Baseline

Determination of sedimentation, diffusion, and mixing rates in coastal sediments of the eastern Red Sea via natural and anthropogenic fallout radionuclides

Bandar A. Al-Mur[a,b], Andrew N. Quicksall[b,*], James M. Kaste[c]

[a] Department of Environmental Sciences, King Abdul-Aziz University, Jeddah 21589, Saudi Arabia
[b] Civil and Environmental Engineering, Southern Methodist University, Dallas, TX 75275, USA
[c] Geology Department, College of William & Mary, Williamsburg, VA 23188, USA

A R T I C L E   I N F O

A B S T R A C T

The Red Sea is a unique ecosystem with high biodiversity in one of the warmest regions of the world. In the last five decades, Red Sea coastal development has rapidly increased. Sediments from continental margins are delivered to depths by advection and diffusion-like processes which are difficult to quantify yet provide invaluable data to researchers. Beryllium-7, lead-210 and ceseium-137 were analyzed from sediment cores from the near-coast Red Sea near Jeddah, Saudi Arabia. The results of this work are the first estimates of diffusion, mixing, and sedimentation rates of the Red Sea coastal sediments. Maximum chemical diffusion and particle mixing rates range from 69.1 to 380 $cm^{-2} y^{-1}$ and 2.54 to 6.80 $cm^{-2} y^{-1}$, respectively. Sedimentation rate is constrained to approximately 0.6 cm/yr via multiple methods. These data provide baselines for tracking changes in various environmental problems including erosion, marine benthic ecosystem silting, and particle-bound contaminant delivery to the seafloor.

The Red Sea represents a complex marine ecosystem with unique biological diversity and an important shipping lane linking the world's major oceans (Ghandour et al., 2014). The Red Sea comprises the main route from Europe to India and Eastern Asia and is linked with the Indian Ocean at the southeastern end (Chung et al., 1982). The coastline of the Kingdom of Saudi Arabia is about 1840 km in length, accounting for 79% of the eastern seaboard of the Red Sea (Pan et al., 2011). Saudi Arabia has undergone a rapid transformation from an under-developed state, with severe constraints, to a modern industrial country (Badr et al., 2009; Al-Mur et al., 2017). The impact of anthropogenic activities on the sediments of the Red Sea has increased and become a major concern (Badr et al., 2009; Pan et al., 2011; Ghandour et al., 2014, Al-Mur et al., 2017). Despite its ecological importance, high biodiversity and endemism, the Red Sea region has been the subject of relatively few research studies (Berumen et al., 2013). There is a lack of information about the concentrations of natural and anthropogenic radionuclides from Saudi Arabian coastal regions of the Red Sea. There are no quantitative data in the current body of literature showing the chemical diffusion, mixing, or sedimentation rates from the eastern side of the Red Sea. Thus collection of these data is vital to understanding many processes including the behavior of contaminants. Contaminants are delivered to depths in sedimentary systems by advection (burial) and diffusion processes; however, these processes can be difficult to quantify in complex ecosystems. There is a clear need to identify the sedimentation processes on the Red Sea via natural and anthropogenic radionuclides. Radionuclides are introduced via fallout from the atmosphere into the marine surface water column and bind to suspended particles by physical, chemical, and biological processes (Kumar et al., 2013). ^{210}Pb is a natural occurring radionuclide and strongly associates with particles that make it a useful tracer (Conrad et al., 2007) and has been the most widely used radionuclide for determining both mixing and sedimentation rates (Cochran, 1985). The ^{210}Pb half-life of 22.3 years makes it a powerful tool in relating sedimentation processes during the last 100 years or more in the marine environment (Zuo et al., 1991). ^{210}Pb is a member of urainum-238 decay series and is identified in sediment samples from supported and unsupported sources. Supported ^{210}Pb is a radioactive decay product of radium-226 (^{226}Ra) with constant activity along a vertical profile of core sediment. However, the unsupported, or excess, ^{210}Pb ($^{210}Pb_{ex}$) is a radioactive decay product from radon-222 (^{222}Rn) gas escaping through the soil pore space to the atmosphere. The ^{222}Rn then decays to ^{210}Pb and attaches to aerosol particles and is delivered to marine surface water via precipitation. The $^{210}Pb_{ex}$ is quickly removed from the water column; it binds to

sediments due to its strong affinity for particulate matter (Martín et al., 2014) thereby increasing the initial ^{210}Pb content of the sediment (De Vleeschouwer et al., 2010). The ^{210}Pb$_{ex}$ activity decreases with its age according with radioactivity decay law. This law can be used as a tool to estimate sedimentation and diffusion rates in marine environments (Szmytkiewicz and Zalewska, 2014).

