Going with the flow: Experimental simulation of sediment transport from a foraminifera perspective

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ABSTRACT

Transport of continental shelf sediments to the deep ocean can be studied from displaced symbiont-bearing larger benthic foraminifera found in turbidity current deposits. The larger benthic foraminifera habitat depth, physical characteristics and preservation serve as indicators for understanding sediment transport dynamics near the seabed and in the water column. Here, an experiment was designed to explore sediment transport in a closed flume system using simulated high current velocities. Shelf sediments from the Gulf of Eilat/Aqaba, dominated by Amphistegina papillosa and Operculina ammonoides, were subjected to 60 cm s⁻¹ and 80 cm s⁻¹ current velocities while collected in a 10 cm vertical sediment trap. Larger benthic foraminifera abundance, shell physical properties and preservation were analyzed and compared with the original bulk sediments. The experiment results showed that at 80 cm s⁻¹ velocity, larger benthic foraminifera shells of all sizes and preservations were efficiently resuspended and transported in large quantities throughout the water column, as opposed to their transport as bedload by the lower velocity current. Larger benthic foraminifera shape also has a role in the transport distances and accumulation depths. Operculina ammonoides shells were found to be more portable, compared to Amphistegina papillosa, due to their flatter discoid shape. The results suggest that a threshold velocity of ca 80 cm s⁻¹ was needed to generate the thick coarse deposits found in the Gulf of Eilat/Aqaba slope sedimentary record, which were previously suggested to be triggered by large magnitude seismic events. Lower velocities probably winnowed minor amounts of larger benthic foraminifera shells (with little or no coarser sediments) that were deposited as a thin sand layer may point to lower magnitude seismic triggers. In conclusion, larger benthic foraminifera shells are transported and deposited in accordance with their hydrodynamic properties, resulting in assemblage differentiation along the transport
INTRODUCTION

Displaced benthic organisms, and particularly foraminifera, are one of the characteristics used for identification of turbidity current, and other mass transport deposits in the geological record, along with coarser grain size, different mineralogy and higher organic carbon content (Gao & Collins, 1994; Zabel & Schulz, 2001; de Haas et al., 2002; Masson et al., 2006; Tesi et al., 2010; Ducassou et al., 2013; Ash-Mor et al., 2017). The composition of turbidites differs from the deep-sea pelagic sediments and may also vary with distance along the transport pathway (Mulder & Alexander, 2001; Stevenson et al., 2015; Mulder et al., 2019). The sedimentology of turbidites can assist in revealing the triggers for events that produce them, the preconditions that can lead to sediment collapse, and the dynamic conditions during the transport event. Considering that submarine mass transport events are potentially hazardous and difficult to predict, these factors may contribute to the assessment of seafloor stability for marine infrastructure and engineering, and can serve for reconstructing past records such as palaeoseismic archives important for geohazard assessment (Masson et al., 2006; Mosher et al., 2010).

Composition of displaced foraminifera assemblages in turbidites serve as useful indicators for the primary living environment and deposition depth, sediment source area and transport distance, at a variety of marine environments related to gravitational transport (Maslin et al., 2005; Ducassou et al., 2013; Ash-Mor et al., 2017), shallow long-shore transport (Benavente et al., 2005) and deep open ocean currents (McCave, 1995). Changes in the assemblage preservation along the transport pathway can also serve as a powerful tool to study the dynamic properties during transportation. Well-preserved microfossils, identified in coarse sediments, have been previously used as evidence to support laminar flow conditions (Hodgson et al., 2018). However, they have not been systematically studied for this purpose yet. Symbiont-bearing larger benthic foraminifera (LBF) that inhabit a narrower and shallower water depth range in accordance with light requirements and restrictions of their symbionts (Leutenegger, 1984; Reiss & Hottinger, 1984; Edelman-Furstenberg et al., 2001; Perelis-Grossowicz et al., 2008) are particularly informative as they can indicate the source and original water depth before displacement.

