MECHANISMS OF FLASHFLOOD DEPOSIT PRESERVATION IN SHALLOW MARINE SEDIMENTS OF A HYPERARID ENVIRONMENT

by

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ABSTRACT

Flashflood deposit preservation was explored on the shallow seafloor in the Gulf of Eilat-Aqaba. Changes to two fine-grained flashflood deposits were tracked throughout the year after their deposition through repeated sediment coring. Resuspension, removal, and vertical mixing of flashflood deposits were investigated by measuring near-bottom water currents, photographing demersal fish activities, and by measuring the depths and magnitudes of bioturbation using fluorescent sediment tracers. Flashflood deposits were generally not identifiable on the seafloor surface within the year after their deposition. Water currents were typically too weak to resuspend sediment, while demersal fish did resuspend sediment when present. Bioturbation was strongest in the upper 2 cm of the seabed. Despite the rapid dissipation of flood layers, lenses of fine sediment persisted in the seabed for years. Deposition within seafloor depressions, and burial by biological mounds and ensuing flashflood deposits are proposed as mechanisms for localized preservation of flood signatures.

LIST OF ABBREVIATIONS AND SYMBOLS

GOA	Gulf of Eilat- Aqaba
IUI	Interuniversity Institute for Marine Sciences
µm	micrometre
nm	nanometre
mm	millimetre
cm	centimetre
m	metre
km	kilometre
mm y^{-1}	millimetres per year
cm s^{-1}	centimetres per second
cm y^{-1}	centimetres per year
m s^{-1}	metres per second
m y^{-1}	metres per year
cm^{2}	centimetres squared
m^{2}	metres squared
km^{2}	kilometres squared
cm^{-2} y^{-1}	per centimetres squared per year
cm^{3}.cm^{-2}. y^{-1}	centimetres cubed per centimetres squared per year
m^{-2} h^{-1}	per metres squared per hour
km day^{-1}	kilometres per day
mab	metres above the bottom
D_b	Biodiffusion coefficient
L_b	Mixed layer depth
L_s	Event layer thickness
w	Sedimentation rate
CTD	Conductivity, Temperature, Depth
OBS	Optical Backscatter
ADCP	Acoustic Doppler Current Profiler
SSC	Suspended Sediment Concentration
Temp.	Temperature
min.	minute
mo.	months
ºC	Degrees Celsius
ppt	parts per thousand
%	percent

º	degrees
~	approximately
<	less than
≤	less than or equal to
=	equals
>	greater than
+	plus
±	plus/ minus
g	grams
kg	kilograms
ml	millilitres
L	litres
mV	millivolts
g L^{-1}	grams per litre
g cm^{-3}	grams per centimetres cubed
kg m^{-2} y^{-1}	kilograms per metres squared per year
kg m^{-3}	kilograms per metres cubed
H_2O ρ	water density
R^{2}	Coefficient of determination
MHz	Megahertz
PVC	Polyvinyl Chloride
UV	Ultra Violet
max.	maximum
n	sample size
d	diameter
l	length
h	height
t	time
t_1	time 1
t_2	time 2
Avg.	Average
p	probability
ANOVA	Analysis of Variance
pic	picture
Fig.	Figure
Vol.	Volume

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CHAPTER 1 INTRODUCTION

1.1 Importance of flashfloods and influence on marine sediment records

Flashfloods on land are generated by intense rainfall events, when the soil fails to absorb the water it is receiving. Under these conditions, water accumulates and flows with increasing velocity toward the closest drainage basin. Flashfloods occur in arid locations with low vegetal coverage, and in areas surrounded by mountains that drain into small- to medium-sized rivers (Milliman & Syvitski, 1992; Mulder et al., 2001, 2003). Vegetative cover is sparse in arid regions, and soils are not tightly bound by plant roots and rhizomes, so flashfloods can erode and transport large quantities of suspended sediment in these locations. Rivers in arid environments are often ephemeral and may be predominantly inactive, therefore, flashfloods in these regions that empty into aquatic environments can account for the dominant supply of terrigenous sediment to the receiving basin, and significantly influence the sediment budget (Katz et al., 2015).

Flashfloods are unpredictable, and can grow considerably on the timescale of hours or days (Postma, 2001; Mulder et al., 2003; Katz et al., 2015). They can be the primary source of fresh water to desert environments, making them important for supporting life in these harsh locations. Although flashfloods essential to arid ecosystems, they also endanger life and destroy infrastructure. For all of these reasons, tools are required to better understand and predict these extreme weather events.

Through erosion and sedimentation, flashfloods can induce major transformations to the geological features they encounter both on land and in aquatic environments (Postma, 2001; Mulder et al., 2003; Lamb & Mohrig, 2009). In locations where the flashflood record is limited, understanding mechanisms of flashflood deposit preservation and the composition of resulting sedimentary signatures can be used to reconstruct past flood records. On land, flashflood deposits are subjected to erosion that may disrupt the stratigraphy. It has been suggested that where flashfloods discharge into the ocean, marine sediments may offer a better record of paleoflood events (Mulder et al., 2001, 2003; Lamb & Mohrig, 2009; Kniskern et al., 2014; Walsh et al., 2014). The sediment load within flood waters and its subsequent contribution to the marine sediment record depend on the intensity and duration of the rainfall event, so marine sediment cores offer a potential record of the magnitude and frequency of past flooding events (Mulder et al., 2001, 2003). Flashflood deposit preservation in marine environments can provide valuable information about the global sediment budget by serving as a direct link between terrigenous sediment sources and marine sediment depositional sinks (Mulder et al., 2001; Lamb & Mohrig, 2009; Kniskern et al., 2014). This link in turn can yield information about geological landscapes, tectonics, and climate affect on the marine sediment stratigraphy (Postma, 2001; Mulder et al., 2001; Lamb & Mohrig, 2009).

Preserved flashflood deposits within marine sediment records have been observed in environments with high sedimentation rates (Mulder et al., 2003; Kniskern et al., 2014) and in deep sea, low energy environments (Postma, 2001; Mulder et al., 2001). However, little is known about the mechanisms of flashflood deposit preservation within marine sediments located in arid environments, where rivers are predominantly ephemeral and sedimentation is low. The goal of this study is to elucidate factors and mechanisms that control the preservation of flashflood deposits in the Gulf of Eilat- Aqaba, Red Sea, in the discharge area on the shallow northern shelf. To this end, the time evolution of flashflood deposits were documented in order to link the transformation of the deposits to the physical and biological processes that disturb them.

1.2 Knowledge of flashfloods and associated deposits in Gulf of Eilat- Aqaba

Eilat is Israel’s most southern city, located on the coast of the most northern point of the Gulf of Eilat- Aqaba (GOA), Red Sea. The climate in this region is hyper arid. Average precipitation is <30 mm year^{-1}, and the evaporation rate in the GOA is ~1.7 m year^{-1} (Ben-Sasson et al., 2009). The sedimentation rate on the shallow shelf of the GOA is low, with estimated average accumulation rates of 1.3 mm y^{-1} at 16 m depth on the northern GOA shelf, and 0.5 mm y^{-1} at 12 m depth along the fringing coral reefs on the northwestern shore of the GOA (Goodman et al., 2016). Aeolian deposition of dust contributes $1\text{x}10^{-4}$ mm y^{-1}, estimated from deep sea sediments (Data from Chen et al., 2008, calculated by Pittauerová et al., 2014). Although they can be rare, flashfloods deliver enough sediment to be the dominant source of terrigenous sediment to the shallow GOA (Pittauerová et al., 2014; Katz et al., 2015). However, there is very limited historical information about flood frequencies and magnitudes.

Sporadic flashfloods occur in the Israeli Negev desert most frequently in spring and autumn. Floods are even rarer in the hyperarid region surrounding the GOA. When rains in this region are intense and prolonged enough, however, floods do form and flow into the Red Sea, bringing in large quantities of sediment. Such flashfloods may be so heavily concentrated with sediment that they produce hyperpycnal flows in which the sediment-laden flood waters are denser than the water in the GOA, causing them to plunge and flow along the bottom of the seafloor despite the high salinity (density) of the ambient seawater (Katz et al., 2015).

Flashflood deposits contain significantly higher proportions of silt- and clay-sized grains compared to the ambient sediments on the seafloor that have not been exposed to flashfloods for at least one year (Katz et al., 2015). For example, a flashflood that entered the GOA in February 2013 brought in a conservative estimate of 21 000 tonnes of sediment into the sea, 92% of which was fine, silt-clay material. This mass of sediment could create a 2 cm thick flood deposit layer over a 1 km^2 area. In a sediment core taken from the shallow GOA 52 days after a flashflood in January 2013, which was the third flooding event within two months, the top 4-5 cm were composed of 81% silt-clay material by mass, while the underlying sediment had 6% fine sediments by mass. Intriguingly, one year following a flashflood that entered the GOA in January 2010, the silt-clay flood deposit 'disappeared' from the surface of the shallow seafloor (Katz et al., 2015). This observation provided the focus for this study, which was to identify the major physical and biological processes responsible for flashflood deposit preservation and alteration on the shallow seafloor.

1.3 Event layer preservation in the presence of physical and biological influences

The links between the properties of sediment layers deposited during floods and the floods that delivered them are complicated by post-depositional physical and biological reworking of flood deposits (Steiner et al., 2016; Wheatcroft & Drake, 2003). Event layer preservation/destruction is mitigated by the competition between rates of sediment accumulation and the biological, and to a lesser extent, physical processes that lead to sediment reworking (Wheatcroft, 1990; Wheatcroft & Drake, 2003). Wheatcroft (1990) defined 'preservation potential' as the probability that sediment layers will remain recognizable prior to burial. The dominant physical forces and transport mechanisms that can cause sediment resuspension and removal in the GOA are bottom shear stresses due to currents and wind-generated surface gravity waves. The main biological processes that can alter surface sediments are biological resuspension from demersal fish and benthic organisms and bioturbation, which is defined as sediment mixing by benthic organisms.

1.4 Physical forces & transport mechanisms in the Gulf of Eilat- Aqaba

Currents on the shallow shelf of the northern GOA have not been monitored extensively. One dataset measured current speeds 16 metres above the bottom (mab) at 30 m water depth, measuring an average speed of 5.5 cm s^{-1} and a maximum speed of 29.6 cm s^{-1} (Data from A. Genin in Katz et al., 2015). Yahel et al. (2002) measured average and maximum current speeds of 4.6 cm s^{-1} and 9.6 cm s^{-1}, 1 mab between 8-15 m water depth over the fringing reefs on the northwestern shore of the GOA. From that 1.5-year study, current speeds were calculated to have the capacity to move surface sand sediments <4 % of the time. These measurements suggest that current speeds on the northern shelf should be low and have limited potential to resuspend sediment. Sediments that are suspended, however, will be distributed and transported according to current direction and magnitude. Katz et al. (2015) suggested that resuspended fine particles on the northern shelf of the GOA are likely to be directed offshore, considering current directions and bottom slope. It was observed by Yahel et al. (2002) that rare storms associated with southern winds produced waves >2 m at the coast, causing sediment resuspension and increased turbidity. The majority of the time (>90 %), however, winds prevail from the north in the GOA (Katz et al., 2015), and are associated with small waves, <0.1 m high (Yahel et al., 2002). Relatively low-energy currents and infrequent wind waves suggest that biological processes are likely to be important to the redistribution of flood sediments.

1.5 Biological resuspension in the GOA

In the shallow coral reefs on the northwestern coast of the GOA, demersal fish have been identified to be the dominant contributors to sediment resuspension when compared to wave and current activities (Yahel et al., 2002). The study examined resuspension of sand-sized grains and found that the majority (54% during the day) of resuspended sediments were between 100-200 μm. Resuspension of sediments smaller than 100 μm was not measured. The observed rate of sediment resuspension was >1.5 resuspension events m^{-2} h^{-1} during the day. When fish were excluded from an area of the reef, the volume of resuspended sediments decreased by 26-86%. Sand resuspension was not correlated to current speeds or tidal activity, even when currents were strong enough to resuspend sediments. The considerable affects that demersal fish had on sediment resuspension in the shallow GOA reefs suggests their activities are relevant to explore on the northern shelf.

