup>Cs were  
332 released to the atmosphere as a result of the nuclear disasters in Chernobyl, 1986 (Petrinec et  
333 al., 2012) and Fukushima-Daiichi, 2011 (Kawamura et al., 2014). In the sediments, cesium  
334 binds very strongly to micaceous minerals but can exhibit some mobility when bound to other  
335 phases (Hamilton-Taylor and Davison, 1995).

336 In the cores collected on August 2011 (Fig. 6) <sup>137</sup>Cs activity peaked at 5-6 cm depth  
337 and peaked again near the surface. This surface peak was not observed in the cores Pittauerová  
338 et al. (2014) collected during 2007-8 indicating that its source was possibly the fallout from the  
339 March 2011 Fukushima-Daiichi nuclear accident which probably had reached the Red Sea by  
340 eolian deposition. A reconstruction of <sup>137</sup>Cs deposition rates over northern GOA based on the  
341 sedimentary profiles and published data regarding its global dispersion (Clark and Smith, 1988;  
342 Evangeliou et al., 2013; Papastefanou et al., 1995; UNSCEAR, 2000) is plotted in Fig. 7.  
343 Calculated deposition rates were lower than the northern hemisphere mean, probably as a result  
344 of latitudinal variability within the northern hemisphere (UNSCEAR, 2000) and scarcity of wet  
345 precipitation in the region (Clark and Smith, 1988; Pittauerová et al., 2014).

### 346 5.3 <sup>210</sup>Pb activity

347 Dating with <sup>210</sup>Pb takes advantage of variations in the physical properties of different  
348 elements from the <sup>238</sup>U decay series: following the decay of <sup>226</sup>Ra to the noble gas radon (<sup>222</sup>Rn,  
349 half life=3.8 d; Singh et al., 2011) , a significant portion of the radon diffuses upward from  
350 water and soil to the atmosphere (Church and Sarin, 2008). Within three weeks all <sup>222</sup>Rn decays  
351 and turns into <sup>210</sup>Pb via several short lived intermediates. In contrast to radon, lead has very  
352 strong affinity to solids (Yang et al., 2013) and rapidly adsorbs to air borne particles and organic  
353 molecules. It then settles with these particles and accumulates on the sediment surface in excess  
354 of the <sup>210</sup>Pb that form in the sediments from insitu disintegrations of <sup>222</sup>Rn (Church and Sarin,  
355 2008). The fraction of <sup>210</sup>Pb that forms in the sediments from <sup>222</sup>Rn disintegrations (supported  
356 <sup>210</sup>Pb) is assumed to be represented by the constant <sup>210</sup>Pb activity attained below a certain depth  
357 in the sediment. This supported <sup>210</sup>Pb is reduced from measured <sup>210</sup>Pb activities to obtain the  
358 activities of <sup>210</sup>Pb precipitated with settling particles (termed excess lead 210 or <sup>210</sup>Pb<sub>ex</sub>).

359 Model fits to <sup>210</sup>Pb<sub>ex</sub> activity measurements suggest higher sedimentation rates and  
360 lower surface bioturbation rates than the fits to *G. sacculifer* abundance and <sup>137</sup>Cs activity. The  
361 lower <sup>210</sup>Pb<sub>ex</sub> surface mixing coefficient is accompanied by slower attenuation of this  
362 coefficient with depth (Fig. 8 and Table 1). This is probably a result of differences in the  
363 sediment fraction represented by the different materials. Pure minerals and large particles seem  
364 to be rapidly mixed near the sediment-water interface by large organisms while organo-clay  
365 assemblages, to which <sup>210</sup>Pb is adsorbed, may be taken preferentially into the burrows of  
366 benthic organisms. Calculated <sup>210</sup>Pb<sub>ex</sub> fluxes from this study are on average 265±25 Bq·m<sup>-2</sup>·y<sup>-1</sup>.  
367 These values are within the range of average latitudinal continental flux densities for 20-30°N  
368 of 195±110 Bq·m<sup>-2</sup>·y<sup>-1</sup> (Baskaran, 2011). Yet they are significantly higher than the 140±50  
369 Bq·m<sup>-2</sup>·y<sup>-1</sup> Pittauerová et al. (2014) calculated for the same region. Supported <sup>210</sup>Pb activities  
370 we calculated based on the deep core steady state <sup>210</sup>Po activities are comparable to <sup>226</sup>Ra  
371 activity measurements Pittauerová et al. (2014) used in their <sup>210</sup>Pb<sub>ex</sub> calculations.