The occurrence of turbidity current deposits is usually considered to be the result of several factors or preconditions that trigger mass transport events (Talling et al., 2013; Talling, 2014). For instance, Japan is frequently affected by earthquakes and tropical storms (Yordanova & Hohenegger, 2002; Sugawara et al., 2009), while in Italy turbidites are essentially a combination of high sedimentation rate, due to river discharge, and tectonic activity occurrence (Polonia et al., 2015). Turbidites were previously described by Ash-Mor et al. (2017) in sediment cores collected from the continental slope of the tectonically active Gulf of Eilat/Aqaba (GEA). These deposits were identified as turbidites due to their graded bedding character, typical for this type of deposit. The GEA is the northeastern arm of the Red Sea and is part of the East African Rift system. It is a long (180 km), narrow (ca 15 km) and deep (up to 1830 m) semi-isolated basin surrounded by deserts (Fig. 1A and E). Turbidites in the GEA were correlated with historical earthquakes documented in seismic catalogues (Ambroseys et al., 1994) and dated fault ruptures described in palaeoseismic trenches (Zilberman et al., 2005; Klinger et al., 2015; Lefevre et al., 2018). These turbidites consisted of more than 70% coarse sediments and high abundance of LBF in various shell sizes and degree of preservation (Fig. 1). The turbidites identified by Ash-Mor et al. (2017) occurred during the Holocene, when sea levels were stable (Biton et al., 2008a). Combined with the low sedimentation rates during this period, due to the hyper-arid conditions (Arz et al., 2003) and the tectonic settings of the area, it was suggested that seismic activity had a major role in triggering the deposition of turbidites.

Keywords Current velocity, flume experiment, sediment transport, symbiont-bearing larger benthic foraminifera, taphonomy, turbidites.
Fig. 1. (A) Regional map (bottom) and the bathymetry map of the Gulf of Eilat/Aqaba (GEA) (top) following Sade et al. (2008). White diamonds indicate the location of bulk sediment samples used for the flume experiment. White dots show cores location sampled by the MG10 survey and analyzed by Ash-Mor et al. (2017). Black dots show location of unanalyzed cores taken during the MG10 survey. (B) A section of core MG10P27 (92 to 132 cm) demonstrating the pelagic and the turbidite sediments. (C) Number of larger benthic foraminifera (LBF) shells >1 mm per g sediment in the core section. (D) Number of poorly preserved LBF shells per g sediment. (E) Bathymetry profile of the western continental shelf and upper slope of the GEA (after Tibor et al., 2010). Yellow stars mark the location of the bulk sediment samples. (F) and (G) Well, moderately and poorly preserved O. ammonoides and A. papillosa, respectively (Ash-Mor et al., 2017).
Therefore, the GEA can serve as a natural laboratory for studying sedimentary processes triggered by seismic activity and their dynamic effects on the seafloor environment. In this paper, further investigation is dedicated to the transport process itself.

Tidal, longshore and surface currents in the GEA shelf will rarely exceed velocity of 20 cm s\(^{-1}\) (Monismith & Genin, 2004; Biton \textit{et al.}, 2008b; Biton & Gildor, 2011; Carlson \textit{et al.}, 2012). Previous studies show entrainment of LBF at such current velocity occurs in laboratory experiments (Yordanova & Hohenegger, 2007; Briguglio \textit{et al.}, 2017). However, LBF shells do not appear in the deep sea fine pelagic sedimentary record of the GEA (Halicz & Reiss, 1981), and therefore it was concluded that they are not transported in the water body through great distances under such conditions in this area (Ash-Mor \textit{et al.}, 2017). However, they were described in turbidites collected on the GEA slope (Ash-Mor \textit{et al.}, 2017) and were likely entrained with displaced sediments transported due to enhanced current velocity triggered by a seismic event (Fig. 1B to D). The approach used in this study was designed to inspect the transport of LBF shells in the water column near the seafloor under different current regimes.

To do so, a flume experiment was designed to simulate sediment transport processes at different flow velocities that occur at the deeper shelf and down the continental slope. So far, studies using flume systems demonstrated the vertical and horizontal changes in grain size and benthic fauna concentrations along the current direction, simulating only the near shore environments (Blom \textit{et al.}, 2003; Fick \textit{et al.}, 2018). In addition, recent and fossil larger foraminifera were studied in relation to suspended load versus bed load and their connection to the formation of 

<table>
<thead>
<tr>
<th>Water depth</th>
<th>Weight</th>
</tr>
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<tbody>
<tr>
<td>70 to 90 m</td>
<td>2.8 kg</td>
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<tr>
<td>68.8</td>
<td>7.4 kg</td>
</tr>
</tbody>
</table>

Material and Methods

Sediment collection – ET14 survey

Approximately 10 kg of bulk sediments were collected from the western shelf of the GEA at water depth ranging between ca. 70 to 90 m (Fig. 1A and E; Table 1), on 6 April 2014, using a Van Veen grab 1000 cm\(^2\) (KC Denmark Research, model 12.210, 15 L; KC Denmark Research Equipment, Silkeborg, Denmark). The LBF assemblages, which inhabit these water depth ranges are well-documented (Reiss & Hottinger, 1984; Perelis-Grossowicz \textit{et al.}, 2008). The collected sediments were transported to the laboratory within the same day.