1.6 Bioturbation vs. sedimentation

Bioturbation, defined as the activity of benthic organisms that alter sediment deposits from their primary structures on millimetre to metre scales (Gerino et al., 1998), occurs nearly ubiquitously in marine sediments. Activities of benthic organisms include feeding, burrowing, and other forms of sediment reworking at or below the sediment-water interface (Gerino et al., 2007). The penetration depth from bioturbation is relatively constant globally, at ~10 cm, but its magnitude will vary depending on environmental conditions (Boudreau, 1994). Bioturbation transforms initial sedimentary structures within the seabed, while sedimentation can bury sediments to depths at which they are no longer affected by physical and biological processes, and are thus preserved (Bentley et al., 2006). Important variables to consider with regard to preservation potential are the biodiffusion coefficient, D_b (cm^2 $year^{-1}$), the depth within the seafloor at which the bioturbation rate becomes vanishingly small, L_b (cm), the thickness of the initial event layer (sediments rapidly deposited from an episodic occurrence; i.e. flashfloods), L_s (cm), and the sedimentation rate, w (cm $year^{-1}$) (Wheatcroft, 1990; Wheatcroft & Drake, 2003; Bentley et al., 2006). The time it takes for an event layer to become buried below the mixed layer equals $[L_b\text{-}L_s/2]/w$ and is referred to as the transit time, while the time it takes for bioturbation to destroy the event signal is called the dissipation time (Wheatcroft, 1990). One way to define the dissipation time is by the time it takes for each grain of sediment in the surface mixed layer to be displaced, which requires estimates for the community reworking rate ($cm^3.cm^{-2}.\ y^{-1}$) and L_b (cm). The dissipation time can be estimated by first using L_b to calculate the volume of displaced particles per area, which in turn can be divided by the community reworking rate (Rhoads, 1967). However, these formulas must be used with caution, as the parameters can be highly variable locally depending on the activities of benthic species and biomass (Wheatcroft, 1990; Wheatcroft & Drake, 2003). Bioturbation has been observed to smear or erase short term event layers within the sediment stratigraphy when the transit time is slower than the dissipation time (Wheatcroft & Drake, 2003; Bentley et al., 2006, Steiner et al., 2016).

Bentley et al. (2006) expands on the preservation concept of Wheatcroft by considering how bioturbation and sedimentation may vary in space or time. They note the importance of a fast transit time through surficial sediments for preservation because bioturbation rates are faster closer to the sediment surface, and decrease with increasing depth within the seabed until the rates are negligible (Boudreau, 1994). Bioturbation activities in the upper half of the mixed layer (L_b) occur 10- 1000 fold faster than in the lower half (Bentley et al., 2006). Episodically high sedimentation in small pulses can preserve event layers better than lower, more continuous sedimentation over longer periods (Wheatcroft & Drake, 2003). If event layers are thicker than the depth of L_b, then the basal portion of the deposit has a higher probability of becoming preserved. Deposits thinner than L_b will show signs of biological activity, and will be modified before preservation (Wheatcroft, 1990; Wheatcroft & Drake, 2003; Steiner et al., 2016). It is the relative magnitudes of these variables that will determine the fate of event layer preservation.

1.7 Research Objectives

The purpose of this study is to gain insights into the preservation mechanisms and potential, as well as the alterations and distribution of flashflood deposits after they settle on the northern shallow shelf of the GOA. This information is most valuable for understanding post-flood sedimentological processes in general, in the GOA in particular, and for enabling better interpretations of paleofloods in the sedimentary record in arid environments. A suite of observations was made offshore of the dominant drainage basin of flashfloods to the GOA from Eilat, where past research showed that flood sediments deposit.

The first assessment tracked changes to the primary silt-clay sedimentary signatures of one flashflood deposit and two consecutive deposits within the year after they settled on the seafloor, through bi/tri-monthly sediment coring. The second dataset obtained was aimed at determining if physical forcing influenced sediment resuspension and transport of flood sediments. This was achieved by setting up a mooring station with a CTD, three Optical Backscatter (OBS) Sensors calibrated to measure suspended sediment concentrations at varying depths within the water column, and deploying an Acoustic Doppler Current Profiler (ADCP) that measured current velocities. A third assessment was carried out to observe the frequency of biological resuspension by fish, which was monitored by deploying GoPro cameras to take photographs of the near bottom environment. Finally, to get insight into the depths and magnitudes that benthic organisms mix and remove surface sediments, an *in situ* experiment was set up to study bioturbation.

CHAPTER 2 METHODS

2.1 Study Region

Eilat is surrounded by a desert mountain range composed of ~500-million-year old magmatic-metamorphic rock that underlies an eroding ~60-million-year old suite of sedimentary sandstone, carbonate, and volcanic rocks (Beyth et al., 2011). Mountains are connected by networks of wadis (dry river beds) that make up the Arava drainage basin, and lead into the northern GOA via the Kinnet Canal outlet (Fig. 1). The GOA is the northeastern upper extension of the Red Sea. It is a long, narrow, and deep water body (max. depth= 1850 m) with steep lateral slopes. The narrow, deep geometry of the basin arises from its positioning on the boundary between the Arabian and African plates (Ben-Avraham, 1985). The GOA has average surface water temperatures ranging from 20-28 °C and a salinity of 40.8 ppt. The eastern and western edges of the GOA bear fringing coral reef ecosystems down to 80 m water depth. The northern shore is a sediment dominated environment, and has a narrow continental shelf that is approximately 1.7 km wide with a mean slope of 3º (Katz et al., 2015). The experiments were carried out on the northern shelf of the GOA, approximately 200 m seaward of the Kinnet Canal outlet, at 13 m water depth (Fig. 1).

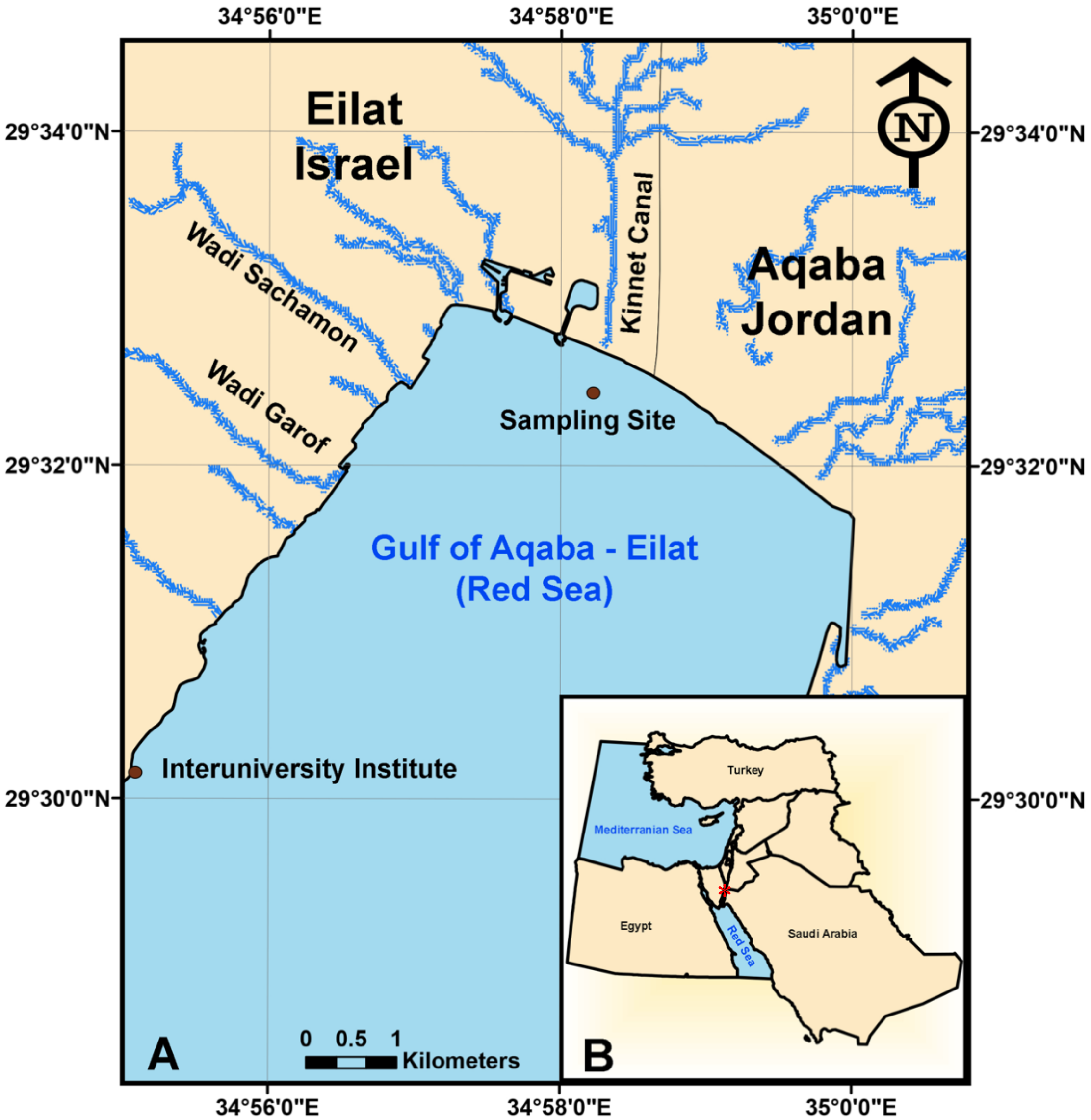

Fig. 1. A) Local map of the study region showing the sampling site, which is ~200 m offshore of the Kinnet Canal outlet, at 13 m water depth. B) Regional map; the sampling site is marked with a red star.

2.2 Time- evolution of flashflood deposits

2.2.1 Bi/tri- monthly core collections

To observe how flashflood deposits changed over time in the shallow GOA, short sediment push cores (l= 30 cm, d= 4.3 cm) were collected by divers in a 50 m^2 area in 2-3 month intervals for 14 months following a flashflood that entered the GOA in May 2014, and for 12 months following two flashflood events on September 15th and October 25th,

2015. Initial cores were taken within 10 days of flashflood events. The standard procedure was to take replicate cores (n=2) within a 1 m^2 area at each collection, but single cores were collected at the beginning of the study prior to the commencement of this research project. Single core collections also were carried out occasionally between scheduled bi-tri monthly collection periods, allowing for additional analyses.

Cores were qualitatively described based on color, grain size, uniformity/ sharp edges, and were measured in length. Each core was sectioned in 1 cm intervals immediately following collection, or cores were placed in a 4 ºC refrigerator until sliced. Notes were made on the presence of relatively large shell or rock fragments and organisms observed during slicing. A small subsample throughout the centre of each centimetre was set aside for grain size analysis.

When collecting and slicing the cores, variations in the porosity within the natural sediment and changes caused to the porosity during slicing could have resulted in sediment compaction or extension, and altered the position of the grains. Therefore, the specific locations of the sediment grain size distributions within the cores should be regarded with caution, as they may have shifted from their natural positions within the seafloor.

2.2.2 Grain size analysis

Flashflood deposits were distinguished by their high percentage of silt and clay (<63 μm) compared to coarser background sediments, so grain size profiles of cores were used to track the time evolution of flashflood deposits. Approximately 0.1 ml of sediment from the centre of each centimetre interval from each core was placed in 15-ml falcon tubes for grain size analysis. Each subsample was subjected to applications of 30% hydrogen peroxide to digest organic matter. Subsamples were homogenized, and a small amount of sediment was inserted into a Beckman Coulter Counter LS 13 320 Laser Diffraction Particle Size Analyzer. The output was the grain size distribution in volumetric percent of sediment belonging to 117 grain size bins, between 0-2000 μm. The grain size distribution of a subsample was assumed to represent the grain size within each centimetre layer of a core.

