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

Steiner Zvi[1*], Lazar Boaz[1], Levi Shani[1], Tsroya Shimon[2], Pelled Omer[2], Bookman Revital[3] and Erez Jonathan[1]

[1] The Fredy and Nadine Herrmann Institute of Earth Sciences, The Hebrew University, Jerusalem, 91904, Israel

[2] Nuclear Research Center Negev, POB 9001, 84190, Beer Sheva, Israel

[3] Dr. Moses Strauss Department of Marine Geosciences, Leon H. Charney School of Marine Sciences, University of Haifa, Israel

[*] Corresponding author (zvika.steiner@mail.huji.ac.il)

Abstract

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

Keywords:

^{137}Cs, ^{210}Pb, recent sediments, *Globigerinoides sacculifer*, event deconvolution, advection diffusion reaction model

1. Introduction

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

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

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

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

2. Study site

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

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

3. Materials and Methods

3.1 Sampling

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

3.2 Alpha spectroscopy

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

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

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

3.3 Gamma spectroscopy

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

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

where m is the sample mass in kg, C_t is the total counting rate (cps) of the 661 keV peak, C_B is the counting rate (cps) of the background, E_γ and P_γ are the detection efficiencies and emission probability, respectively.

The gamma detector suffered significant instability during the analyses of core 707Aug11. To correct this artifact, measured ^{137}Cs activities from core 707Aug11 were divided by measured ^{40}K activities. Validity of this correction was verified by the constant ^{40}K activities

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

3.4 Foraminifera picking

10 gr bulk sediment samples were wet sieved through a 250 μm mesh. The >250μm fraction was collected, dried at 50˚C and used for picking and counting of planktonic foraminifera shells of the species: *Globigerinoides sacculifer, Globigerinoides ruber, Globigerinella siphonifera* and *Orbulina universa*. Species identification was done according to the handbook of Hottinger et al. (1993).

4. A mass conservation model for a sedimentary profile

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

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

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

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), φ^s the solid volume (φ^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 ($cm^2 \cdot y^{-1}$), ω rate of sediment accumulation ($gr \cdot cm^{-2} \cdot y^{-1}$) and ρ^s is the solid density (=2.70±0.03
204 $gr \cdot cm^{-3}$, 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 $^{210}Pb_{ex}$ and ^{137}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 $$\frac{\partial C}{\partial t}\varphi^s = \frac{\partial}{\partial x}\left[\varphi^s D_B \frac{\partial C}{\partial x}\right] - \frac{\omega}{\rho^s}\frac{\partial C}{\partial x} - \varphi^s \lambda C \qquad (3)$$

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

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

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

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

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

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

4.1 Numerical solution

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

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

4.2 Profile formation following the arrival of a pollution spike

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

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

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

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

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

4.3 Bioturbation in a two-layer model

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

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

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

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

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

5. Results

5.1 *Globigerinoides sacculifer* abundance

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

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

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

5.2 ^{137}Cs activity

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

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

5.3 ^{210}Pb activity

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

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

5.4 Northern Gulf of Aqaba accumulation and mixing rates

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

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

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

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

6. Discussion

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

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

6.1 Predictions of future *Globigerinoides sacculifer* sedimentary profiles

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

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

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

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

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

6.2 Reconstructing the evolution of the ^{137}Cs profile

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

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

7. Conclusions

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

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

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

Acknowledgements

We thank Timor Katz, Sefi Baruch, Asaph Rivlin and Moti Ohavia for their assistance before and during the cruises. Adam Levi and Michael Ben-Haroush provided valuable technical assistance during the experimental work. Nimer Taha performed the ^{210}Pb activity calibrations. We thank Aviv Bachan and Eyal Wurgaft for their helpful comments on a previous version of this manuscript. This study was supported by the University of Calgary CCS Initiative. An Eshkol fellowship from the Israeli Ministry of Science and Technology and a research grant from the Interuniversity Institute for Marine Science in Eilat supported ZS.