### 372 5.4 Northern Gulf of Aqaba accumulation and mixing rates

373 Modeled sedimentation and mixing rates calculated in the present study are summarized  
374 in Table 1 and plotted as a time-depth diagram in Fig. 9. In a previous study, sediment  
375 accumulation rates of 40-70 cm·ka<sup>-1</sup> were calculated for northern GOA cores using radiocarbon  
376 dating (Al-Rousan et al., 2004; Arz et al., 2003; Lamy et al., 2006). Accumulation rates ~70  
377 cm·ka<sup>-1</sup> are in agreement with the rates we calculated based on <sup>137</sup>Cs and *G. sacculifer*

378 abundance in cores 520May12, 707Aug11 and 720Jan13 but are lower than the rates we  
379 calculated in the same cores based on  $^{210}\text{Pb}_{\text{ex}}$ . Sedimentation rates in northern GOA were also  
380 calculated by Pittauerová et al. (2014) in six short cores based on  $^{210}\text{Pb}_{\text{ex}}$  and  $^{137}\text{Cs}$   
381 measurements. Their calculated  $^{210}\text{Pb}_{\text{ex}}$  sedimentation rates were higher than the rates  
382 calculated in the present study since they separated sedimentation and bioturbation into two  
383 equations and did not include a mixing term in their  $^{210}\text{Pb}_{\text{ex}}$  sedimentation model. Pittauerová  
384 et al. (2014) also attempted to calculate  $^{137}\text{Cs}$  sedimentation rates in the same cores by assuming  
385 it arrived as a single 1963 spike. This calculation produced very low sedimentation rates which  
386 they considered to be unrealistic.

387 Variations in northern GOA sediment accumulation rates are a function of the local  
388 bathymetry: the lowest accumulation rates from Meteor cruise 44/3 were measured in cores  
389 GeoB 5810-3 and 5804-4, retrieved from the summit of a submerged ridge (the Ayla High)  
390 with increasing rates with water depth (Al-Rousan et al., 2004). Cores for the present study  
391 were all collected west of the Ayla High (Fig. 1). The importance of the local bathymetry in  
392 determining accumulation rates is evident by sediment accumulation rates from the present  
393 study as well (Fig. 9): accumulation rates in core 400Aug11, collected inside a submerged  
394 canyon, are ~60% higher than the accumulation rates outside that canyon (all other cores).

395 Bioturbation coefficients calculated in the present study (Table 1) are ranging between  
396  $0.5\text{-}4\text{ cm}^2\cdot\text{y}^{-1}$  near the sediment-water interface, in general agreement with global averages  
397 from similar depths (Middelburg et al., 1997). The surface values we calculate are higher than  
398 the values calculated by Pittauerová et al. (2014), however this difference can be accounted for  
399 by the different mathematical representation we chose for the coefficient. In the present study  
400 we assumed that bioturbation rates decreased exponentially with depth. Pittauerová et al.  
401 (2014), on the other hand, assumed constant bioturbation in the top 5-8 cm. While both  
402 representations are applied frequently in the literature, the rationale in representing the  
403 bioturbation coefficient as a decreasing exponent rather than a constant mixed layer value is  
404 that it follows the decrease in redox potentials: within the top five cm oxygen, nitrate and  
405 manganese oxides were all completely consumed, gradually creating unfavorable living  
406 conditions for large benthic organisms.