2.3 Bottom boundary layer observations

Physical characteristics of the near bottom environment and water column were monitored to determine their influences on sediment resuspension and transportation. A mooring station was set up with a Sea-bird SBE19 plus CTD placed on the seafloor, which was attached to three Campbell Scientific Optical Backscatter (OBS-3+) Turbidity Sensors positioned on a rope at 8, 2, and 0.1 metres above the bottom (mab). The CTD provided time series data of salinity, temperature, and water depth, and the OBS sensors provided time series measurements of suspended sediment concentrations (SSC). The OBS sensors measured intensity of backscattered infrared light (850±5 nm) in mV, which was converted to particle concentration (g L^{-1}) using calibration curves. Each OBS sensor had both high and low sensitivity channels, which were calibrated in the laboratory by exposing the sensors to volumes of seawater with known concentrations of flood sediments. To establish the calibration curves, the OBS sensors were attached to the inside of a large tank (~100 L). Increasing increments of 2.5 ml of flashflood sediment from the study site were mixed with 1 L of seawater, and were introduced to the tank for the OBS sensors to measure. Following each sediment addition, once the OBS readings stabilized, 200 ml of tank water were filtered on pre-weighed glass microfibre filters to gravimetrically obtain the concentration of suspended solids in g L^{-1}. There were 10 points on the calibration curves created from the high sensitivity channels, and 19 points on the curves from the low sensitivity channels. The average voltages measured by the sensors at each sediment increment were recorded in mV, with an upper detection limit of 5 mV per sensitivity channel. The calibration provided upper detection limits of ~0.6 and 2.3 g L^{-1} for the high and low sensitivity channels, respectively. R^2 values ranged from 0.98-0.99 for the six curves created (Appendix A). Field measurements from the CTD and OBS sensors were averaged over one second in 5 minute intervals from April 21st, 2016- January 5th, 2017 over 5 deployments.

Approximately 3 m shoreward and to the east of the mooring, a Nortek Aquadopp Profiler ADCP, which measured the acoustic frequency at 2.0 MHz, was placed on the seafloor to track current velocities at heights between 0.15-1.5 mab. Each current measurement was averaged over a 60-second period every 10 or 20 minutes from April 21st, 2016- February 23rd, 2017 over 7 deployments. Daily data on wind speed and direction were obtained from the National Monitoring Program at the Gulf of Eilat, which is located at the Interuniversity Institute for Marine Sciences on the northwestern shore of the GOA (Fig. 1) (Israel National Monitoring Program, 2017).

All instrument sensors were cleaned on site weekly or biweekly, and instruments were recovered monthly or bimonthly to offload the data over a period of a few days. From the OBS sensors, data that showed exponentially increasing values of SSC before a cleaning event were interpreted to be affected by fouling, so they were not included in reported observations.

2.4 Monitoring of sediment resuspension by fish

To assess the role of demersal fish in the resuspension of surface sediments, a GoPro Hero 4 camera was used. The camera was mounted on a 1-m long polyvinyl chloride (PVC) plastic pole, which was pushed into the seabed so that the sub-bottom environment was within its frame. The camera was deployed 8 times during daylight hours, taking pictures in 20 or 30 second intervals for a duration of 1-2 hours per deployment. Three deployments were in June, three in July, and the remaining two were in September, 2016. This assessment was carried out to provide qualitative data on fish-induced resuspension of sediment. The number of photographs were counted where demersal fish were present and where local resuspension events were observed. Local resuspension was defined as the occurrence of plume-like structures immediately above the seabed.

2.5 Bioturbation

An *in situ* experiment was set up to measure mixing and removal of surficial sediments using fluorescent sediment tracers. Short sediment cores were collected from the field, a tracer disc was placed on the surface of each core, and cores were transplanted back into the seafloor at the study site. Three treatments with varying exposures to physical and biological resuspension processes were formed on the seafloor, and the cores were transplanted into those locations. Cores were collected in three time intervals from each location.

2.5.1 Tracking surface sediment movement with tracers

Movement and removal of surficial sediments were tracked using luminophores, which are sediments that were dyed green and fluoresce under Ultra Violet (UV) light. Luminophores were sieved to select for grains <63 µm to represent flashflood sediments. Tracers consisted of a mixture of 1.5 g of luminophores <63 µm, 3.5 g of dry surface sediment from the study region, and a small amount of a water and soap (soap used to disaggregate luminophores in solution). Tracers were homogenized and placed in the freezer to form a solid unit in a plastic cup (tracer: h= 0.5 cm, d= 2.9 cm). From the study site, 27 short cores ranging in length from 22.5-26.5 cm were collected by divers and brought back to the lab, where a tracer disc was placed on the surface of each. Cores were then transferred into a salt water pool and left uncovered for up to 6 days, to keep organisms alive.

2.5.2 Study site setup

Vertical mixing and removal of the tracer were tracked in three treatments. Triplicates of caged, fenced, and open sites (n= 9) were established on the seafloor in a grid formation, with 10 m between each site. Sites were connected via rope with PVC poles at each end. Cages were made of mesh with a hole size of 1 cm^2, on a metal frame 50 cm^2, 20 cm above the seafloor, and were designed to block physical and biological resuspension processes. Fences were made from two pieces of mesh with a hole size of 1 cm^2 (l= 50 cm, h= 20 cm), a PVC pole connecting the two sheets, and an additional two poles at the end of each sheet to place within the seafloor. Fences were designed to block east-west currents, and be exposed to potential biological resuspension from fish. Open sites were exposed to all potential sediment resuspension processes.

2.5.3 Core transplantation in seafloor

At each site, three PVC poles were oriented and placed in the seafloor so that a custom made PVC plate could fit over the poles. The plate had four larger holes (d= 6.5 cm), one in each corner, which were used to mark the core locations at each site. A prototype was created to transplant sediment cores into the seafloor, which consisted of an outer metal bottomless tube (h= 33, d= 5.6 cm), and an inner tube with a bottom. The procedure for transplantation was to first place the plate over the three centre poles, then the transplant device was hammered into the seafloor in one of the corner holes of the plate. The inner tube was then removed from the device, leaving a space within the seafloor in the outer tube. The bottom plug of a core with a surface tracer was removed, and the core was placed inside the outer tube. The outer tube was then removed, and the surrounding sediment collapsed around the core liner. The top plug of the core was gently removed, and the core liner was pulled out, leaving nothing but the sediment and tracer within the seafloor. Two more cores were transplanted in two remaining corner holes of the location plate, leaving three cores with surface tracers in the seafloor. The plate was then gently removed, and the same procedure was carried out at all sites. A total of 27 cores with surface tracers were transplanted into the seafloor, three in each of the 9 sites, in May 2016.

2.5.4 Core recovery and tracer analysis

One core was recovered from each site in three time intervals: 1 week (t=1); 3 weeks (t=2); and 6 weeks (t=3). Cores were recovered by placing the location plate over the three centre poles at each site, and taking a short core within one of the corner holes of the plate. Cores were brought back to the laboratory, sectioned in 1 cm intervals, and dried. A subsample of 15 g was selected from the centre of each centimetre slab that contained tracer in each core, which was crushed with a mortar and pestle to separate sediment grains that had stuck together during drying. The subsample was homogenized, and three 1.2 cm^2 pieces of tape were weighed, dipped into the subsample, and weighed again. Sediment weights ranged from ~0.005-0.015 g/ tape. Each piece of tape was photographed in a dark room under UV light with 1x magnification using a binocular microscope. The area of fluorescence (pixels)/ picture (3 from each cm containing tracer) was measured by a custom-made macro code designed in MatLab, using Otsu's thresholding. The average area of fluorescence/ picture was determined within each centimetre, and profiles of tracer distributions were established for each core.

Accuracy in measuring the tracer area/ picture was determined by creating two calibration curves from the first centimetres of two cores with surface tracers that were transplanted into the seafloor, and were immediately recovered. The first centimetres were dried, and the centre 15 g of each was crushed and homogenized. The subsample from each core was split and diluted 7 times with sediment collected from the site. After each split and dilution, the resulting sediment-tracer mixture was subsampled on three 1.2 cm^2 pieces of tape. The areas of fluorescence/ picture from the three pieces of tape were averaged for each split, and two calibration curves were formed (Fig. 2). R^2 values were 0.94 and 0.99. The final split and dilution accounted for 128th of the original 1.5 g of luminophores in the tracer, therefore 1.17 %.

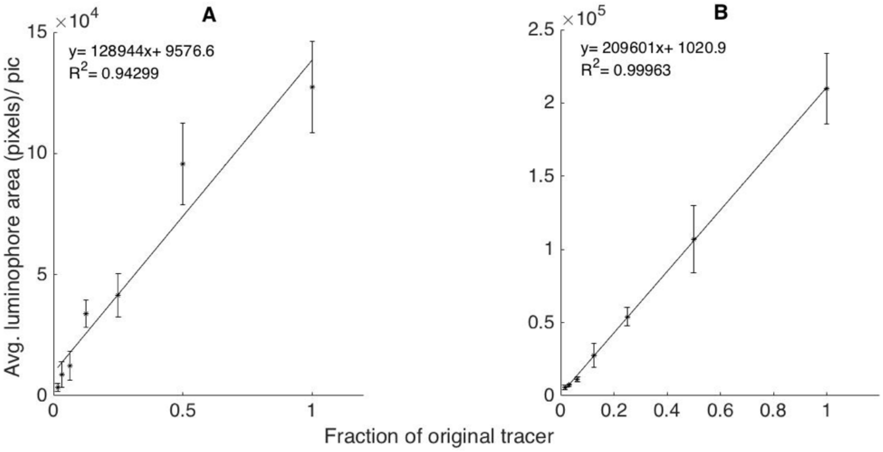

Fig. 2. Calibration curves of the 1st cm of cores with tracers on their surfaces that were transplanted into the seafloor and immediately recovered. Error bars represent the standard deviation from the three luminophore areas measured/ picture/ cm.

2.6 Transects, measurements and grain size of biological mounds and depressions

The presence of sediment mounds and depressions created by burrowing organisms within the seafloor may influence the preservation/destruction of flashflood deposits, so six transects were conducted to count the number of mounds and depressions (diameter >5 cm) over an area of 9m x 1m, at 13 m water depth. As well, measurements were carried out on the widths and heights of 13 mounds and depths and diameters of 6 depressions that were randomly selected to best represent all sizes.

To explore the possibility that biological mounds and depressions within the seafloor influenced the preservation of flashflood deposits, three short cores were collected from the ambient seafloor, within a depression (depth= ~15 cm), and within a mound (height= ~15 cm), in May 2017, respectively. This was two months after a flashflood that entered the GOA in March 2017, and 6 months after the flood that discharged into the sea in October 2016. Grain size analyses were carried out on subsamples from each centimetre of each core, and the distributions of fine grains were established.

CHAPTER 3 RESULTS

3.1 Flashflood deposit observations

Cores taken immediately following flashfloods had significantly higher proportions of silt and clay at their core tops compared to the deeper, coarser, background sediment typical in the absence of floods. These fine layers ranged in thickness from 1-4 cm (Fig. 3, Panels: 1, 12-15, 27-28). With the passage of time after a flooding event, fine sediments penetrated down to ~15 cm within the seabed, and disappeared from the surface sediments (Fig. 3). The combination of downward mixing and removal of fine sediments via bioturbation and physical and/or biological resuspension resulted in coarsening of the flood deposits from the surface at locally variable rates.