The isotope ^{210}Pb is a tracer for sediments deposited during a time of approximately 150 years ago through present time due to its half-life ($T_{1/2}$ = 22 years). This period of time is disproportionately important due to changes in the environment from human impact such as urbanization and industrialization (Ruiz-Fernández et al., 2009). However, the natural occurring radionuclide ^{210}Pb chronology is often corroborated by the anthropogenic radionuclide ^{137}Cs ($T_{1/2}$ = 30.1 years) measurement (Ruiz-Fernández et al., 2009). The radionuclide ^{137}Cs is commonly used as an independent tracer to confirm the ^{210}Pb age dating method (Dai et al., 2007). In fact, ^{210}Pb and ^{137}Cs, both sourced from the atmosphere, are used as standard tools to determine sedimentation rates over the last 150 years in sediment environments (Conrad et al., 2007). ^{137}Cs is present in the environment mostly due to global scale fallout from the atmospheric testing of nuclear weapons. The initial testing occurred in the early 1950s and peaked in 1963. The use of ^{137}Cs, therefore, relies on identifying its peak atmospheric deposition that took place in 1963 (Ruiz-Fernández et al., 2009). Generally, both ^{210}Pb and ^{137}Cs provide two independent measurements of estimating the same burial processes happening within a specified sediment profile (Ruiz-Fernández et al., 2009). Typically, ^{210}Pb activities assign an age to each layer of sediment from the surface down, and the presence of ^{137}Cs in the layers assigned to 1955–1966 is used as an independent check on the ^{210}Pb chronology.

Beryllium 7 (^{7}Be) is a naturally occurring radionuclide and is produced in the earth's atmosphere from spallation of gas molecules (Olsen et al., 1981). It has a strong affinity by adsorption for particulate matter after being delivered to the air-water interface (Kaste et al., 2011). ^{7}Be, a short-lived radioactive nuclide ($T_{1/2}$ = 53 day), is a powerful tool for examination of environmental processes (Olsen et al., 1985). It can provide information on diffusion processes of the ocean layer, but it a poor tracer of sedimentation rates in natural environments due to its short half-life of 53 days (Bloom and Crecelius, 1983). Mixing by physical or biological activities alter the rate of dissolution of minerals and can speed up reactions (Henderson et al., 1999). The typical advection-diffusion model includes the effect of particle mixing, sediment accumulation, and radioactive decay (Cochran, 1985). A significant consideration in any study is to determine rate of particle mixing in time scale and use of tracers with different half-life to characterize mixing in a signal core to check on the reliability of mixing rate (DeMaster and Cochran, 1982). The mixing rate can be determined via radionuclides, though difficult, as diffusional mixing competes with decay (Henderson et al., 1999). Mixing of sediments (physical and biological processes) often complicates the use of radionuclide activity in shallow estuarine environments (Conrad et al., 2007). Determining the sedimentation rate is usually a complicated task because both advection (burial) and diffusion-like processes control the distribution of radionuclides with depth in the core (Szmytkiewicz and Zalewska, 2014). Currently there are no published radionuclide measurements in coastal sediments of the eastern Red Sea. Furthermore, there are no quantitative data available regarding sedimentation processes in marine sediments in same region. In this paper, we focus on quantifying the chemical diffusion and particle mixing as well as the sedimentation rates for sediments of the Red Sea near Jeddah. These data are critical in establishing a baseline of sediment processes for future work in a rapidly developing area.