## 407 **6. Discussion**

408 The sedimentation and mixing rate calculations presented in the previous section  
409 verified the appropriateness of the numerical model for time dependent calculations. The next



410 step we had undertaken was to calculate how these records evolved with time based on the  
411 known history of  $^{137}\text{Cs}$  deposition and *G. sacculifer* abundance as well as a possible future  
412 scenario. The objective of these predictions was to use this recent and well-constrained case  
413 study as a tool for the interpretation of high resolution sedimentary records across sharp  
414 transitions.

### 415 **6.1 Predictions of future *Globigerinoides sacculifer* sedimentary profiles**

416 The first scenario we consider is the evolution of the sedimentary record following the  
417 disappearance of a major planktonic species. A reconstruction of the *G. sacculifer* profile  
418 following its disappearance from the water column is presented in Fig. 10a-c. *G. sacculifer*'s  
419 abundance was very high and fairly constant until ~1990 when its flux to the sediment ceased  
420 following its disappearance from the water column. As a result, its abundance in the top  
421 sediments is determined by mixing with deeper sediments and gradually declines. This decline  
422 appears as if it started 30 y before the disappearance event. The model was extended to predict  
423 how the profile will evolve in the future. Fig. 10d predicts that 50 y after the disappearance  
424 event *G. sacculifer* top core abundance will still be very high. In fact, the model predicts that  
425 the relative abundance of *G. sacculifer* will drop below 10% of the large foraminifera only 100  
426 y after its disappearance from the water column and below 1% ~260 y (25 cm) after its  
427 disappearance, using average sedimentation and mixing rates for the region ( $\omega=0.1 \text{ gr}\cdot\text{cm}^{-2}\cdot\text{y}^{-1}$ ,  
428  $D_0=2 \text{ cm}^2\cdot\text{y}^{-1}$ ,  $D_x=1 \text{ cm}$ ). At this point the decline will appear to have started 3 cm before the  
429 abrupt disappearance event and gradually tail 25 cm above it.

430 In the second part of this simulation we consider a scenario in which *G. sacculifer* will  
431 re-appear in GOA's water column in the future. *G. sacculifer* is highly abundant in core tops  
432 from the central and northern parts of the Red Sea (Siccha et al., 2009), meaning that it has a  
433 significant reproduction nucleus if its Red Sea populations did not suffer a similar fate to its  
434 northern GOA population. Its local disappearance from GOA coincided with a period of  
435 increased nutrient load from anthropogenic sources that were only ameliorated in 2008 (Oron  
436 et al., 2014). If indeed this was the cause for its disappearance, it is expected that its population  
437 should recover in the future. For the clarity of presentation, we placed the re-introduction event  
438 50 y after the disappearance to allow the abundance to decrease first (Fig. 10e-g).

439 This sequence of events will produce a minimum representing the disappearance event.  
440 However, the calculated minimum is rather weak, especially in high bioturbation cases and  
441 appears deeper in the sediment column than expected. Within the first years after the repeated

442 appearance, bioturbation will move material from the sacculifer-rich top-core toward the  
443 minimum, fill the former minimum and shift it below the depth representing the re-introduction  
444 event. This process will continue until the minimum will escape the rapid mixing zone. The  
445 final location of the minimum stabilized in this simulation at a depth representing 20 years  
446 before the re-introduction event. The minimum itself falls between the events and does not  
447 represent any of them. The cause for this artifact is the asymmetric nature of bioturbation and  
448 physical mixing which mostly affect the uppermost sediment. In this simulation mixing rates  
449 were assumed to decay exponentially with depth. As a result, the material that accumulates  
450 close to the surface will be shifted downward by mixing while deeper material will barely be  
451 affected, resulting in uneven movement of the sedimentary matter. The minimum will be filled  
452 with *G. sacculifer* shells from above and a deeper layer will contain the lowest number of  
453 shells.