In some of the cores distinct fine sediment layers were found at depth, which presumably derived from previous flood deposits that were buried between 10-25 cm below the seafloor (Fig. 3, Panels: 7, 10, 12-15, 19, 20). In other cores grain size distributions were more uniform and coarser below 5 cm (Fig. 3, Panels: 6, 18, 24- 26), while other cores showed variable amounts of silt and clay throughout their profiles. In many cases, replicate cores had grain size profiles that were different from one another (Fig. 3, Panels: 6-8, 10-11, 14-15, 16-17, 21-24). The heterogeneous distributions of fines in the cores suggests that there was locally variable preservation of flashflood deposits, which could have arisen from variable mixing, removal, and burial mechanisms and rates in the seabed.

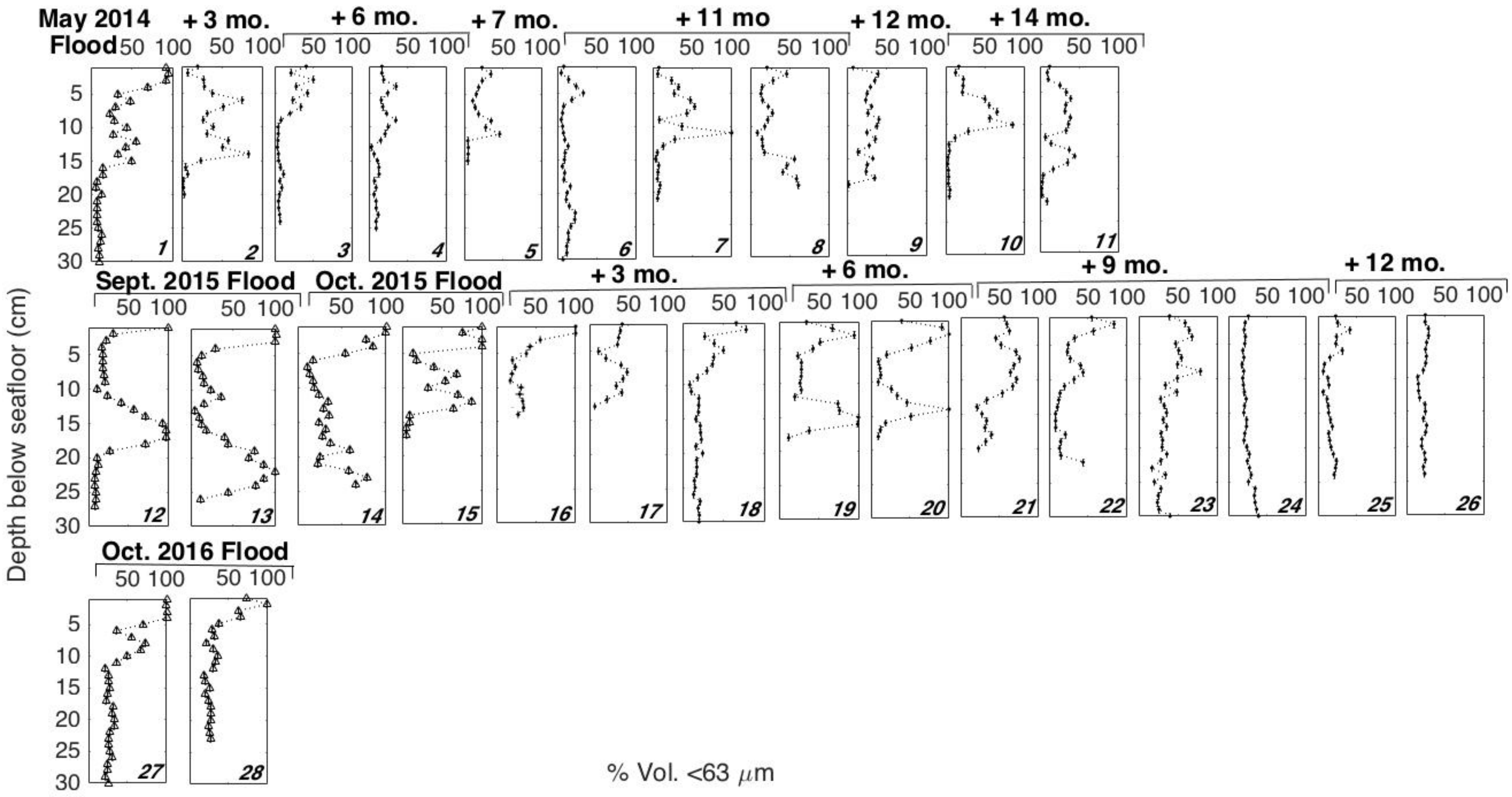

Fig. 3. Grain size distributions of % volume of sediment <63 µm in cores taken at 13 m water depth, in front of the Kinnet Canal outlet. Flood cores are labelled and are represented with triangles, and the label "mo." on the remaining cores represent the number of months passed since the last flood event. Replicate cores are in brackets, and each panel is numbered in the bottom right corn

3.2 Physical resuspension & sediment transport

Current velocities were low (Avg.= 3.7 ± 2.5 cm s^{-1}), and were generally not strong enough to resuspend sediments at the study site (Fig. 4 a, b). Given the average grain size of surface sediments (top 3 cm) unexposed to flashfloods for at least 3 months (187 μm) and the average grain size of surface sediments measured immediately following a flashflood (14 μm), current velocities of at least 41 cm s^{-1} and 13 cm s^{-1} 25 cm above the seafloor were required to resuspend sediments (assuming sediment density of 2.65 g cm^{-3}, water temperature of 25 °C, salinity of 40 ppt, and zero bottom slope), respectively (Wiberg & Smith, 1987). These calculations assume sediments are non-cohesive, which is reasonable for the coarser background sediment, but not for the finer flood sediment. Stronger velocities would be required to resuspend cohesive fine sediments. Current speeds exceeded the minimum velocities to resuspend flashflood sediments only 0.28% of the time during the observational record.

In the middle of the record, a sharp peak in SSC that occurred simultaneously with a drop in water salinity was the result of a flashflood that entered the GOA via the Kinnet Canal on October 28th, 2016 (Fig. 4 a, d (in the grey box)). This drop in water salinity was due to increased freshwater input from the flood. In reality, the flood water was denser than the ambient seawater as its high sediment input overwhelmed the drop in salinity (max. sediment concentration measured from Kinnet Canal outlet was 33.5 kg m^{-3}). Throughout the ~15-hour flashflood event, incoming flood water was sampled 7 times directly from the location where the Kinnet Canal drained into the GOA. These samples were homogenized and subsamples were taken from each, which were then dried to calculate sediment concentrations.

The causes of other peaks recorded by the OBS sensors between May and June, at the end of July through the beginning of August, and in November and December (Fig. 4 a) remain unresolved after possible scenarios were explored. With regard to wave measurements, there were no data available as wave periods and heights are very short in the GOA, making it difficult to accurately measure them. However, the prolonged peaks in turbidity were not correlated to wind speeds, which were considered to potentially induce near shore sediment resuspension by waves and cause increased OBS readings.

Measurements from the OBS sensors were not correlated to chlorophyll levels (representing plankton blooms) measured daily from the northwestern shore of the GOA (Israel National Monitoring Program, 2017). Daily data on chlorophyll was not available from the northern shelf. An additional possible explanation for the prolonged increased turbidity measurements could be from construction activities on the north beach in Aqaba, Jordan, which could have been discharging particles into the marine environment.

Throughout much of the time-series, currents were not preferentially directed offshore. From November to December, however, associated with cooling of the water column, flow became preferentially directed offshore, so any sediments that were resuspended would be preferentially transported south and directed offshelf (Fig. 4). Enhanced southward flow in the fall and winter could be caused by formation of dense water on the shelf that flows downslope across the shelf (Manasrah et al., 2004). Elevated wind speeds from the south occurred almost simultaneously with a rise in water density, enhanced southward flowing water currents, and a slight increase in SSC (Fig. 4). This observation could provide evidence that resuspended flood sediments were directed toward the deep basin in the winter months.

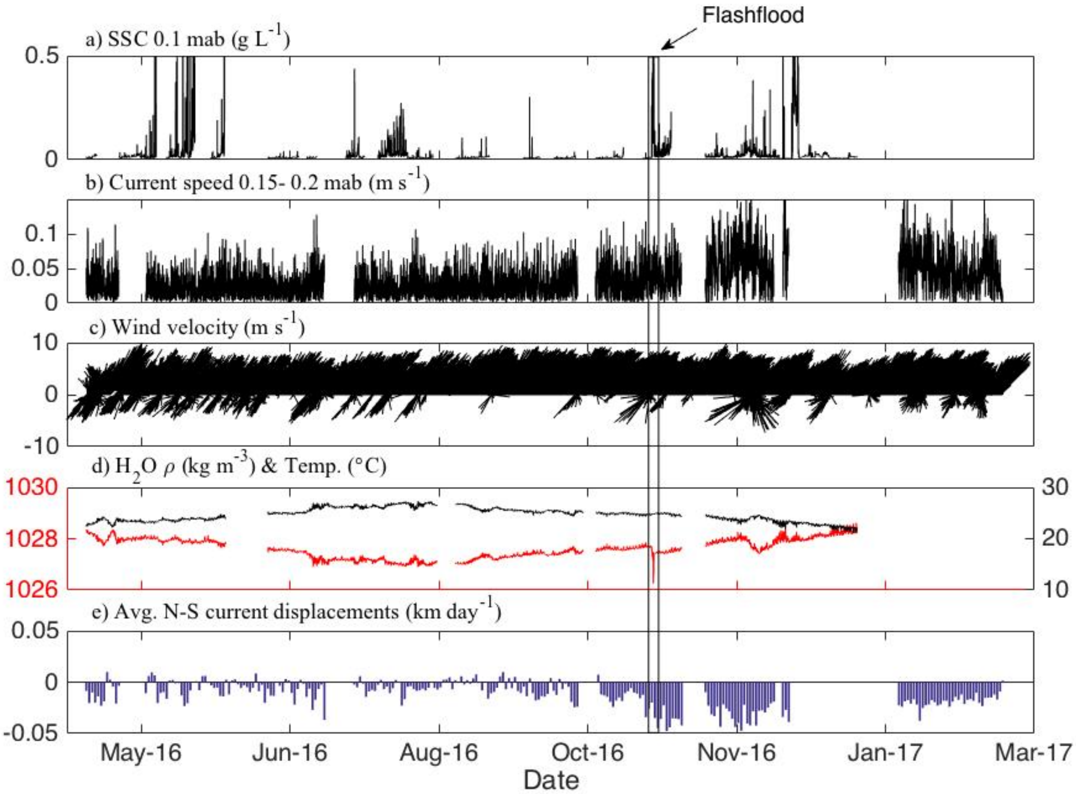

Fig. 4. Physical time-series showing (a) suspended sediment concentrations (SSC) measured from an OBS sensor in relation to potentially influential physical forces. Only clean sections are shown with no observed fouling. Other physical forces and transport mechanisms include (b) current speeds, measured in 10-20 min. intervals, (c) wind velocities, presented in 3 hour intervals (vectors point in the direction from which the wind originated) (d) water density and temperature, measured in 10-20 min. intervals, and (e) Average N-S current displacements, measured per day. Measurements within the grey rectangle show a recorded flashflood event on Oct. 28th, 2016.