Sample treatment

The sediments were decanted in freshwater four times in order to avoid sediment aggregation and for the removal of soluble components affecting the seawater salinity and density used in the experiment. After decantation, the sediments were freeze-dried and weighed. The sample was split nine times (1/512) up to a portion of 16.5 g (= ‘bulk sample’), which was used for determining grain-size distribution and to characterize the foraminifera assemblages in the bulk sediments. The bulk sample was dry weighed, wet sieved to >150 µm and dried again. The dry sample was dry-sieved to 150–250, 250–500, 500–1000 and >1000 µm size fractions and the weight of each size fraction was documented. The rest of the sediment was used in the experiment. The bulk sample was characterized mostly by a mixture of fine to very coarse sand, with 65% of the sediment being coarser than 150 µm, negatively skewed and poorly sorted (Fig. 2).

Table 1. The location of bulk sediment samples taken from the GEA for the experiment.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>UTM E (m)</th>
<th>UTM N (m)</th>
<th>Water depth (m)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET14G7</td>
<td>686701</td>
<td>3265384</td>
<td>89.4</td>
<td>2.8</td>
</tr>
<tr>
<td>ET14G8</td>
<td>686433</td>
<td>3265496</td>
<td>68.8</td>
<td>7.4</td>
</tr>
</tbody>
</table>
A closed elliptical flume was used for this experiment (for dimensions see Fig. 3). The current was induced by a set of rotating vertical PVC wheels, located on one side of the tank, and operated by an external motor. The rotation of the wheels linearly relates to current velocity $v$ (cm s$^{-1}$) that was calibrated by measuring the time taken by a small drifter (i.e. 12 cm long plastic tube, 3 cm in diameter, weighted to stand vertically in the water) to move along the linear part of the flume. Each wheel rotation velocity was assessed 20 times. Furthermore, a cross-calibration was run between surface flow velocity and high-frequency (100 Hz) hot-film velocimetry measurements (for further details regarding the system calibration see Seuront et al., 2001; Seuront & Schmitt, 2005; Seuront et al., 2005; Denis et al., 2007), subsequently producing a vertical profile of high-frequency velocimetry which showed that velocity non-significantly differs vertically over the depth of the flume (i.e. 30 cm) nor does it differ horizontally over the width of the flume (i.e. 30 cm). Current velocities of 20, 40, 60 and 80 cm s$^{-1}$ were examined prior to the experiment. The current velocity of 20 cm s$^{-1}$ represents the maximum natural velocities in the GEA (Biton & Gildor, 2011) under which LBF are absent from the deep-sea pelagic sediments in the field (Ash-Mor et al., 2017). During the 20 cm s$^{-1}$ test, the water in the flume became murky as a result of resuspension of the fine fractions; however, no larger particles were visible in the water column. During current velocity of 40 cm s$^{-1}$ ripple marks appeared, suggesting sediment winnowing and sorting at the bottom of the flume. These ripple marks disappeared at 60 cm s$^{-1}$ due to the increased velocity. Therefore, two flow velocities were considered for the experiment, i.e. 60 cm s$^{-1}$ and 80 cm s$^{-1}$, representative of the turbulent flows expected along the continental shelf during a mass transport (Toyofuku et al., 2014) and within the system limitation of 100 cm s$^{-1}$ velocity. Such velocities were also measured directly during a turbidity current in the...
submarine canyons offshore California (Paull et al., 2002; Xu et al., 2004).

**Vertical sediment trap**

The vertical sediment trap (VST) consists of an array of ten rectangular plastic cells stacked vertically (Fig. 4). The side facing the current remained open while the down-stream side was covered with a 200 µm mesh. Each cube opening is 1 cm high, and therefore represents a 1 cm section in the water column.

The VST samples used at the lower 60 cm s\(^{-1}\) velocity were defined as L1 to L10 and those used at higher 80 cm s\(^{-1}\) velocity were defined as H1 to H10 where L1 and H1 were located at the bottom of the tank.