454 As shown above, bioturbation has a marked effect on the interpretation of the  
455 sedimentary record for dating appearances/disappearances of organisms by shifting both the  
456 apparent time of first appearances/disappearances and the apparent time of the peak. The  
457 Signor-Lipps effect (Signor and Lipps, 1982) may add another source of interference to this  
458 interpretation because upon approaching an extinction event the probability of detecting  
459 members of each of the species in an assemblage decreases as a result of sampling biases.  
460 Likewise, the probability of detecting the first appearance of a new species increases with time.  
461 The result of this effect may be that an abrupt disappearance event will appear as a gradual one  
462 in the record. Bioturbation on the other hand causes an organism to appear in the sedimentary  
463 record in layers that are dated to be of an older age than the time of its actual appearance and  
464 to be present in layers that are dated to be of a younger age than the time of its actual  
465 disappearance. Both bioturbation and the Signor-Lipps effect, probably complicated the  
466 interpretation of the K-T boundary mass extinction as a gradual decline (Abramovich et al.,  
467 1998) or an abrupt event (Witts et al., 2015).

## 468 **6.2 Reconstructing the evolution of the $^{137}\text{Cs}$ profile**

469 The deposition of  $^{137}\text{Cs}$  occurred as a series of short term spikes (Fig. 7). This pattern  
470 creates an intermediate case between the long square wave (*G. sacculifer* disappearance-  
471 reappearance) and single spike input functions discussed above.  $^{137}\text{Cs}$  was not found in the  
472 environment until the nuclear bomb experiments of 1945 (Fig. 11a). Its release rates became  
473 significant in 1952 and peaked in 1959 and 1963 (Fig. 7). The peak of 1962-4 was significantly



474 larger than previous emissions, suppressing their peaks to form a single steep increase toward  
475 the surface (Fig 11b). The base of the increase was slightly pushed downward due to  
476 bioturbation making it appear prior to the first release of  $^{137}\text{Cs}$  to the environment. During the  
477 following years the magnitude and numbers of atmospheric nuclear experiments decreased  
478 until they ceased after 1980 (UNSCEAR, 2000). In the sediment, bioturbation mixed the 1963  
479 peak upward into the new sediment that accumulated on top. This significantly lowered the  
480 magnitude of the 1963 peak but did not shift its position (Fig. 11c). The deposition of  
481 Chernobyl fallout in 1986 formed a new surface peak (Fig. 11d) that was quickly mixed  
482 downward toward the 1963 peak. This resulted in a united peak that appeared at the end of the  
483 1970's (Fig. 11e). Adjoining of these peaks due to bioturbation explains why they could not be  
484 separated in a previous study (Pittauerová et al., 2014). Hence, similarly to the long square  
485 wave input case, the influence of bioturbation significantly altered both the shape and location  
486 of the peaks. Running the simulation with the same input function but without radioactive  
487 disintegrations shows virtually the same profile development as the radioactive case but pushes  
488 the united peak downward toward the early 1970's since it increased the size of the 1963 peak.

## 489 **7. Conclusions**

490 Our analysis of the two-layer model (see definition in section 4.3 above) indicates that  
491 in this scenario the sedimentary record preserves the locations of two original depths: 1. the  
492 location of the base of the bioturbation layer at the onset of an event. This depth is marked by  
493 the first appearance of the inert variable; and 2. Location of the base of the bioturbation layer  
494 during termination of the event. This depth is marked by the location of the peak. In practice,  
495 exponentially decreasing bioturbation is suitable for the description of short lived radioisotopes  
496 or records of high sedimentation rates while the homogeneously mixed surface layer is often  
497 used to describe  $^{14}\text{C}$  profiles in deep sea cores or  $^{210}\text{Pb}$  profiles in shelf sediments. Large  
498 anomalies in the peak location observed in the two-layer model (Guinasso and Schink, 1975;  
499 Johannessen and Macdonald, 2012; Löwemark et al., 2008) seem to be an artifact of the discrete  
500 mathematical description of bioturbation in this model as they do not faithfully represent record  
501 formation following punctuated deposition. This suggests that while the two layer model is  
502 often suitable for sedimentation rate calculations it does not provide a reliable description of  
503 the mixing activity and is therefore not recommended for use in sedimentary record  
504 reconstructions.