3.3 Biological resuspension

Overall, physical forces were not strongly correlated with SSC at the study site, suggesting sediment resuspension was predominantly biological. Results from the GoPro camera are neither conclusive nor quantitative. In many cases, the visibility was too poor for photographs to be analyzed accurately. The abundance of demersal fish that are known to resuspend sediments varied between the summer and fall, with more fish observed in September compared to in June and July. Growth of a seagrass from the *Halophila* genus was also observed in the September deployments. From six deployments in June and July, demersal fish were present in 0-3.5% of useable photographs per deployment, and local resuspension events occurred in 0-7.0% of useable photographs per deployment. In some photographs near bottom sediment plumes were observed when fish were absent, suggesting they could have arisen from fish that were not in the frame or from other benthic organisms. From two deployments in September, demersal fish were observed in 15.1 and 100% of useable photographs per deployment, and local resuspension events were present in 5 and 100% of the useable photographs per deployment. The enhanced presence of demersal fish observed in the September deployments did not reflect in the readings from the OBS sensors at that time (Fig. 4 a). However, since the sources of the OBS measurements were inconclusive, this correlation should be further investigated by linking the abundance and activities of demersal fish to resuspended sediment directly.

3.4 Bioturbation experiment

The vertical distribution of tracer and the amount of tracer recovered per core were analyzed for cores belonging to the triplicates of the three treatments of caged, fenced, and open sites, and the three collection intervals from each site, of t=1 (1 week), t=2 (3 weeks), and t=3 (6 weeks) (n=27). One of the experimental cores from a fenced site collected at t=1 was not recovered properly, and was therefore not included in the reported results. The total number of useable experimental cores was 26. The majority of tracer distributions decreased and formed diffusive profiles from the tracer maxima within each core (Appendix B). In three cores there was evidence of subsurface tracer peaks (Fig. 5, Panels: 3, 7, 10). The average tracer penetration depth within the 26 cores was 4.4 ± 1.8 cm, which stabilized after t=1 (1 week), and the maximum depth interval that contained tracer was 9 cm. There were no apparent effects of time or treatment on variations in tracer distribution or recovery (Shapiro-Wilks normality test, $p>0.05$; 2-way ANOVA, $p>0.05$) (Matlab (R2015b, MathWorks)). Tracer distribution was based on the number of centimetres in a core that contained tracer, and tracer recovery was based on the total tracer area (averaged for each cm) calculated per core.

The depths of peak tracer concentrations varied from 0-7 cm depth within the cores. The observed locations of the tracer maxima were interpreted to be linked to differential emplacement depths of the initial tracers within the seabed. It was assumed that the depressions created from cores transplanted with their surfaces below the ambient seafloor were rapidly buried by surrounding sediment. Alternatively, the observed locations of the tracer maxima within the cores could have been a result of advection of the tracer from the surface from non-local biological mixing, or from burial of the tracer if it was initially placed flush with the ambient seafloor.

Visually, for cores in which the maximum concentration of tracer was located within the top 2 cm of the core, tracers experienced enhanced removal and were more uniformly mixed compared to cores in which the maximum concentration of tracer was located deeper than 2 cm below the seafloor (Fig. 5). To determine if total tracer recovery differed among cores with shallower ($\leq$2 cm) and deeper (3-5 cm) transplant depths, the total tracer area (averaged for each cm) calculated per core in the two groups of cores were compared ($n=11$) using a 2-sample t-test ($p= 0.0148$) (Matlab (R2015b, MathWorks)). This test revealed that significantly less tracer was recovered from cores with tracers emplaced to depths $\leq$2 cm compared to cores with tracers emplaced deeper within the seabed. To test if the variance in tracer distributions varied between the cores with shallower and deeper emplacement depths, the average tracer concentration in each of the 5 cm surrounding the tracer peak were compared ($n=55$) using Barlett's test of equal variance ($p= 0$). This test revealed that tracers in cores emplaced to depths $\leq$2 cm had more uniform distributions than cores with tracers emplaced deeper within the seabed. These results suggest that differential emplacement depth of the tracers masked the effects that time and treatment had on tracer recovery and distribution. More importantly, they demonstrate that mixing and removal were more active in the top 2 cm of the seabed at this site, so preservation potential of a flood layer is increased by processes that reduce the transit time through this zone of active mixing and removal (Bentley et al., 2006).

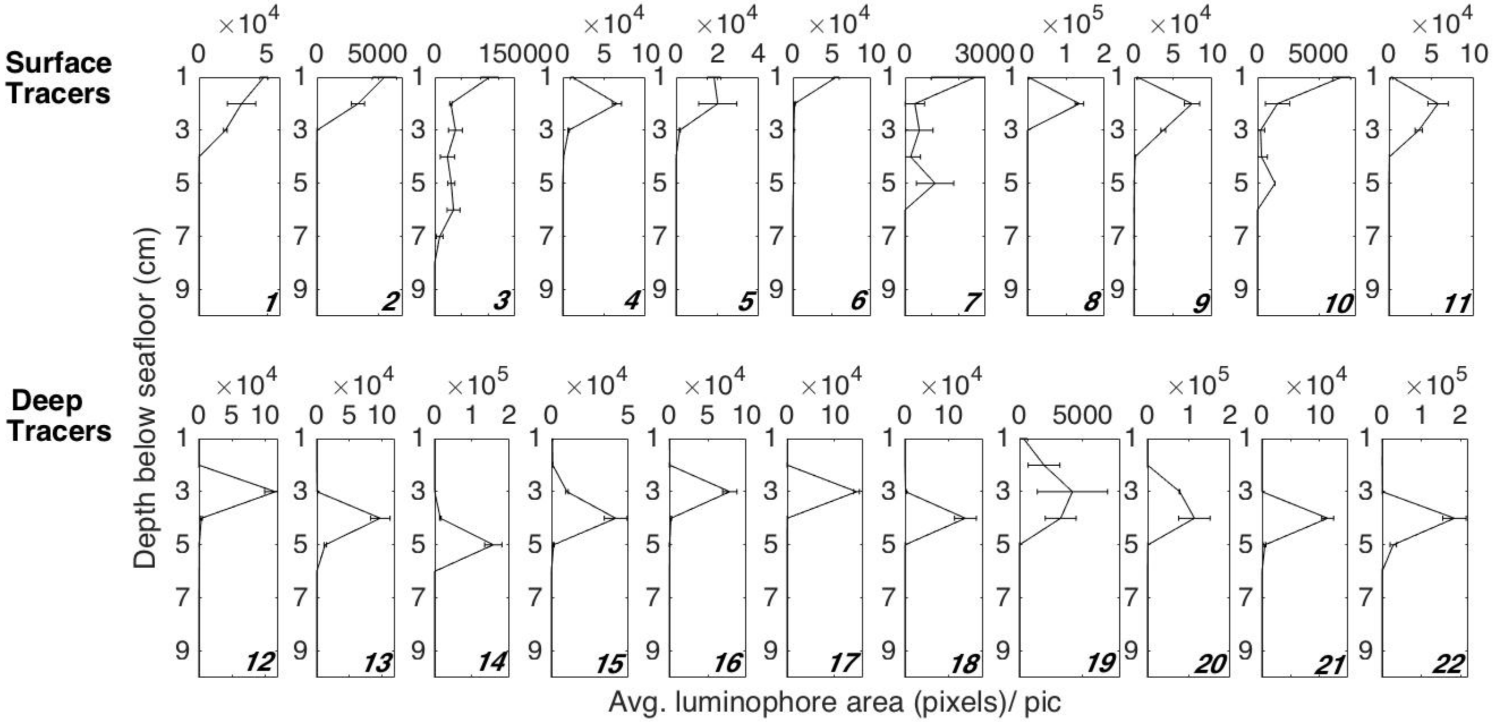

Fig. 5. Profiles showing the distributions of the luminophore tracer down to 10 cm below the seafloor in cores with tracers initially placed $\leq$2 cm below the seafloor (surface tracers) and tracers placed 3-5 cm below the seafloor (deep tracers). Error bars represent the standard deviation from the three luminophore areas measured/ picture/ cm. Note that the x-axis range varies per core, and each panel is numbered in the bottom right corner.

The results from the bioturbation experiment suggest that burial of at least 2 cm below the seafloor significantly increases the preservation potential of flashflood deposits in the shallow GOA. Terrigenous sedimentation in the absence of flooding events, however, is low, so layers are unlikely to be buried deeper than 2 cm by continuous background sedimentation rapidly enough to be preserved.

Other mechanisms must explain why, in some cores, evidence of past flood layers remained. Rapid burial by succeeding flood deposits and burial by sediment redistributed by organisms are two possibilities.

3.5 Biological mounds and depressions

The seabed at the study site was covered by biogenic sediment mounds and depressions (Fig. 6). An average of 1.27 mounds, and 0.94 holes m^{-2} were enumerated, and measurements of the widths and heights of 13 mounds and depths and diameters of 6 holes were recorded (Table 1). The dimensions of some of these features were 5 or more times higher and deeper than the observed thicknesses of flashflood deposits, implying that flashflood sediments deposited within deep holes or subsequently buried by large sediment mounds would be subjected to enhanced preservation potential. The frequency of the deposition of flashflood deposits within deep holes and subsequent burial by large biological mounds varied locally throughout the seabed, which contributed to the resulting lenses of preserved floods in the seafloor.

Within the cores collected from the ambient seafloor, within a hole, and within a mound two and six months after flashflood events, the grain size profiles of fine sediments were established (Fig. 7). From the core from the ambient seafloor, there was evidence of two fine grained layers between the surface and 10 cm depth. Both at the surface and between the layers the sediment coarsened. Within the hole fine sediments accumulated with depth within the core, and within the grain size profile from the mound, a fine grained deposit was buried and preserved at depth.

Fig. 6. Photograph showing seafloor topography at the study site in June, 2017.

Table 1. Measurements of biological mounds and holes from 13 m water depth taken in Feb. & Apr., 2017.

Number	Mound height (cm)	Mound width (cm)	Hole depth (cm)	Hole diameter (cm)
1	12	36	18	27.5
2	19	90	21.5	60
3	14.5	35	9	10
4	20	44	9	15
5	16	44	15	18
6	14.5	51	7	5
7	13.75	46		
8	8.75	41		
9	17.5	46		
10	20.5	80		
11	15	38		
12	16	40		
13	11	7		

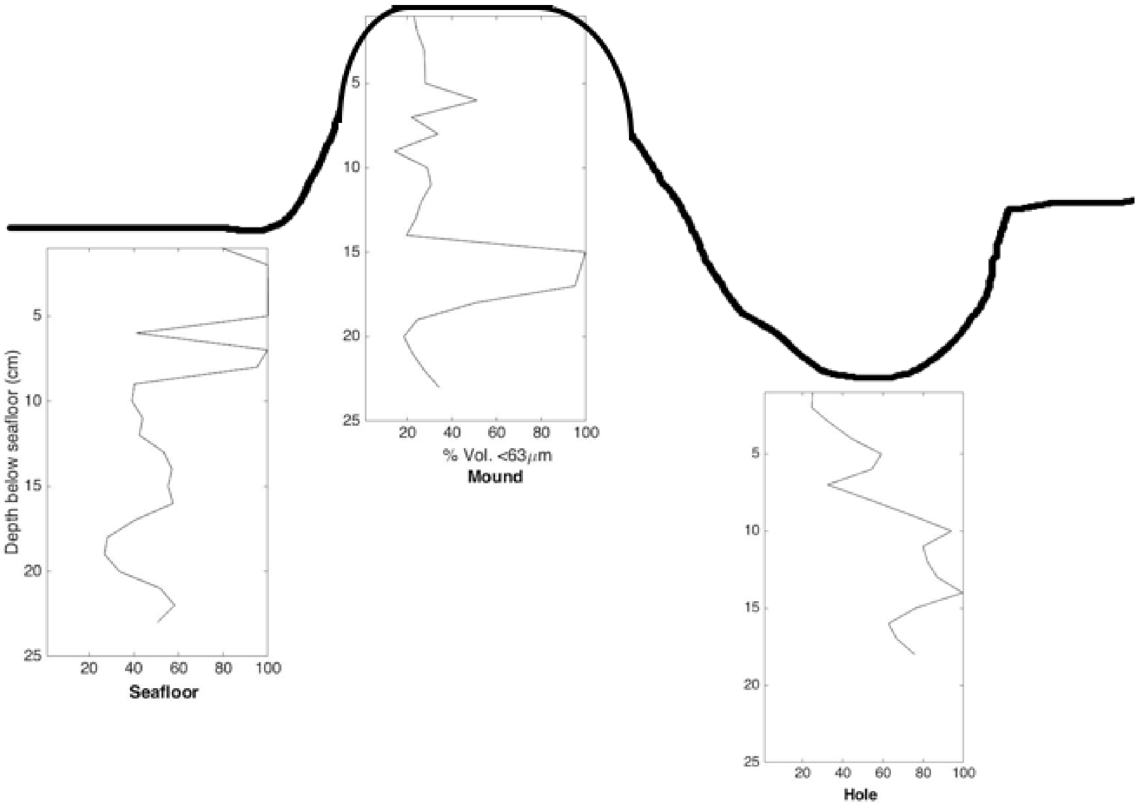

Fig. 7. Distributions of the % volume of sediment <63 μm within cores taken from the ambient seafloor, within a mound, and within a hole.