**Experimental procedure**

The ca 10 kg of sediments collected from the GEA were inserted into the dry empty tank and spread evenly as a bed of a few centimetres thick entirely covering the base floor of the tank. The tank was filled with 300 L of seawater in order to create an isotropic flow, i.e. the water level height equals the width of the tank (0.3 m). Once the tank was full, the motor was set into motion for 5 min of acceleration until steady velocity was achieved. At steady velocity, the VST was inserted and held down manually to the bottom, positioned at the centre line at the end of the long and straight section of the flume with an anticlockwise flow direction (see black arrow, Fig. 3) for 5 min. After 5 min, the VST was closed and extracted, and the motor was shut down. This time frame was determined to avoid the overload of the sediment trap cells due to their gradual filling. Ten minutes were used for the current to decelerate and for the sediments to accumulate. This procedure was applied with both velocities.

The bottom was not replaced between the runs and the same sediments were used to examine both velocities because of limited ability to extract, treat and ship larger amounts of sediments from the GEA to the laboratory in Lille, France. However, the amount of sediments collected during the experiments by the VST was a total of ca 0.12% of the total amount of sediments inserted into the flume and, therefore, negligible. In addition, the preservation of the shells in the experiment samples showed no deterioration compared to the bulk sample (Fig. 5).

The samples from each cube were transferred to a closed container by rinsing with double-distilled water and held overnight. The following day, the excess water was removed, and the samples were dried at 50°C for 1 to 2 h, depending on the sample size. The VST samples were weighed, wet sieved to >150 µm and dried again. The dry samples were dry-sieved to 150–250, 250–500, 500–1000 and >1000 µm size fractions and the weight of each size fraction was documented.

**Foraminiferal analysis**

Large benthic foraminifera were identified to species level according to Hottinger et al. (1993) and counted separately for each size fraction by using a stereomicroscope (Leica

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**Fig. 4.** (A) A side-view scheme showing the dimensions of the vertical sediment trap. The inner dimensions of each cell is 1 cm high and 2 cm wide. (B) The open side facing the current. (C) The down-stream side closed with a 200 µm mesh.
M205 C; Leica Microsystems, Wetzlar, Germany). Samples consisting of numerous individuals, mostly 150–250 µm and 250–500 µm size fractions, were split to a countable sample size. All foraminifera in the split sample were counted (see Data S1). The total number of foraminifera per g sediments (\(F_t\)) in each grain-size fraction was calculated according to Eq. 1:

\[
F_t = \frac{F_n \cdot 2^n}{\text{total sample wt. (gr)}}
\]

where \(F_n\) is the number of foraminifera counted in the split fraction, and \(n\) the number of splits. The total sample wt. refers either to the bulk sample or to each of the VST samples individually. The specimens were counted and divided by species and state of preservation. Three states of preservation were distinguished following Ash-Mor et al. (2017): (i) <10%; (ii) 10–50%; (iii) >50% of the original shell is missing (Fig. 1F and G), denoted as ‘good’, ‘medium’ and ‘bad’, correspondingly.

**Statistical analyses**

All species, including the rare species, and their preservation states were considered in the statistical analysis. The relationship between sediment trap height and the number of LBF species of different size fraction and preservation status was first assessed with scatterplots. As a result of the non-linear relationship between species counts and height, generalized additive models (GAM) were used to model the data (link = Poisson, \(k = 3\)), using the packages mgcv (Wood, 2017) implemented in R statistics version 4.0.3 (R Development Core Team, 2020). The GAM plots were scanned visually to find negative or positive trends.

Prior to the multivariate analyses, the data was log(x + 1) transformed to reduce the effect of the most abundant species. The assemblage composition of the samples was examined visually by distance-based Redundancy Analysis (dbRDA) based on Bray-Curtis similarity matrix using PRIMER-E version 6 software (Anderson et al., 2008). Permutational multivariate analysis of variance (PERMANOVA) was performed with 9999 permutations to test the relative importance of the factors ‘speed’ (0 = bulk, 60 and 80 cm s\(^{-1}\)) and ‘height’ (10 height layers), and their interaction in the assemblage composition. SIMPER (Similarity Percentages) analysis was performed to detect the species (including size fraction and preservation state) mostly contributing to the dis/similarities within and between the samples.

