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

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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

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processes such as: organic matter remineralization, sediment mixing by burrowing organisms, physical sediment transport processes and variations in sediment accumulation rates (Berner, 1980; Aller, 2014). 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 (Kramer et al., 1991; Klaminder et al., 2012) 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 (Berger et al., 1977; Schiffelbein, 1985; Bard et al., 1987; 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 (Wheatcroft and Drake, 2003; Bentley et al., 2006). 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 (Müller and Suess, 1979; Suess, 1980; Boudreau, 1994; Tromp et al., 1995; Middelburg et al., 1997; Trauth et al., 1997); 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 (Hines and Comtois, 1985; Flach and Heip, 1996). 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 (Lazar et al., 2008; Black et al., 2012; 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