505           When bioturbation is described as a gradually decreasing function of depth, the peak of  
506 a very short term event is expected to appear in the right position (Fig. 3). However, if a similar  
507 short term event repeats while the first spike is still mixed in the upper sediment, bioturbation  
508 will unify the adjacent peaks (Fig. 11). The united peak will appear at an intermediate depth  
509 that does not necessarily correlate with the actual sedimentary events. In a third case, a  
510 sedimentary event that persisted for longer time and was affected by bioturbation, the peak is  
511 etched on both sides. In this case a flat peak will turn into a sharper one in the record and the  
512 location of the peak appears between the starting and termination of the event (Fig. 10). The  
513 exact location of the peak mostly depends on the length of the event and its shape on the rate  
514 of bioturbation. The likely vertical scale of peak shifting depends on the attenuation of the  
515 bioturbation intensity with depth and will normally be smaller than 10 cm.

516           As a general approach to sedimentary record interpretation we join the conclusion of  
517 Johannessen and Macdonald (2012) that precise description of past events based on  
518 sedimentary records necessitates the use of a mass conservation model. Yet it is imperative to  
519 use a continuous function to describe bioturbation since the discretization of this process into  
520 mixed and unmixed layers automatically shifts the modeled event downward. As long as a  
521 continuous function is used to describe bioturbation, the location of the peak always falls within  
522 the timeframe of the event under question. In most cases, however, it will not precisely  
523 represent the timing of initiation/ termination of the event but rather fall in between them.  
524 Another important implication of the mass balance equations used for reconstructing  
525 sedimentation history is that as long as sedimentation and bioturbation continue without  
526 interruptions no abrupt changes will appear in the record. Therefore, any abrupt change in the  
527 record requires special attention and means that the ratio between bioturbation and  
528 sedimentation rates decreased. Such changes can result for example from turbidity currents,  
529 flash floods, anoxia, and post depositional removal of the top sediments as well as many other  
530 site specific possibilities.

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539 **Glossary**

A	abundance (%)
a.u.	arbitrary units
C	activity ( $\text{Bq}\cdot\text{Kg}^{-1}$ )
$C_B$	background counting rate (counts per second)
$C_{ML}$	mixed layer concentration
$C_S$	concentration in the sedimenting layer
$C_t$	total counting rate (counts per second)
$D_0$	mixing coefficient at the sediment-water interface ( $\text{cm}^2\cdot\text{y}^{-1}$ )
$D_B$	mixing coefficient ( $\text{cm}^2\cdot\text{y}^{-1}$ )
$D_x$	attenuation coefficient of the mixing intensity with depth (cm)
dt	delta t
dx	delta x
$E_\gamma$	detection efficiency
GOA	Gulf of Aqaba
i	current time step
i-1	previous time step
J	flux ( $\text{concentration}\cdot\text{l}^{-2}\cdot\text{t}^{-1}$ )
m	mass (Kg)
$n_{ML}$	number of cells in the mixed layer
$P_\gamma$	emission probability
t	time
x	depth (cm)
$\lambda$	radioactive decay constant ( $\text{y}^{-1}$ )
$\rho^s$	solid density ( $\text{gr}\cdot\text{cm}^{-3}$ )
$\phi$	porosity
$\phi^s$	solid volume
$\omega$	rate of sediment accumulation ( $\text{gr}\cdot\text{cm}^{-2}\cdot\text{y}^{-1}$ )
$^{210}\text{Pb}_{\text{ex}}$	excess lead 210 ( $\text{Bq}\cdot\text{Kg}^{-1}$ )

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730

731 **Figures**

732

733 **Figure 1:** Google Earth images of the study area. (a) Regional map. (b) A bathymetric map  
734 of the northern Gulf of Aqaba showing 20 m isobaths and the locations of the cores used in  
735 this study (redrawn after Tibor et al., 2010).