**RESULTS**

**Bulk sediments**

A total of 2851 specimens per g of sediment were collected from the bulk sediments, dominated by 1542 and 1112 specimens per g sediment of *Amphistegina papillosa* and *Operculina ammonoides*, comprising 54% and 39% of the total assemblage, respectively (see ‘bulk’ at the top of Fig. 6A ‘a’). This distribution is in accordance with the GEA assemblage composition at the sample location depth (Table 1). As shell size increases to 250–500 µm and 500–1000 µm size fractions, the dominance of *A. papillosa* became slightly more distinct. In the largest size fraction (>1000 µm) no *A. papillosa* occur and *O. ammonoides* comprise 96% of the assemblage of this size (see ‘bulk’ at the top of Fig. 6A ‘b’ to ‘e’).
Other LBF species, such as *Amphistegina bicirculata*, *Amphistegina lessonii*, *Peneroplis planatus*, *Sorites orbiculus*, *Heterostegina depressa*, *Elphidium jenseni* and *Elphidium cf. E. limbatum* occur in lower abundances, comprising together 6.9% of the total LBF assemblage. Therefore, these species were combined into one group of ‘rare species’ (Fig. 6A ‘a’). *Amphistegina bicirculata*, which also inhabits water depths of 60 to 90 m, comprises 5% of the total LBF assemblage, in agreement with previous measurements (Perelis-Grossowicz et al., 2008).

A total of 796 poorly preserved shells were counted in the bulk sediments, comprising 28% of the entire assemblage. The well-preserved and moderately fragmented shells comprise 43%
and 29% of the entire assemblage, respectively (see ‘Bulk’ in Fig. 5 and Fig. 7A ‘a’).

**Experiment samples**

Permutational multivariate analysis of variance (PERMANOVA) showed that the significant factor contributing to the dis/similarity between experimental groups is the current velocity ($P = 0.003$), as opposed to the height above the flume base ($P = 0.128$; Table 2; Fig. 8). In addition, pairwise tests showed no significant difference between the bulk sample and the samples of 60 cm s$^{-1}$ ($P = 0.169$) or 80 cm s$^{-1}$.
(P = 0.098) velocities. However, the sample sets of both velocities were found to be significantly different from one another (P = 0.002) (Table 2; Fig. 8; Data S2).

60 cm s\(^{-1}\) current velocity

Total assemblage

The total species abundance is higher at the bottom sample of the trap and decreases gradually upward by up to 50% (Supplementary 3 and 4, p. 10). The samples are dominated by an average of 1043 \(\pm\) 121 and 510 \(\pm\) 316 specimens per g sediment of \(O. ammonoides\) and \(A. papillosa\), comprising ca 66% and ca 29% of the total assemblage, respectively. In addition, \(A. papillosa\) demonstrates a sharp decrease in abundance upward as 40% of its population is restricted to the bottom two samples (L1 and L2). In contrast, \(O. ammonoides\) demonstrates a relatively equal distribution throughout the VST samples (Fig. 6A ‘a’; supplementary 3 and 4, compare p. 22 and p. 34).

Sample L1 is most similar to the bulk sample by 85.9% compared to its lower resemblance (<78.6%) to the other 60 cm s\(^{-1}\) VST samples (Fig. 8). In addition, sample L2 shares an average similarity of 84.1% with all ‘H’ samples, as opposed to 76.5% with the bulk sample and the rest of the ‘L’ samples (Fig. 8). Samples L3 to L10 are all similar by an average of 84.15%.
Shell size fractions
A sharp decline in LBF abundance co-occurs with the increase in shell size (see X axis values, Fig. 6A ‘b’ to ‘e’; Supplementary 4, p. 1, 4 and 7). In addition, as shell size increases LBF occurrence is confined to the bottom sample L1. At the smallest size fraction (Fig. 6A ‘b’), the total number of LBF shells collected from sample L1 constitutes 8% of the total number of specimens collected from all samples of the VST (L1 to L10). The portion of the bottom sample increases to 30%, 67% and 100% in the following size fractions, respectively (Fig. 6A ‘c’ to ‘e’).

The 150–250 µm, 250–500 µm and 500–1000 µm size fractions of the bottom sample L1 are dominated by 513, 571 and 228 specimens per g sediment of A. papillosa, comprising 47%, 57% and 66% of the total LBF assemblage of each size fraction, respectively. The same sample contains 517, 351 and 89 specimens of O. ammonoides, comprising 48%, 35% and 26% of the LBF assemblage of the same size fractions, respectively. With distance from the base, the dominance of O. ammonoides is gradually established with 776, 164 and 12 specimens per g sediment at the top sample L10, comprising 73%, 81% and 83% of the LBF assemblage of each size fraction, respectively (Fig. 6A ‘b’ to ‘d’).