Glossary

A	abundance (%)
a.u.	arbitrary units
C	activity ($Bq \cdot Kg^{-1}$)
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 ($cm^2 \cdot y^{-1}$)
D_B	mixing coefficient ($cm^2 \cdot y^{-1}$)
D_x	attenuation coefficient of the mixing intensity with depth (cm)
dt	delta t
dx	delta x
E_γ	detection efficiency
GOA	Gulf of Aqaba
i	current time step
i-1	previous time step
J	flux ($concentration \cdot l^{-2} \cdot t^{-1}$)
m	mass (Kg)
n_{ML}	number of cells in the mixed layer
P_γ	emission probability
t	time
x	depth (cm)
λ	radioactive decay constant (y^{-1})
ρ^s	solid density ($gr \cdot cm^{-3}$)
φ	porosity
φ^s	solid volume
ω	rate of sediment accumulation ($gr \cdot cm^{-2} \cdot y^{-1}$)
$^{210}Pb_{ex}$	excess lead 210 ($Bq \cdot Kg^{-1}$)

References

Abramovich, S., Almogi-Labin, A. and Benjamini, C. (1998) Decline of the Maastrichtian pelagic ecosystem based on planktic foraminifera assemblage change: Implication for the terminal Cretaceous faunal crisis. Geology 26, 63-66.

Al-Rousan, S., Patzold, J., Al-Moghrabi, S. and Wefer, G. (2004) Invasion of anthropogenic CO_2 recorded in planktonic foraminifera from the northern Gulf of Aqaba. International Journal of Earth Sciences 93, 1066-1076.

Aller, R.C. (2014) Sedimentary diagenesis, depositional environments, and benthic fluxes, in: Holland, H.D., Turekian, K.K. (Eds.), Treatise on Geochemistry, 2nd ed. Elsevier, Oxford, pp. 293-334.

Almogi-Labin, A. (1984) Population dynamics of planktic foraminifera and pteropoda Gulf of Aqaba, Red-Sea. Proceedings of the Koninklijke Nederlandse Akademie Van Wetenschappen Series B-Palaeontology Geology Physics Chemistry Anthropology 87, 481-511.

Arz, H.W., Lamy, F., Patzold, J., Muller, P.J. and Prins, M. (2003) Mediterranean moisture source for an early-Holocene humid period in the northern Red Sea. Science 300, 118-121.

Bard, E., Arnold, M., Duprat, J., Moyes, J. and Duplessy, J.C. (1987) Reconstruction of the last deglaciation: deconvolved records of delta O-18 profiles, micropaleontological variations and accelerator mass spectrometric C-14 dating. Climate Dynamics 1, 101-112.

Baskaran, M. (2011) Po-210 and Pb-210 as atmospheric tracers and global atmospheric Pb-210 fallout: a Review. Journal of Environmental Radioactivity 102, 500-513.

Basunia, M.S. (2014) Nuclear Data Sheets for A=210. Nuclear Data Sheets 121, 561-693.

Ben Avraham, Z., Garfunkel, Z., Almagor, G. and Hall, J.K. (1979) Continental breakup by a leaky transform: The Gulf of Elat (Aqaba). Science 206, 214-216.

Bentley, S.J., Sheremet, A. and Jaeger, J.M. (2006) Event sedimentation, bioturbation, and preserved sedimentary fabric: Field and model comparisons in three contrasting marine settings. Continental Shelf Research 26, 2108-2124.

Berger, W.H. and Heath, G.R. (1968) Vertical mixing in pelagic sediments. Journal of Marine Research 26, 134-&.

Berger, W.H., Johnson, R.F. and Killingley, J.S. (1977) 'Unmixing' of the deep-sea record and the deglacial meltwater spike. Nature 269, 661-663.

Berner, R.A. (1980) Early diagenesis : A theoretical approach. Princeton University Press, Princeton, N.J.

Bijma, J., Erez, J. and Hemleben, C. (1990) Lunar and semi-lunar reproductive cycles in some spinose planktonic foraminifers. Journal of Foraminiferal Research 20, 117-127.

Biton, E. and Gildor, H. (2011) Stepwise seasonal restratification and the evolution of salinity minimum in the Gulf of Aqaba (Gulf of Eilat). Journal of Geophysical Research-Oceans 116.