Two sediment cores were collected in January 2015 near the coast of Jeddah along the Red Sea for this study. The Prince Naif and the Downtown sites are located in close proximity to central Jeddah city in the Red Sea. Each sampling location was determined using a GPS and located between 39° 6′ 21″ N and 39° 9′ 26″ E, respectively (Fig. 1). The

distance of the Prince Naif core site from the shore was approximately 1000 m and in 25 m water depth while the Downtown core site was close to the shore, about 10 m, and in 2 m water depth (Table 1). Sediment cores were collected by scuba divers; using PVC tubes of 50 cm long and 4.5 cm in diameter. The cores were kept in an icebox at 4 °C until delivered to the laboratory for analysis. After core samples were obtained at selected locations across the study area, samples were stored frozen at − 20 °C for 24 h.

Radionuclides were measured in sediment samples by ultra-low background gamma counting on Canberra Broad Energy 5030 high purity Intrinsic Ge detectors housed in the Geology Department at the College of William & Mary. These detectors were designed with ultra-low background cryostat hardware and remote detector chambers housed in copper-lined 1000 kg + lead shields. Typically, 10–15 oven-dried grams of sediment were packed into 12 mL plastic petri dishes that were sealed in paraffin wax to retain ^{222}Rn. After 3 weeks, ^{210}Pb, ^{226}Ra, ^{7}Be, ^{137}Cs and ^{40}K were determined at 46 keV, 352 keV (via ^{214}Pb), 477 keV, 662 keV and 1461 keV respectively. Detector efficiency at these energies for ^{238}U series radionuclides was determined using certified uranium ore (Canadian Certified Reference Materials Project BL-4a) measured in the identical geometry as the samples, but efficiencies for ^{40}K and ^{137}Cs were determined using a calibrated multinuclear solution containing ^{137}Cs and radionuclides decaying up through 1800 keV (Isotope Products). To keep counting errors below 8%, samples were typically counted for 72–100 h. All ^{210}Pb measurements were corrected for self-attenuation using the point-source method (Cutshall et al., 1983). Typical 2-sigma uncertainties for ^{210}Pb$_{ex}$ were 2.5 Bq/kg, which was largely controlled by uncertainty in the supported ^{210}Pb; uncertainties for ^{7}Be and ^{137}Cs are 0.5 and 0.2 Bq/kg, respectively, and are largely controlled by counting statistics (Kaste et al., 2011).

In this study, we calculated the maximum chemical diffusion and sediment mixing rates by using the advection-diffusion model. The overall equation describing the excess ^{210}Pb sediment profile controlled by the following equation (Roberts et al., 1997):

$$\frac{dA}{dt} = D_B \frac{d^2A}{dx^2} - S \frac{dA}{dx} - \lambda A \tag{1}$$

where D_B is the diffusion-like particle mixing rate (cm^{-2} yr^{-1}); S is the sedimentation rate (cm/yr); A is the activity of excess ^{210}Pb (Bq/kg); x is the depth (cm); and λ is ^{210}Pb radioactive decay constant (0.03114 y^{-1}). If the sediment rate term is considered negligible, this equation is reduced to:

$$\frac{dA}{dt} = D_B \frac{d^2A}{dx^2} - \lambda A \tag{2}$$

Then, the solution under the conditions of A = A_0 when x = 0 and A → 0 as x → ∞ is:

$$A = A_0 \exp\left[-\left(, \frac{\lambda}{D_B}\right)^{\frac{1}{2}} x \right] \tag{3}$$

Two models of ^{210}Pb activities versus the vertical profiles were applied to determine the rate of sedimentation in the sediment of the Red Sea. The first model is known as Constant Initial Concentration (CIC) model assumes that the system is in a steady state and a constant flux of ^{210}Pb from the atmosphere and rate of sedimentation deposition is constant as well (Szmytkiewicz and Zalewska, 2014). The profiles of excess ^{210}Pb activity were modeled using the constant initial activity and constant accumulation rate assumption as the following equation (Appleby and Oldfield, 1992):

$$C_m = C_{(0)} e^{-\lambda m/r} \tag{4}$$

where $C_{(m)}$ is ^{210}Pb$_{ex}$ activity at cumulative dry mass depth (Bq/kg); $C_{(0)}$ is the activity of excess ^{210}Pb at the surface layer of the sediment core (Bq/kg); λ is the ^{210}Pb radioactive decay constant (0.03114 y^{-1});