At the >1000 µm size fraction, O. ammonoides occurs only at the bottom sample comprising 97% of the assemblage. No LBF shells of this size were found in the rest of the VST samples (Fig. 6A e).

State of preservation
Well-preserved shells were found to be distributed relatively homogenously in the VST, with an average of 807 ± 144 specimens per g dry sediment. Nevertheless, their portion increases from 36% of the entire assemblage at sample L1 to 51% in sample L10 due to the sharp relative decrease of the poorly preserved shells (Fig. 5A and Fig. 9A ‘a’; Data S4, p. 11–12). The abundance of poorly preserved shells decreases upward from a maximum of 890 specimens per g sediment at sample L1 to 183 specimens at sample L10, comprising 36% and 14% of the entire LBF assemblage, respectively (Fig. 5A and Fig. 7A ‘a’).

The abundance of well-preserved shells of 150 to 250 µm size fraction (Fig. 9A ‘b’) increases with distance from the base. The two most dominant species, O. ammonoides and A. papillosa, show opposing distribution trends. The former abundance increases from 13% at the bottom sample L1 to 37% at the top sample L10, while the latter decreases from 23% to 14% (Fig. 9A ‘b’; Data S4, compare p. 14 and p. 26).

At the same size fraction, poorly preserved O. ammonoides distribution along the VST remains relatively similar with no distinct trend. However, poorly preserved A. papillosa are highly abundant at sample L1, with 164 specimens per g sediment, abruptly decreasing upward with 43 specimens at sample L3 (Fig. 7A ‘b’). These results are supported by the high contribution (39%) of both species of this shell size, regarding their preservation state (excluding poorly preserved A. papillosa) to the similarity between all of the ‘L’ samples (see Data S2).

The 250–500 µm and 500–1000 µm shell size fractions are characterized by a relatively homogenous distribution of well-preserved O. ammonoides with a slight decrease upward (Data S4, p. 17 and p. 20, respectively). Amphis- tegina papillosa, however, dominates sample L1, with 216 and 80 specimens per g sediment, and rapidly decreases to 45 and 3 specimens in sample L3, respectively (Fig. 9A ‘c’ and ‘d’; Data S4, p. 29 and p. 32, respectively). Poorly preserved shells of both dominant species at these size fractions are highly concentrated at sample L1. This sample consists of 238 and 73 specimens of A. papillosa, comprising 24% and 21% of the total LBF assemblage, respectively. In addition, 162 and 54 poorly preserved specimens of O. ammonoides occur in this sample, each consisting of 16% of the total LBF assemblage. The abundance of poorly preserved shells of both species and of both size fractions in sample L2 decreases by 80% (Fig. 7A ‘c’ and ‘d’; see Data S4, p. 18, 21, 30 and 33). These results are supported by the high contribution of A. papillosa (21.32%) to the dissimilarity between all ‘L’ samples and the bulk sample (see Data S2).

At the >1000 µm size fraction, only 3 and 2 specimens per g sediment of well and poorly preserved O. ammonoides occur in sample L1, respectively. No LBF shells occur at the rest of the VST samples (Fig. 7A ‘e’ and Fig. 9A ‘e’).

80 cm s⁻¹ current velocity
Total assemblage
The total species abundance is relatively equal throughout the water column with no distinct trend (Data S3 and S4, p. 50) supported by an average similarity of 84.9% between all ‘H’ samples (Fig. 8; Data S2). The samples are dominated by an average of 1155 ± 116 and
804 ± 112 specimens per g of sediment of *O. ammonoides* and *A. papillosa*, comprising ca 55% and 38% of the total assemblage, respectively. Both species demonstrate a relatively equal distribution throughout the VST samples with no significant decreasing trend towards the top (Fig. 6B ‘a’; Data S3 and S4, p. 64 and p. 76).

**Shell size fractions**

All shell size fractions are more equally distributed and transported in the water column at the 80 cm s⁻¹ current velocity, including *O. ammonoides* >1000 μm (Fig. 6B ‘b’ to ‘e’). The portion of sample H1 in the different size fractions constitutes between 8 to 15% of the total amount of LBF shells collected from all ten
samples of the VST (H1 to H10). The bottom sample H1 is characterized by relatively lower abundance of 150 to 250 µm shells of both species, whereas the rest of the trap samples contain a similar amount of shells of this size fraction (Fig. 6B ‘b’). The other shell size fractions demonstrate a slight decreasing trend towards the top of the VST (Fig. 6B ‘c’ and ‘e’; Data S4).