Black, K.D., Calder, L.A., Nickell, T.D., Sayer, M.D.J., Orr, H., Brand, T., Cook, E.J., Magill, S.H., Katz, T., Eden, N., Jones, K.J., Tsapakis, M. and Angel, D. (2012) Chlorophyll, lipid profiles and bioturbation in sediments around a fish cage farm in the Gulf of Eilat, Israel. Aquaculture 356, 317-327.

Boer, W., van den Bergh, G.D., de Haas, H., de Stigter, H.C., Gleles, R. and van Weering, T.C.E. (2006) Validation of accumulation rates in Teluk Banten (Indonesia) from commonly applied ^{210}Pb models, using the 1883 Krakatau tephra as time marker. Marine Geology 227, 263-277.

Boudreau, B.P. (1994) Is burial velocity a master parameter for bioturbation? Geochimica et Cosmochimica Acta 58, 1243-1249.

Boudreau, B.P. (1996) A method-of-lines code for carbon and nutrient diagenesis in aquatic sediments. Computers & Geosciences 22, 479-496.

Boudreau, B.P. (1997) Diagenetic models and their implementation. Springer.

Browne, E. and Tuli, J.K. (2007) Nuclear data sheets for A=137. Nuclear Data Sheets 108, 2173-2318.

Burdige, D.J. (2006) Geochemistry of marine sediments. Princeton University Press, Princeton, NJ.

Cai, W.J., Luther, G.W., III, Cornwell, J.C. and Giblin, A.E. (2010) Carbon cycling and the coupling between proton and electron transfer reactions in aquatic sediments in Lake Champlain. Aquatic Geochemistry 16, 421-446.
Chen, Y., Mills, S., Street, J., Golan, D., Post, A., Jacobson, M. and Paytan, A. (2007) Estimates of atmospheric dry deposition and associated input of nutrients to Gulf of Aqaba seawater. Journal of Geophysical Research-Atmospheres 112.
Church, T.M. and Sarin, M.M. (2008) U- and Th- series nuclides in the atmosphere: Supply, exchange, scavenging, and applications to aquatic processes, in: Krishnaswami, S., Cochran, J.K. (Eds.), U-Th Series Nuclides in Aquatic Systems. Elsevier, pp. 11-47.
Clark, M.J. and Smith, F.B. (1988) Wet and dry deposition of Chernobyl releases. Nature 332, 245-249.
Erez, J., Almogi-Labin, A. and Avraham, S. (1991) On the life history of planktonic foraminifera: Lunar reproduction cycle in Globigerinoides sacculifer (Brady). Paleoceanography 6, 295-306.
Evangeliou, N., Balkanski, Y., Cozic, A. and Moller, A.P. (2013) Global transport and deposition of ^{137}Cs following the Fukushima nuclear power plant accident in Japan: Emphasis on Europe and Asia using high-resolution model versions and radiological impact assessment of the human population and the environment using interactive tools. Environmental Science & Technology 47, 5803-5812.
Flach, E. and Heip, C. (1996) Vertical distribution of macrozoobenthos within the sediment on the continental slope of the Goban Spur area (NE Atlantic). Marine Ecology Progress Series 141, 55-66.
Flynn, W.W. (1968) The determination of low levels of polonium-210 in environmental materials. Analytica Chimica Acta 43, 221-227.
Fuller, C.C., van Geen, A., Baskaran, M. and Anima, R. (1999) Sediment chronology in San Francisco Bay, California, defined by ^{210}Pb, ^{234}Th, ^{137}Cs, and ^{239,240}Pu. Marine Chemistry 64, 7-27.
Guinasso, N.L. and Schink, D.R. (1975) Quantitative estimates of biological mixing rates in abyssal sediments. Journal of Geophysical Research-Oceans and Atmospheres 80, 3032-3043.
Hamilton-Taylor, J. and Davison, W. (1995) Redox-driven cycling of trace elements in lakes, in: Lerman, A., Imboden, D.M., Gat, J.R. (Eds.), Physics and Chemistry of Lakes, Second edition ed. Springer, Berlin Heidelberg, pp. 217-264.
Hastings, D.W., Emerson, S.R., Erez, J. and Nelson, B.K. (1996) Vanadium in foraminiferal calcite: Evaluation of a method to determine paleo-seawater vanadium concentrations. Geochimica et Cosmochimica Acta 60, 3701-3715.
Hines, A.H. and Comtois, K.L. (1985) Vertical distribution of infauna in sediments of a subestuary of central Chesapeake Bay. Estuaries 8, 296-304.
Hornberger, G. and Wiberg, P. (2005) Numerical methods in the hydrological sciences. American Geophysical Union.
Hottinger, L., Halicz, E. and Reiss, Z. (1993) Recent foraminiferida from the Gulf of Aqaba, Red Sea. Slovenska Akademija Znanosti in Umetnosti, Ljubljana.
Hull, P.M., Franks, P.J.S. and Norris, R.D. (2011) Mechanisms and models of iridium anomaly shape across the Cretaceous-Paleogene boundary. Earth and Planetary Science Letters 301, 98-106.
Johannessen, S.C. and Macdonald, R.W. (2012) There is no 1954 in that core! Interpreting sedimentation rates and contaminant trends in marine sediment cores. Marine Pollution Bulletin 64, 675-678.
Katz, T., Ginat, H., Eyal, G., Steiner, Z., Braun, Y., Shalev, S. and Goodman-Tchernov, B.N. (2015) Desert flash floods form hyperpycnal flows in the coral-rich Gulf of Aqaba, Red Sea. Earth and Planetary Science Letters 417, 87-98.
Kawamura, H., Kobayashi, T., Furuno, A., Usui, N. and Kamachi, M. (2014) Numerical simulation on the long-term variation of radioactive cesium concentration in the North Pacific due to the Fukushima disaster. Journal of Environmental Radioactivity 136, 64-75.
Klaminder, J., Appleby, P., Crook, P. and Renberg, I. (2012) Post-deposition diffusion of ^{137}Cs in lake sediment: Implications for radiocaesium dating. Sedimentology 59, 2259-2267.