CHAPTER 4 DISCUSSION

In this hyperarid marine environment with low consistent sedimentation rates, flashflood deposits were not uniformly preserved within the seafloor. Surficial sediments were reworked rapidly by bioturbation activities from benthic organisms and were resuspended by demersal fish. Lenses of flood deposits were locally preserved within the seabed for a few years at least, as deposition within seafloor depressions and subsequent rapid burial by consecutive flooding events or by organism mounds brought the deposits to depths below the mixed layer. In the absence of efficient burial, exposed surface flood sediments were resuspended by organisms and subsequently transported by currents, presumably to deeper depths, where they may have formed a paleoflood record. The slight downward slope of the seafloor caused resuspended sediments to travel farther in the southward (offshore) direction, and sediment transport was enhanced in the winter months when currents were elevated and were preferentially directed offshelf.

4.1 Recent flashflood history

The record of flashfloods entering the GOA via the Kinnet Canal outlet goes back to 1994. Prior to 2012 there was a 14-year drought, with only two floods entering the northern GOA in February 2006 (arrived from Aqaba, Jordan) and in January 2010. In the fall of 2012 three flooding events occurred within 25 days of each other, and after less than two months, two more flashfloods occurred within 10 days of each other in 2013. This high frequency of flooding events could have buried and preserved some of the initially deposited flood sediments. After the final flashflood of that year in February 2013, the following flashflood entered the GOA 13 months later in March 2014. Therefore, by the time the data collection began for the present study in May 2014, flood sediments could have been present within the seafloor from the previous 2.5 years.

4.2 Interpretation of time evolution of flood deposits

The initial thicknesses of flashflood deposits varied spatially on the seafloor between 1-4 cm, shown in replicate cores taken immediately after flashflood events (Fig.

3, Panels: 1, 12-15, 27-28). The variability in flashflood deposit thickness can be attributed to the heterogeneity in the seafloor topography on the scale of metres, through the presence mounds and depressions. Additionally, locally variable biological reworking immediately after emplacement may have contributed to variable initial thicknesses of flood deposits.

Flashflood sediments coarsened from the surface over time, and the rates and magnitudes of coarsening were spatially and temporally variable (Fig. 3). Within three months after the May 2014 flood, a considerable amount of fine flood material was removed from the surface of the seafloor (Fig. 3, Panel: 2). In contrast, following the September and October, 2015 flashflood events, one core retained a fine sediment layer at the surface nine months after emplacement (Fig. 3, panel: 22). Coarsening of surficial sediments resulted from a combination of sediment mixing by bioturbation that both transported fine flood sediments downwards and coarse sediments from below the deposit upwards, and from biological processes that resuspended flood sediments, winnowing them away. Physical processes ultimately removed resuspended flood sediments from the sediment-water interface. The removal of a fine-grained flood deposit from the surface of the seafloor was observed on the continental shelf offshore of the Eel River in California. In 1995, three episodic flood events discharged from the Eel River to the adjacent continental shelf and created a distinct silt-clay deposit that was 5-10 cm thick. In approximately 6 months, the upper portion of the flood deposit thinned and coarsened as a result of sediment resuspension and transport (Bentley et al., 2003). Active biological mixing destroyed the upper portion of the event layer, as it mixed flood sediments with coarser, overlying grains. The most active depth of bioturbation in that region was in the uppermost 5 cm of the seabed, therefore, it was suggested that event layers >5 cm thick would be more likely to become preserved compared to thinner deposits. These works mentioned the preferential removal of fine particles from the sediment-water interface that was observed in the grain size profiles (e.g. in Fig 3, Panels: 18-23), which created “diffusive like” profiles of fine particle concentrations decreasing towards the surface.

Several grain size profiles showed peaks of fine sediment at depth. The appearance of fine sediment peaks between 10-25 cm depth within the core profiles is interpreted to be evidence of flashflood deposit burial from the previous floods of 2012-13. The lack of consistency in the locations and magnitudes of these fine sediment layers within the cores provides further evidence for a high degree of heterogeneity in local sediment mixing, removal, and burial processes. Additional evidence supporting variability in the processes that occurred on and within the seafloor was shown in cores that did not have any pristine flood sediments at depth, and in replicate cores that had different vertical grain size distributions (Fig. 3). Kniskern et al. (2014) and Walsh et al. (2014) found a flood deposit that settled on the shallow seafloor off the coast of New Zealand to be rapidly reworked by different mechanisms and rates of physical and biological processes. This was true for inner regions of the continental shelf, rather than the identified depocentres (between 20-70 m water depth) where contrastingly high concentrations of flood sediment accumulated and remained. It was concluded that a record of flooding events has potential to form within the depocentres, where flood sediments form thicker layers and are subjected to less active biological and physical reworking.

Baumann et al. (2017) explored the sediment record (1.5 m cores, ~ 2000 years) of marine flooding events in back barrier marshes. Distinct alternations between marine flood sedimentation and inter-flood sedimentation were not evident, which was attributed to low sedimentation rates and/or active bioturbation. The benthic environment in the shallow GOA also is characterized by low sedimentation rates and active bioturbation, which may explain the lack of uniform preservation of flashflood deposits.

4.3 Physical forces & transport mechanisms

Current speeds measured by the ADCP were generally not strong enough to resuspend sediments in 13 m water depth. Measured current speeds averaged at 3.7 cm s^{-1} were similar to previous measurements recorded in the northwestern shallow waters of the GOA, at 4.6 cm s^{-1} (Yahel et al., 2002).

Northeastern winds prevailed throughout the 10-month data collection period of this study. Yahel et al. (2002) measured maximal wave heights of <0.1 m during northerly winds throughout a 1.5-year period on the shallow northwestern shore of the GOA. When winds originated from the south, however, wave heights >2 m were recorded and were associated with increased turbidity in the water column. The datasets obtained from this study were insufficient for resolving the causes of the prolonged OBS recordings measured throughout the time-series. Since the currents in this environment were too weak to resuspend sediments at 13 m depth, the prolonged increases in OBS readings were not a reflection of current induced physical resuspension. Turbidity measurements were not correlated to enhanced wind speeds or direction, which could have caused wave stresses capable of resuspending shallow sediment on the northern shore that were then transported south and measured by the OBS sensors. This interpretation is speculative, however, because measurements on wave height and period were not available at the study site. Enhanced SSC measurements were also not correlated to daily chlorophyll measurements (i.e. plankton blooms) from the northwestern GOA shore, although measurements could have differed on the northern shelf. Prolonged increased turbidity may have been a result of sediment input from construction on the north GOA shore in Aqaba, Jordan, where rapid development takes place, however this too is speculation, and further investigation is required.

Katz et al. (2015) proposed that rapid removal of the majority of fine flood sediments was attributable to biological resuspension, and that subsequent transport of flood sediments offshelf was controlled by currents and bottom slope. In the present study, current directions on the northern shelf were primarily longshore, which would have caused alongshore transport and redistribution of resuspended flood sediments rather than cross shore transport. However, due to the mean slope of the seafloor of 3°, resuspended sediment that was subjected to southward directed currents would travel farther compared to suspended particles that were transported by northern currents (Katz et al., 2015), therefore, over time, the net direction resuspended flood sediments would travel would be south and potentially offshelf. To catalyze this process, in the fall and winter months, current velocities increased and were oriented preferentially offshore and to the south (Fig. 4 e). It was noted by Milliman & Syvitski (1992) that the sediment load carried within energetic, episodic events such as flashfloods, which originate from small drainage basins surrounded by mountains, is more likely to travel to the deep basin when the continental shelf is narrow.

Other mechanisms that can cause sediments to accumulate at deeper depths are post-depositional biological and physical processes. On the continental shelf off the Eel River in California, both recent and historical flood sediments deposited and appeared in the sediment record in the middle of the continental shelf due to transportation by wind-induced suspension and seaward flowing currents (Sommerfield & Nittrouer, 1999). This suggests that current directions and magnitudes could infer locations where sediments accumulate and potential event layer preservation can occur. Rapid dispersal of flood sediments on and off of New Zealand's narrow continental shelf occurred within two weeks of a large flood event in 2010 due to initial transport of the flood water and/or due to multiple resuspension events that occurred after the event (Kniskern et al., 2014). Effective transport mechanisms in shallow waters caused flood sediments to be better preserved in the intermediate shelf area, which was characterized by less active biological and physical reworking activities (Walsh et al., 2014).

Elevated southward currents during November and December were associated with elevated wind speeds from the south, increased water density from lowered atmospheric temperatures, and enhanced near bottom turbidity measurements (Fig. 4). This can be explained by the occurrence of dense water formation, which begins when cooler surface water from the Red Sea travels through the Straits of Tiran into the GOA. As this water reaches the northern gulf, it undergoes additional cooling from the atmosphere in the fall and winter, subducts due to its increased density, and flows along the bottom back out towards the mouth of the Red Sea (Biton & Gildor, 2011). This offshelf transport, in addition to the more diffusive transport caused by biological resuspension year round, potentially could create a flashflood record within sediments in the deep basin. In order to get insight into the locations on the seafloor with highest sediment accumulation rates and minimal biological and physical reworking, it is important to sample multiple depths on and off of the continental shelf both immediately after a flood and shortly after (~1 year) (e.g. Sommerfield & Nittrouer, 1999; Kniskern et al., 2014; Walsh et al., 2014).

4.4 Biological resuspension

The observation that surface sediments coarsened during the year after flooding events and the inconsistent presence of fine sediments at depth within the seabed suggest that surface flood sediments undergo removal. Data obtained from the GoPro camera deployments, which photographed the near bottom environment, revealed that demersal fish were present episodically at the study site and that they were associated with the appearance of sediment plumes above the seabed.

Qualitative observations included an increased abundance of demersal fish in the September deployments compared to the footage from June and July. The presence of *Halophila* seagrass was only observed in the September deployments, suggesting there may be seasonal changes in fish abundance. Within the photographs, Forsskal's goatfish (*Parupeneus forsskali*) were observed on multiple occasions. Yahel et al. (2002) identified these benthivorous fish to be the primary sediment-resuspending fish in the shallow coral reefs of the GOA, and they were occasionally observed to dig trenches 10-15 cm deep and >10 cm long within a single resuspension event. As well, their study showed sediment resuspension was primarily associated with fish activity as opposed to physical forces. This conclusion was based on the finding that sediment resuspension decreased when fish were excluded from areas of the reef (26-86% less) and on the lack of correlation between turbidity and currents.