State of preservation
The distribution of LBF shells with different degrees of preservation was found to remain relatively constant throughout the water column with no distinct trend. Well-preserved shells consist on average 47 ± 2% of the entire assemblage, while poorly preserved shells consist of 21 ± 2% (Fig. 5B; Data S3 and S4, p. 50–51).

The LBF with shell size of 150 to 250 µm are less abundant at the basal sample H1, yet the proportion between the different degrees of preservation remains similar. Well-preserved O. ammonoides and A. papillosa appear throughout the water column, each comprise on average 24 ± 2% of the total size assemblage, while poorly preserved shells comprise 11 ± 2% and 6 ± 1%, respectively (Figs 7B ‘b’; 9B ‘b’; Data S4, p. 53 and 69). Both species of this size fraction (excluding poorly preserved A. papillosa) contribute the most (29.2%) to the similarity between all ‘H’ samples (see Data S2).

In the 250–500 µm and 500–1000 µm size fractions, both well and poorly preserved shells of both species are well-distributed in the water column with a moderate decreasing trend towards the top of the VST (Fig. 7B ‘c’ and ‘d’; Fig. 9B ‘c’ and ‘d’; Data S4, p. 56–60 and p. 71–75). Well and poorly preserved O. ammonoides >1 mm occur in very low abundance. Nevertheless, both are well-distributed in the water column and present in all of the VST samples (Figs 7B ‘e’ and 9B ‘e’; Data S4, p. 61–63).

The dissimilarity between both velocity patterns can be characterized by the dimensionless Reynolds numbers, providing a proxy for the turbulence at the grain (shell)–fluid boundary considering fluid density, dynamic viscosity of seawater, nominal shell diameter and shell length (Boggs, 2005). A Reynolds number of 150 and 100 was calculated for a 1.5 mm O. ammonoides and a 1 mm A. papillosa, respectively (Yordanova & Hohenegger, 2007), which suggests that the flow surrounding these shells remains relatively laminar compared to particles with higher Reynolds number. Therefore, the entrainment velocity necessary to lift these species from a rough seafloor surface is relatively high (17 cm s⁻¹). The lower turbulence associated with these species also resulted in lower settling velocities of ca 5.0 and 5.4 cm s⁻¹, respectively. In comparison, a 1.5 mm Alveolinella quoyi and Amphistegina lobifera, which have a higher Reynolds number of ca 400 and 200, respectively, were characterized by a lower entrainment velocity of 14 cm s⁻¹ and higher settling velocity of ca 8 cm s⁻¹, (Yordanova & Hohenegger, 2007). According to the study of Ash-Mor et al. (2017), the occurrence of A. papillosa and O. ammonoides in the GEA turbidites is related to the source area which was concluded as the deeper shelf area. In addition, the absence of shallow water LBF species in these turbidites was attributed to the presence of Halophila meadows and coral reefs serving as a physical barrier. It is suggested that the portability of the different shell shapes (influenced by their physical parameters) is an additional factor, contributing to the spatial differentiation in the deposited assemblages along the continental slope; thus meaning that sphere-shaped and rod-shaped shells are carried along the slope for shorter distances compared to the discoid shaped shells.

Another factor to consider in sediment transport is the ‘Hiding effect’ (Briguglio et al., 2017; McCarron et al., 2019). This refers to small grains blocked in small concavities or by larger grains and, therefore, are prevented from transport and the larger grains are transported first. However, in such cases, only turbulence can lead to entrainment and transport. Briguglio et al. (2017) examined the transportability and ‘Hiding effect’ of recent and fossil foraminifera on fine sand, coarse sand and bioclast substrates. In their study, the authors examined one to five foraminifera shells at a time and the substrate grains were glued by epoxy to prevent