736 **Figure 2:** Schematic representation of asymmetric transport by bioturbation (Eq. 6). While  
737 bioturbation is often expressed mathematically as a diffusive process, the bioturbation  
738 diffusion coefficient rapidly decreases from high near surface values to ~zero within a few  
739 cm. As a result, transport due to mixing close to the sediment-water interface is much larger  
740 than transport deeper in the sediment regardless of the concentration gradient (the arrows  
741 illustrate the relative size and direction of transport by bioturbation). The illustration shows  
742 how this effect will alter the shape of a symmetrical negative peak. Similarly, increased  
743 transport from above can push the peak downward and place it earlier than the modeled  
744 event.

745 **Figure 3:** Calculated sedimentary profile of an inert spike after 100 y of mixing and  
746 sedimentation (red line), based on the  $^{137}\text{Cs}$  mixing and sedimentation rates of core  
747 400Aug11 (Table 1). The horizontal gray line represents the location and shape of the spike if  
748 sedimentary burial was the only process affecting the formation of the profile. Modeled spike  
749 length is 5000 arbitrary units distributed over a layer that precipitated in 0.5 years (~0.8 mm).

750 **Figure 4:** A two layer model (a homogeneous surface layer mixed by bioturbation overlying  
751 a non-bioturbated layer) for describing the distribution and peak location of an inert  
752 sedimentary variable (black solid) in response to an abrupt disappearing (decrease to 0  
753 arbitrary concentration units, CU) and reappearing (increase to 100 CU) of this sedimentary  
754 variable (gray line). Three different durations of variable disappearance are shown: **a-** 1  
755 arbitrary time unit (TU) long abrupt disappearing/reappearing event; **b-** 10 TU long abrupt  
756 disappearing/reappearing event; **c-** 20 TU long abrupt disappearing/reappearing event. The  
757 sedimentation rate in all cases is constant and hence the time is linearly correlated to depth  
758 within the core, where 50 TU marks the interface between bottom water and sediment  
759 surface; and the thickness of the bioturbation layer is equivalent to the sediment layer that  
760 accumulates during 10 TU. The gray line represents the timing and duration of the  
761 disappearing/reappearing events in each of the 3 cases and the concentration of the  
762 sedimentary variable until the disappearing event (starting at 15 TU) was taken to be 100 CU.  
763 In all 3 cases the model reveals four distinct features regarding the sedimentary record of the  
764 inert variable: 1. It starts to decrease at the bottom of the mixed layer during the time of  
765 disappearance; 2. The minimum peak appears at the bottom of the mixed layer during time  
766 of reappearance; 3. The shorter the duration of the disappearance/reappearance event, the  
767 earlier the “apparent” time of the minimum peak, it may even appear “earlier” than the time  
768 of the “real” disappearing event (e.g. plate **a**); and 4. The interval of the observed decrease in  
769 the variable (from concentration maximum to concentration minimum in the solid line) is  
770 equal to the duration of the disappearance event.

771 **Figure 5:** model fit (solid line) to *Globigerinoides sacculifer* counts (open circles) based on  
772 the assumptions that it disappeared from the water column at 1990 and the total abundance of  
773 *G. ruber* and *G. siphonifera* in the water column remained constant.