Yahel et al. (2002, 2008) showed that demersal fish have the capacity to rework the upper centimetres of the seabed within days. The measured rate of fish induced sediment resuspension was >36 events m^{-2} day^{-1} in the shallow coral reefs of the GOA, which translated to reworking of surficial sediments over a period of only 5 days (Yahel et al., 2002). As well, Yahel et al. (2008) measured fish resuspension events at ~90 m depth in the Saanich Inlet in Canada, where current speeds were similar to those measured in the present study, and found that reworking of surficial sediments occurred within 2.5 days. These findings shed light on how important fish induced biological resuspension can be in influencing the preservation of event beds at the sediment surface.

4.5 Influences of bioturbation on the integrity of flashflood deposits

The results from the bioturbation experiment support the observations from the bi/tri-monthly grain size profiles, where flood deposits on the seafloor were removed from the surface and mixed vertically within the seabed over time. The distributions of the luminophore tracer within the majority of the cores decreased from the location of the tracer maxima. This profile shape was similar to those in experimental cores from Gerino et al. (1998), who conducted an *in situ* bioturbation experiment using luminophore tracers over 2-3 weeks in a low energy marine environment. Subsurface tracer peaks were present within three core profiles at ~ 3 cm and 5-6 cm below the seafloor (Fig. 5, Panels: 3, 7, 10). Gerino et al. (1990, 2007) also observed subsurface peaks in luminophore tracers used to quantify bioturbation rates *in situ*, and attributed this to bio-advective activities resulting from non-local mixing. The average and maximum penetration depth of the tracer was 4.4 and 9 cm, respectively, which is in line with the universally estimated mixing depth (L_b) in marine sediments of ~9.8 ± 4.5 cm (Boudreau, 1994).

The primary result from the bioturbation experiment was that differential tracer emplacement depth had the strongest influence on vertical mixing and removal of the tracer. This potentially masked the effects of time and differential exposures to sediment resuspension processes. The results imply that flashflood deposits thicker than 2 cm have greater preservation potential compared to thinner deposits, as the top 2 cm were exposed to the strongest mixing and removal. Black & Calder (2012) conducted a survey of macro infauna at ~23 m water depth on the northern shelf of the GOA, and found 84% of species in the top 3 cm of the seabed. Assuming the distribution of macrofauna is similar at 13 m depth, this finding supports the results in the present study. As well, Bentley et al. (2006) calculated bioturbation rates to be 1-3 orders of magnitude stronger in the upper half of the mixed layer depth (L_b) compared to the lower half, consistent with the results of the bioturbation experiment.

Experimental evidence of event layer preservation in the lower half of L_b was shown on areas of the continental shelf off California, where preservation of flood deposits that formed a layer 5-10 cm thick of silt-clay material was enhanced when deeper than 5 cm (Bentley et al., 2003). However, the preservation potential decreased in areas of the shelf colonized by relatively larger, deeper dwelling organisms that moved through and altered the sediment stratigraphy down to 25 cm. If flashflood deposits are thicker than $L_b/2$, their bottom portions are more likely to become preserved within the sediment stratigraphy. Additional evidence of bioturbation activities effecting the preservation potential of event layer signatures was found in the shallow marine sediment stratigraphy off the coast of Japan, where a tsunami deposited in 2011. Three years following the event, sediment cores revealed burrows created by deep-dwelling organisms traveled throughout the distinct tsunami deposit (Seike et al., 2016). Burrows were present down to the bottom of the 25 cm long sediment cores, which did not reach the bottom of the tsunami deposit. Therefore, if the deposit was deeper than the bioturbation depth, preservation of the primarily deposited tsunamigenic sediment would be expected. It was concluded from this study that within 3 years, the preservation potential of event layers was reduced due to recolonization of the sediment by organisms responsible for effective bioturbation processes.

Flashflood deposits were preserved in some locations throughout the seafloor between 10-25 cm depth. These deposits were presumably from the 5 consecutive flashflood events that occurred within a 4-month period between 2012-13. If the resulting flood deposits were thick enough in some locations, to depths at least below $L_b/2$, then those fabrics would have a better chance of maintaining their integrity and becoming preserved within the seabed. Since the following flashflood event after 2013 occurred 13 months later, bioturbation and biological and physical resuspension and removal processes had the opportunity to mix and remove flood sediments. The preservation potential was therefore dependent on local rates and magnitudes of post-depositional mixing, removal, and burial. Gerino et al. (2007) found high local variability in bioturbation activities in the shallow waters of the Venice Lagoon, suggesting local heterogeneity in biological mixing may be common in marine environments.

With regard to the significantly enhanced removal of tracer sediments that were initially placed $\leq$2 cm below the seafloor compared to deeper emplaced tracers, benthic organisms could have been responsible for this enhanced resuspension. Bioturbation activities can significantly enhance biologically induced resuspension by increasing the roughness height of the sediments (Graf & Rosenberg, 1997) and by breaking down the cohesion between silt-clay sediments (Davis, 1993). It has been suggested that resuspension from bioturbation activities is important to consider within the marine sediment budget, as it can increase particle resuspension by a factor of 3-8 depending on species and population density (Davis, 1993). If very fine sediments are resuspended by benthic organisms, removal is likely due to their very slow settling velocities (Graf & Rosenberg, 1997). Sediment mounds created by the thalassinid mud shrimp, *Callianasa subterranean*, increased sediment turnover by an average of 11 kg m^{-2} $year^{-1}$ in the North Sea (Rowden et al., 1998). Sediment reworking rates by *C. subterranean* varied throughout the year, highlighting the importance of considering intra-annual variability in biological reworking by an organism. Bioresuspension from the bivalve *Yoldia limatula* ejected ~ 20 kg m^{-2} $year^{-1}$ in Narragansett Bay in Rhode Island, and preferentially ejected finer sediments, thereby influencing the grain size distribution within the seafloor (Bender & Davis, 1984). These experiments highlight the considerable influence benthic organisms can have on biological resuspension, and therefore on their potential influence on event layer alteration.

4.6 Influences of mounds and depressions on preservation of flashflood deposits

Because the initial thickness of flashflood deposits varied between 1-4 cm, the preservation potential from one flashflood event was spatially heterogeneous at the same water depth and general location. In many observed locations, initial flood layers in the shallow GOA were thinner than the universal mixed layer depth, therefore over time they were likely to get destroyed by bioturbation, and fail to become preserved as 'historical layers' within the seabed (coined by Berger et al., 1979, from Bentley et al., 2006; Wheatcroft & Drake, 2003). If thick enough, the initial sediment deposited from a flooding event would have greater preservation potential compared to sediment that settled later on during the event (Steiner et al., 2016). The local heterogeneity in the magnitude of the initial deposition of flood deposits and subsequent burial by biological mounds and by consecutive flooding events resulted in lenses of preserved floods throughout the seafloor. The transects conducted counting and measuring biological mounds and depressions on and within the seafloor revealed that these features were abundant (~1.27 mounds and 0.94 depressions m^{-2}) and some were >5 times higher and deeper compared to flood deposit layers. Therefore, their presence likely contributed to differential flashflood deposition and subsequent burial.

Within the core taken from the ambient seafloor, the coarsening that occurred at the surface and between the two fine-grained layers in the top 10 cm provides further evidence that surface flood sediments become winnowed if they are exposed to resuspension and removal. Within the hole, fine sediments accumulated with depth within the core, indicating that fine sediments can become trapped within seafloor depressions, and flashflood deposits may be better preserved in those locations. This has been investigated by Yager et al. (1993), who found fine sediments sink and accumulate within pits formed in the seafloor at faster rates than on flat seafloor patches, and that particle flux was positively correlated with increasing pit size. Within the grain size profile from the mound, a fine grained deposit was buried and preserved at depth within the core, further supporting the enhanced preservation biological mounds can offer if they form (or spill sideways) over flashflood deposits, keeping the layers at a depth (distance) from the surface where they are safe from biological and physical reworking. It is thought that mound-building organisms expel sediments from below the seafloor surface, and therefore expel mostly coarser, sand sized sediments in this environment. If rates of biological sediment resuspension are measured, then the time required to form mounds and the masses of ejected sediment can be calculated and used in the sediment budget.

4.7 Preservation of event layers in biologically active environments

The preserved layers or lenses of flashflood deposits were likely attributable to relatively high deposition in locations with depressions in the seabed, and to subsequent rapid burial by biological mounds and consecutive flashfloods. Considering the measured sedimentation rate of 1.3 mm year^{-1} at 16 m water depth on the northern GOA shelf (Goodman et al., 2016), it would take 100 years to bury sediments to 13 cm depth. Given the fast dissipation time of surface flood sediments of <1 year, burial processes must occur at comparable speeds, therefore within months. In environments with fast sedimentation rates, or if episodic sedimentation is high, event layers can become preserved in the sediment record (Wheatcroft & Drake, 2003; Bentley et al., 2003; Steiner et al., 2016). It is imperative that sedimentation processes bury flood deposits to depths where they are no longer affected by physical and biological processes to become preserved (Wheatcroft, 1990; Bentley et al., 2006). The only ways a distinct flashflood deposit could have the potential to become uniformly preserved within the seafloor at a single water depth in this environment is if (1) the initial flood deposit was uniformly substantially thicker than L_b, (2) the deposit was quickly buried by consecutive floods, bringing an entire portion of the primary deposited flood sediments to depths below L_b (Wheatcroft & Drake, 2003; Bentley et al., 2006), or (3) if the benthic environment was anoxic, and bioturbation rates were negligible (even then, this would depend on rates of resuspension). Since sedimentation rates are low in the shallow GOA, consecutive flooding events contributing large quantities of sediment would be the most efficient means of uniformly preserving flood deposits (Bentley et al., 2006).

Even if a flood deposit does become buried to depths below physical and biological reworking depths, if sediments are being resuspended, removed, and mixed at rates faster than sediment is accumulating, then the bioturbation depth will eventually penetrate deeper into the seabed as the seafloor surface subsides, and the chances of the event layer remaining preserved within the sediment record will be reduced (Fig. 8). This occurred in the preserved tsunami deposit off the coast of Japan, where in the years following burrowing organisms travelled through the deposit and altered its signature (Seike et al., 2016). Since sedimentation rates in the GOA are low in the absence of flashflood events, surface sediments that are subjected to active mixing, resuspension, and removal will eventually expose preserved flashflood deposits to these processes, and will lessen their preservation potential.

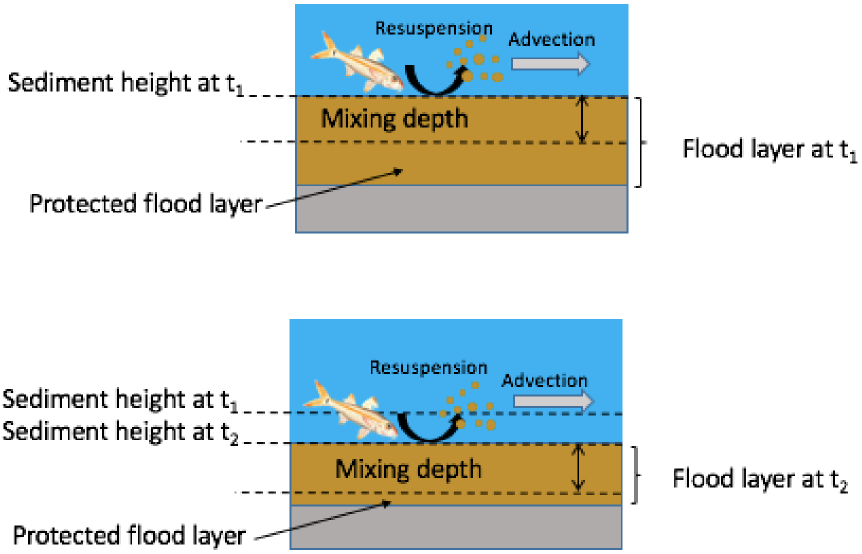

Fig. 8. Diagrams depicting how the preservation potential of an event layer can be reduced if bioturbation and resuspension rates exceed sedimentation rates.