Kramer, K.J.M., Misdorp, R., Berger, G. and Duijts, R. (1991) Maximum pollutant concentrations at the wrong depth: a misleading pollution history in a sediment core. Marine Chemistry 36, 183-198.
Krumins, V., Gehlen, M., Arndt, S., Van Cappellen, P. and Regnier, P. (2013) Dissolved inorganic carbon and alkalinity fluxes from coastal marine sediments: model estimates for different shelf environments and sensitivity to global change. Biogeosciences 10, 371-398.
Lamy, F., Arz, H.W., Bond, G.C., Bahr, A. and Patzold, J. (2006) Multicentennial-scale hydrological changes in the Black Sea and northern Red Sea during the Holocene and the Arctic/North Atlantic oscillation. Paleoceanography 21.
Lazar, B., Erez, J., Silverman, J., Rivlin, T., Rivlin, A., Dray, M., Meeder, E. and Iluz, D. (2008) Recent environmental changes in the chemical-biological oceanography of the Gulf of Aqaba (Eilat), in: Por, F.D. (Ed.), Aqaba-Eilat, the improbable gulf. Environment, biodiversity and preservation. Magnes Press, Jerusalem.
Löwemark, L., Konstantinou, K.I. and Steinke, S. (2008) Bias in foraminiferal multispecies reconstructions of paleohydrographic conditions caused by foraminiferal abundance variations and bioturbational mixing: A model approach. Marine Geology 256, 101-106.
Maire, O., Lecroart, P., Meysman, F., Rosenberg, R., Duchene, J.C. and Gremare, A. (2008) Quantification of sediment reworking rates in bioturbation research: a review. Aquatic Biology 2, 219-238.
Meysman, F.J.R., Boudreau, B.P. and Middelburg, J.J. (2005) Modeling reactive transport in sediments subject to bioturbation and compaction. Geochimica et Cosmochimica Acta 69, 3601-3617.
Meysman, F.J.R., Boudreau, B.P. and Middelburg, J.J. (2010) When and why does bioturbation lead to diffusive mixing? Journal of Marine Research 68, 881-920.
Middelburg, J.J., Soetaert, K. and Herman, P.M.J. (1997) Empirical relationships for use in global diagenetic models. Deep-Sea Research Part I-Oceanographic Research Papers 44, 327-344.
Müller, P.J. and Suess, E. (1979) Productivity, sedimentation rate, and sedimentary organic matter in the oceans-1. Organic carbon preservation. Deep-Sea Research Part I-Oceanographic Research Papers 26, 1347-1362.
Oron, S., Angel, D., Goodman-Tchernov, B., Merkado, G., Kiflawi, M. and Abramovich, S. (2014) Benthic foraminiferal response to the removal of aquaculture fish cages in the Gulf of Aqaba-Eilat, Red Sea. Marine Micropaleontology 107, 8-17.
Papastefanou, C., Ioannidou, A., Stoulos, S. and Manolopoulou, M. (1995) Atmospheric deposition of cosmogenic ^{7}Be and ^{137}Cs from fallout of the Chernobyl accident. Science of the Total Environment 170, 151-156.
Peng, T.H., Broecker, W.S. and Berger, W.H. (1979) Rates of benthic mixing in deep-sea sediment as determined by radioactive tracers. Quaternary Research 11, 141-149.
Pennington, W., Cambray, R.S. and Fisher, E.M. (1973) Observations on lake sediments using fallout ^{137}Cs as a tracer. Nature 242, 324-326.
Petrinec, B., Franic, Z., Ilijanic, N., Miko, S., Strok, M. and Smodis, B. (2012) Estimation of sedimentation rate in the Middle and South Adriatic Sea using ^{137}Cs. Radiation Protection Dosimetry 151, 102-111.
Pittauerová, D., Kirchner, G., Garbe-Schönberg, D., Herut, B., Nishri, A. and Fischer, H.W. (2014) Radionuclides and recent sedimentation and mixing rates in Northern Gulf of Eilat/Aqaba, Red Sea. Journal of Marine Systems 139, 1-8.
Reiss, Z., Halicz, E. and Perelis, L. (1974) Planktonic foraminiferida from recent sediments in Gulf of Elat. Israel Journal of Earth Sciences 23, 69-105.
Reiss, Z. and Hottinger, L. (1984) The Gulf of Aqaba: Ecological micropaleontology. Springer Berlin Heidelberg.
Reiss, Z., Luz, B., Almogilabin, A., Halicz, E., Winter, A., Wolf, M. and Ross, D.A. (1980) Late Quaternary paleoceanography of the Gulf of Aqaba (Elat), Red Sea. Quaternary Research 14, 294-308.