774

775 **Figure 6:** Model fit (solid lines) to  $^{137}\text{Cs}$  activity concentrations in cores 400A11 and 707A11  
776 (open circles). Average counting statistic error was 30% for core 400A11 and 45% for core  
777 707A11.  $^{137}\text{Cs}$  activities from core 707A11 were divided by the measured  $^{40}\text{K}$  activities to  
778 correct for instrumental instability during the analysis of this core.

779 **Figure 7:** Reconstructed  $^{137}\text{Cs}$  deposition history in the northern Gulf of Aqaba. Fallout data  
780 due to atmospheric nuclear testing was derived from UNSCEAR report (2000).  $^{137}\text{Cs}$  fallout  
781 due to the Chernobyl accident was based on the measurements of Papastefanou et al. (1995)  
782 divided by two to account for the double distance of Eilat from Chernobyl. Fallout from  
783 Fukushima-Daiichi over this region was derived from the estimate of Evangeliou et al.  
784 (2013). Since there was large longitudinal variability in bomb fallout deposition rates within  
785 the northern hemisphere (UNSCEAR, 2000) and a significant portion of the atmospheric  
786  $^{137}\text{Cs}$  normally reaches the ground as wet deposition (Clark and Smith, 1988), it was  
787 predicted that  $^{137}\text{Cs}$  deposition in this hyper arid region should be lower than the northern  
788 hemisphere average. This was confirmed in the model fit to the data which required that  
789 deposition rates in the Gulf of Aqaba were one third lower than the average northern  
790 hemisphere rates.

791

792 **Figure 8:** Model fit to excess  $^{210}\text{Pb}$  data (solid lines). Black dots are measured excess  $^{210}\text{Pb}$   
793 activities; error bars mark the average difference between duplicate measurements for cores  
794 400Aug11, 707Aug11 and 720Jan13.

795 **Figure 9:** A time-depth plot for the cores dated in this study assuming constant sedimentation  
796 rates. Accumulation rates used for generating the plot were the average of the rates calculated  
797 using the different dating methods (Table 1). The curvature of the lines stems from the  
798 decrease in porosity with depth (see supplementary material for porosity data). Note that the  
799 techniques applied in this work are only suitable for dating sediments from the last century.

800



801 **Figure 10:** Reconstructed and predicted future *G. sacculifer* relative abundance assuming  
802  $S=0.1 \text{ gr}\cdot\text{cm}^{-2}\cdot\text{y}^{-1}$ ,  $D_0=2 \text{ cm}^2\cdot\text{y}^{-1}$ ,  $D_x=1 \text{ cm}$ . The plots were drawn for the following scenario:  
803 *G. sacculifer* was the dominant planktonic foraminifer until it abruptly disappeared at 1990  
804 and will not appear in the water column for 50 y. After 50 y of absence it will return to the  
805 region and quickly resume its past abundance. To eliminate the effects of compaction and  
806 moving upper boundary due to sedimentation, the model results are plotted as accumulation  
807 of sediment on top of the 1900 layer with time. Each of the vertical gridlines marks the range  
808 0-80%. a- the profile at 1990, b-2000, c-2015 (present), d-2040 (50 y after the disappearance  
809 event), e-2045 (5 y after re-appearance), f-2090 (50 y after re-appearance), g-2140 (100 y  
810 after re-appearance).

811

812 **Figure 11:** Reconstructed  $^{137}\text{Cs}$  profile development with time in core 400Aug11 showing  
813  $^{137}\text{Cs}$  activity in the accumulating sediments above a fixed reference depth. a-the profile at  
814 1944, b-1964, c-1985, d-1987, e-2005, f-2011. Empty circles in f are the raw data points used  
815 for sedimentation and mixing rate calculations (Fig. 6a).

816 **Table 1:** Summary of calculated sediment accumulation ( $\omega$ ) and mixing rates by the mass  
817 balance model in the 4 cores utilized in this study from  $^{210}\text{Pb}_{\text{ex}}$  activity, *G. sacculifer* shell  
818 counts and  $^{137}\text{Cs}$  activity.