For future work, it is important to quantify year-round rates of sediment resuspension by demersal fish and benthic organisms on the northern shelf of the GOA, and to link these rates to the fate of flashflood deposits. Data on wave height and period collected by an ADCP would be relevant to provide insight into wave-induced resuspension of sediments at various water depths. As well, quantifying local, short timescale bioturbation rates and sediment accumulation rates at a single water depth would contribute to elucidating the preservation potential of flashflood deposits. Surveys on the abundance, sizes, and activities of benthic organisms present would be useful in interpreting the fate of surface sediment mixing and biological resuspension. It is also relevant to further study the formation processes of biological mounds and depressions on the seafloor, to get more information on rates and mechanisms of local sediment accumulation and removal. Finally, sampling at deeper water depths on and off of the continental shelf to find depocentres of flashflood deposits years after known events occurred would be relevant in identifying more ideal locations for reconstructing paleoflood records.

CHAPTER 5 CONCLUSION

Flashflood deposits that settle on the shallow seafloor of the GOA form a distinct fine-grained deposit, which can be distinguished from the coarser sediments that remain in this environment in the absence of flashflood events for at least one year. The initial thickness of flashflood deposits varied between 1-4 cm, due to the high variability in the seafloor topography created by sediment mounds and depressions formed by burrowing organisms. Over the course of a year from a flashflood event, the surface flood sediments coarsened from the top down via efficient downward mixing of the flood deposit from bioturbation activities, and resuspension and removal of fine flood deposits from the surface of the seafloor. Despite this efficient removal, fine-grained sediment layers were preserved within some locations of the seabed between 10-25 cm depth. Three mechanisms of flashflood deposit preservation in this environment are suggested. The first is if the flashflood was deposited within a hole or depression in the seafloor, that flood layer would be less exposed to resuspension and removal processes compared to that experienced on the ambient seafloor level. The second and third mechanisms of flood layer preservation are if flashflood deposits become rapidly buried by sediment mounds built by organisms or by ensuing flashfloods, which bring the flood deposits to depths where they are no longer affected by biological and physical mixing and removal processes.

In general, water currents were too weak to resuspend flood sediments at 13 m depth, and demersal fish were observed to interact with and resuspend sediments periodically at the study site. However, biological resuspension rates from fish were not quantified within this study. Dense water formation in the fall/winter caused enhanced southward currents, and catalyzed the process of transporting resuspended flood sediments to deeper depths, providing a possible indicator that flashflood records formed at deeper depths in the GOA. Bioturbation was most active in the top 2 cm of the seabed, and luminophore tracers experienced significantly enhanced removal and were more uniformly mixed compared to tracers >2 cm below the seafloor. This suggests burial of at least 2 cm better preserves the sediment stratigraphy. Due to variability in seafloor relief, in addition to locally variable rates of sediment resuspension and mixing processes dominated by biology, lenses of flashflood deposits were preserved throughout the seabed, for at least a few years. Additional flashflood events would further enhance the preservation potential of those preserved deposits by burying them deeper. In the absence of sedimentation and in the presence of strong bioturbation and biological resuspension activities, preserved flashflood deposits may eventually become exposed to processes that can destroy their signatures.

With regard to reconstructing a record of the frequencies and magnitudes of flashflood events in marine sediments in the GOA, deeper depths on the shelf or the deep basin may be more ideal than the shallow shelf if enough flood sediments are transported south and offshelf. To better interpret the deep sea sediment record, it would be relevant to consider if large quantities of sediment are removed from the shelf break to the deep when certain mass thresholds are exceeded, as well as differentiating flashflood sediment signatures from sediment deposited from slope instabilities (Postma, 2001). The shallow shelf is characterized by high biological activity with regard to sediment mixing and resuspension, which destroys flashflood deposit signatures within one year if they are not buried. Unless flashflood frequencies and magnitudes were exceptionally high for a period of time, uniform preservation within the seabed is unlikely at shallow depths. This information is relevant to consider when interpreting the marine sediment record, especially in arid locations with low sedimentation rates, and in locations characterized by active processes of sediment reworking.

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APPENDIX A: OBS Calibration Curves

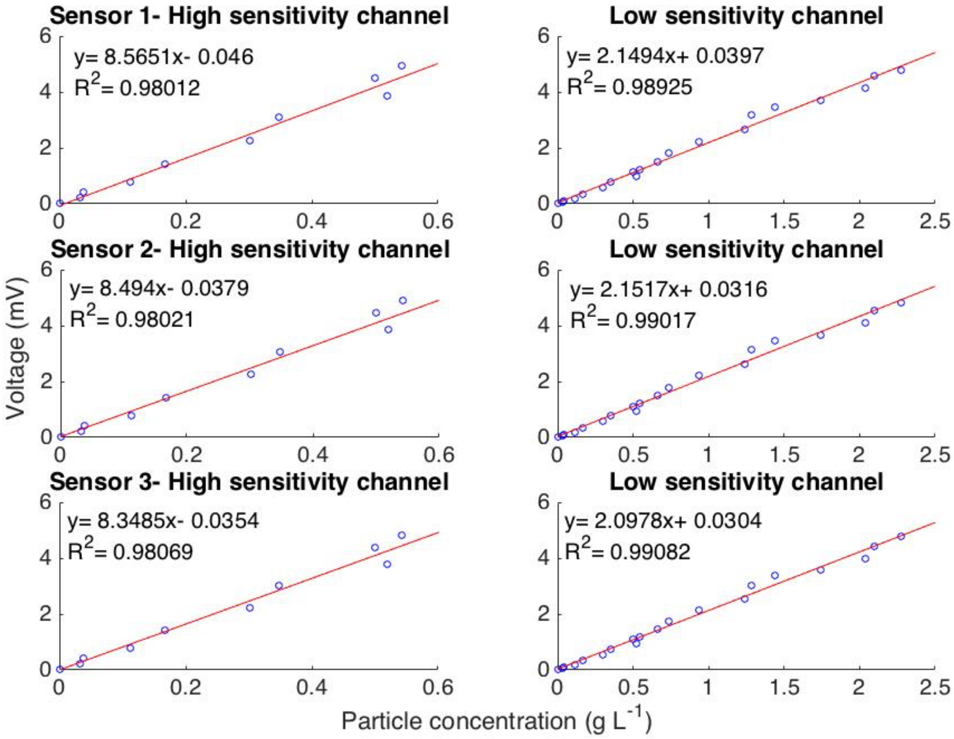

Fig. 9. Calibration curves for both channels of the three OBS sensors.

APPENDIX B: All Bioturbation Core Profiles

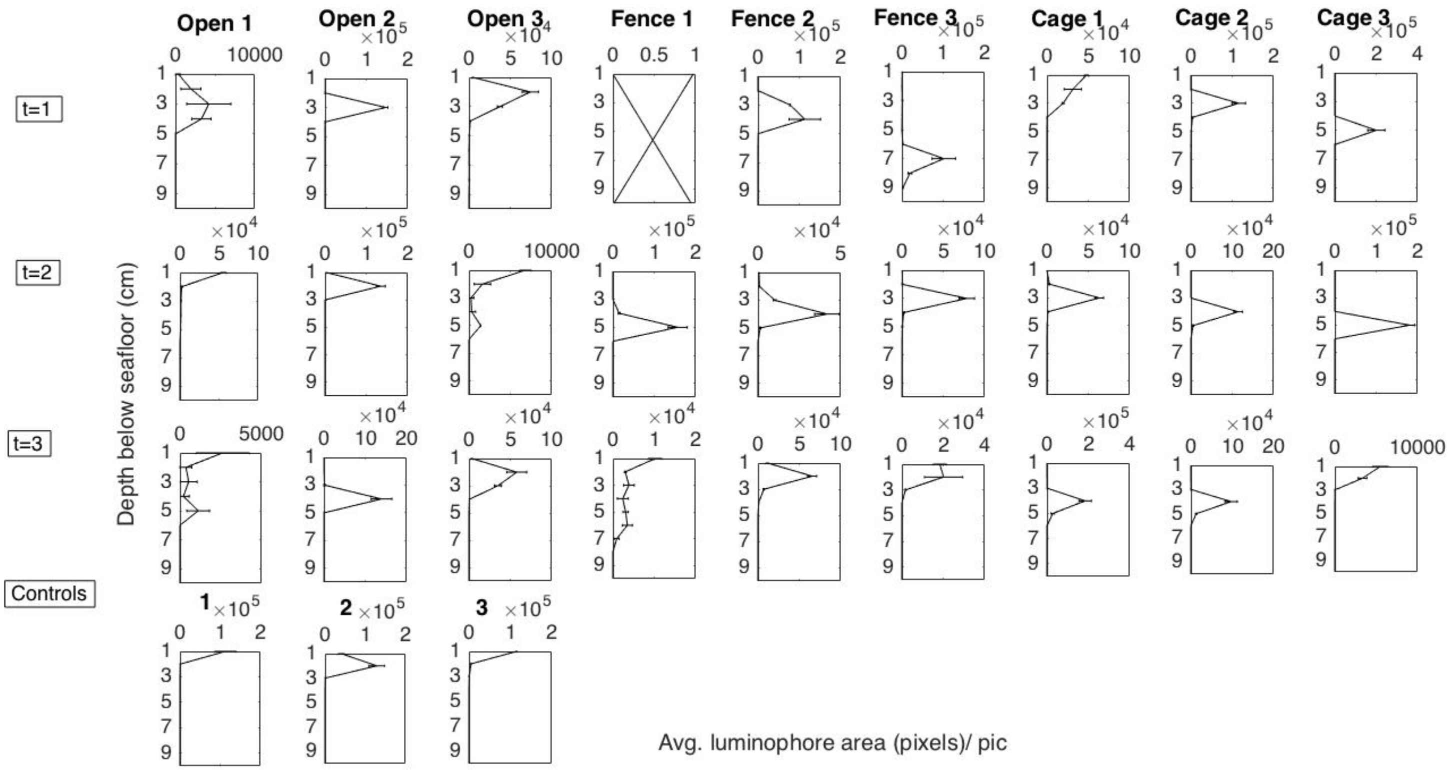

Fig. 10. Profiles showing the distributions of the luminophore tracer down to 10 cm below the seafloor in cores placed in three open sites, fenced sites, and caged sites, respectively (columns), and recovered at three time intervals of 1 week (t=1), 3 weeks (t=2), and 6 weeks (t=3) (rows). As well, there are the profiles of three control cores that were organism free, which were emplaced at t=1 and removed at t=3. Note that the x-axis range varies per core.

APPENDIX C: Bioturbation Experiment- Cores With Bottom Tracers

Nine additional short cores were collected from the study region, and 1.5 g of luminophores >250 µm were mixed with 2 g of surface sediment to form tracers, which were placed at 20 cm depth within each core. The intention for cores with bottom tracers was to track sediment accumulation or removal over time, by having the tracer positioned at a fixed depth in the seafloor below biological and physical reworking processes. One core with a bottom tracer was transplanted into the seafloor in the remaining corner hole in the location plate at each site (3 caged, 3 fenced, and 3 open sites). These cores were left in the seafloor for 4 months. They were recovered using longer cores, to ensure the tracers would be retrieved. Upon collection they were immediately sectioned in the lab in 1 cm intervals to determine the length of sediment above the tracer, compared to the original sediment length of 20 cm.

Tracers were recovered in 7 out of 9 of the cores. Within the 7 cores, sediment was removed, with an average of 6 ± 2.4 cm removed within the 4-month period. Within two of the cores the tracer was present in >10 cm, suggesting that bioturbation activity occurred deeper in those locations compared to in the cores with surface tracers. This could have been because these cores were in the seafloor for 4 months as apposed to a maximum of 6 weeks, as in the cores with surface tracers. This experiment should be repeated, as well as with using more accurate devices such as a sediMeter to measure local rates of sediment accumulation/removal over time.