689 Russell, A.D., Emerson, S., Nelson, B.K., Erez, J. and Lea, D.W. (1994) Uranium in foraminiferal calcite
690 as a recorder of seawater uranium concentrations. Geochimica et Cosmochimica Acta 58, 671-681.
691 Schiffelbein, P. (1985) Extracting the benthic mixing impulse response function: a constrained
692 deonvolution technique. Marine Geology 64, 313-336.
693 Siccha, M., Trommer, G., Schulz, H., Hemleben, C. and Kucera, M. (2009) Factors controlling the
694 distribution of planktonic foraminifera in the Red Sea and implications for the development of
695 transfer functions. Marine Micropaleontology 72, 146-156.
696 Signor, P.W.I. and Lipps, J.H. (1982) Sampling bias, gradual extinction patterns and catastrophes in
697 the fossil record in: Silver, L.T., Schultz, P.H. (Eds.), Geological implications of impacts of large
698 asteroids and comets on the Earth. Geological Society of America Special Paper, pp. 291-296.
699 Singh, S., Jain, A.K. and Tuli, J.K. (2011) Nuclear Data Sheets for A=222. Nuclear Data Sheets 112,
700 2851-2886.
701 Steiner, Z., Erez, J., Shemesh, A., Yam, R., Katz, A. and Lazar, B. (2014) Basin-scale estimates of
702 pelagic and coral reef calcification in the Red Sea and Western Indian Ocean. Proceedings of the
703 National Academy of Sciences of the United States of America 111, 16303-16308.
704 Suess, E. (1980) Particulate organic carbon flux in the oceans - surface productivity and oxygen
705 utilization. Nature 288, 260-263.
706 Sultan, S. (2014) Global and local anthropogenic influences on the recent sedimentary record of the
707 Gulf of Eilat, Institute of Earth Sciences. The Hebrew University, Jerusalem, p. 71.
708 Tibor, G., Niemi, T.M., Ben-Avraham, Z., Al-Zoubi, A., Sade, R.A., Hall, J.K., Hartman, G., Akawi, E.,
709 Abueladas, A. and Al-Ruzouq, R. (2010) Active tectonic morphology and submarine deformation of
710 the northern Gulf of Eilat/Aqaba from analyses of multibeam data. Geo-Marine Letters 30, 561-573.
711 Trauth, M.H. (2013) TURBO2: A MATLAB simulation to study the effects of bioturbation on
712 paleoceanographic time series. Computers & Geosciences 61, 1-10.
713 Trauth, M.H., Sarnthein, M. and Arnold, M. (1997) Bioturbational mixing depth and carbon flux at
714 the seafloor. Paleoceanography 12, 517-526.
715 Tromp, T.K., Van Cappellen, P. and Key, R.M. (1995) A global model for the early diagenesis of
716 organic carbon and organic phosphorus in marine sediments. Geochimica et Cosmochimica Acta 59,
717 1259-1284.
718 UNSCEAR (2000) Exposures to the public from man-made sources of radiation, Sources and effects
719 of ionizing radiation. United Nations, New York, pp. 157-291.
720 Wheatcroft, R.A. and Drake, D.E. (2003) Post-depositional alteration and preservation of
721 sedimentary event layers on continental margins, I. The role of episodic sedimentation. Marine
722 Geology 199, 123-137.
723 Witts, J.D., Bowman, V.C., Wignall, P.B., Crame, J.A., Francis, J.E. and Newton, R.J. (2015) Evolution
724 and extinction of Maastrichtian (Late Cretaceous) cephalopods from the Lopez de Bertodano
725 Formation, Seymour Island, Antarctica. Palaeogeography Palaeoclimatology Palaeoecology 418, 193-
726 212.
727 Yang, W., Guo, L., Chuang, C.-Y., Schumann, D., Ayranov, M. and Santschi, P.H. (2013) Adsorption
728 characteristics of ^{210}Pb, ^{210}Po and ^{7}Be onto micro-particle surfaces and the effects of macromolecular
729 organic compounds. Geochimica et Cosmochimica Acta 107, 47-64.

730

Figures

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

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

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

Figure 4: A two layer model (a homogeneous surface layer mixed by bioturbation overlying a non-bioturbated layer) for describing the distribution and peak location of an inert sedimentary variable (black solid) in response to an abrupt disappearing (decrease to 0 arbitrary concentration units, CU) and reappearing (increase to 100 CU) of this sedimentary variable (gray line). Three different durations of variable disappearance are shown: **a-** 1 arbitrary time unit (TU) long abrupt disappearing/reappearing event; **b-** 10 TU long abrupt disappearing/reappearing event; **c-** 20 TU long abrupt disappearing/reappearing event. The sedimentation rate in all cases is constant and hence the time is linearly correlated to depth within the core, where 50 TU marks the interface between bottom water and sediment surface; and the thickness of the bioturbation layer is equivalent to the sediment layer that accumulates during 10 TU. The gray line represents the timing and duration of the disappearing/reappearing events in each of the 3 cases and the concentration of the sedimentary variable until the disappearing event (starting at 15 TU) was taken to be 100 CU. In all 3 cases the model reveals four distinct features regarding the sedimentary record of the inert variable: 1. It starts to decrease at the bottom of the mixed layer during the time of disappearance; 2. The minimum peak appears at the bottom of the mixed layer during time of reappearance; 3. The shorter the duration of the disappearance/reappearance event, the earlier the "apparent" time of the minimum peak, it may even appear "earlier" than the time of the "real" disappearing event (e.g. plate **a**); and 4. The interval of the observed decrease in the variable (from concentration maximum to concentration minimum in the solid line) is 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}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}Cs activities from core 707A11 were divided by the measured ^{40}K activities to
778 correct for instrumental instability during the analysis of this core.

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

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

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

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

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

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