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DISCUSSION

Foraminifera as transported particles
Species shell shape
The disk-like shape of both dominant species contributes to their propensity to be resuspended during transport. Flow and transport patterns can be characterized by the dimensionless Reynolds numbers, providing a proxy for the turbulence at the grain (shell)–fluid boundary considering fluid density, dynamic viscosity of seawater, nominal shell diameter and shell length (Boggs, 2005). A Reynolds number of 150 and 100 was calculated for a 1.5 mm O. ammonoides and a 1 mm A. papillosa, respectively (Yordanova & Hohenegger, 2007), which suggests that the flow surrounding these shells remains relatively laminar compared to particles with higher Reynolds number. Therefore, the entrainment velocity necessary to lift these species from a rough seafloor surface is relatively high (17 cm s⁻¹). The lower turbulence associated with these species also resulted in lower settling velocities of ca 5.0 and 5.4 cm s⁻¹, respectively. In comparison, a 1.5 mm Alveolinella quoyi and Amphistegina lobifera, which have a higher Reynolds number of ca 400 and 200, respectively, were characterized by a lower entrainment velocity of 14 cm s⁻¹ and higher settling velocity of ca 8 cm s⁻¹, (Yordanova & Hohenegger, 2007). According to the study of Ash-Mor et al. (2017), the occurrence of A. papillosa and O. ammonoides in the GEA turbidites is related to the source area which was concluded as the deeper shelf area. In addition, the absence of shallow water LBF species in these turbidites was attributed to the presence of Halophila meadows and coral reefs serving as a physical barrier. It is suggested that the portability of the different shell shapes (influenced by their physical parameters) is an additional factor, contributing to the spatial differentiation in the deposited assemblages along the continental slope; thus meaning that sphere-shaped and rod-shaped shells are carried along the slope for shorter distances compared to the discoid shaped shells.

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them from moving. In the present study, the use of bulk sediments provides an insight into foraminifera transport as part of a diverse and heterogenic sediments collection, as found in the GEA. In addition, considering the high and similar abundance of 150 to 250 µm shells throughout the VST in both velocities, the ‘Hiding effect’ of smaller shells appears to be minor.

It should be mentioned that the grain size fraction <150 µm comprises ca 35% of the bulk sample (Fig. 2). These fine particles were completely resuspended in the water column by both velocities during the experiment, as well as the 150 to 250 µm size fraction (see Fig. 6A ‘b’ and 6B ‘b’) and accumulated after the current ceased. This fine size fraction is most likely winnowed/sorted from the coarser sediments, which accumulate on the slope seafloor, and carried to greater distances and depths (Mulder & Alexander, 2001). In turbidites from the GEA the size fraction <150 µm comprises only 3 to 25% of the sediment samples (Ash-Mor et al., 2017), in accordance with this conclusion.

Species shell size and internal structure
The bulk sample and the VST samples show opposing dominance of *A. papillosa* and *O. ammonoides*, respectively (compare ‘bulk’ and ‘1–10’ samples in Fig. 6A ‘a’ and 6B ‘a’). The reverse dominance is likely associated with the inner shell structure of each species (Fig. 10) that controls their hydrodynamic properties. Shell structure of LBF represents an adaptation to water depth (Reiss & Hottinger, 1984). The micro algae living in obligatory endosymbiosis with the foraminifera have restricted light intensity requirements (Lee, 2006). Therefore, in shallow water depth *O. ammonoides* specimens have an involute structure with thicker shell walls reducing light penetration, protecting the symbionts from photoinhibition. This is opposite to the greater surface area and thinner shell wall of the evolute structure of the deeper water specimens of the same species (Reiss & Hottinger, 1984; Hohenegger, 1994; Oron et al., 2018). *Amphistegina lessonii* and *A. lobifera*, that thrive in shallower water depth, demonstrate thicker shell walls compared to deeper water species of the same genus, also attributed for restricting light intensity (Hallock, 1979; ter Kuile & Erez, 1984). Sediments sampled for the experiment consist of semi-involute to evolute form of *O. ammonoides* and the flat-shaped *A. papillosa*, corresponding with the low light intensity and seawater energy typical of their sampled water depth on the outer shelf (Reiss & Hottinger, 1984; Fig. 1A and E, Table 1).

The dominance of *O. ammonoides* larger than 250 µm in the VST samples can be explained by a smaller ratio of maximum shell thickness to maximum shell diameter, which results in a flatter discoid shape (Fig. 10) prone to suspension rather than deposition compared to *A. papillosa* (Yordanova & Hohenegger, 2007; Seddighi et al., 2015). The results from the lower velocity experiment show a homogenous distribution of well-preserved *O. ammonoides* in the size range of 250 to 1000 µm in the VST, as opposed to the sharp decrease of *A. papillosa* of the same size fractions and preservation upward in the VST (Fig. 9A ‘c’ and ‘d’; compare Data S4, p. 17 and 20 with p. 29 and 32). While the physical dimensions of these mature-size species determined their propensity to be resuspended, juvenile (150 to 250 µm) specimens are transported according to the chamber cavity proportions of their shells. The larger cavity volume of juvenile *O. ammonoides* (Yordanova & Hohenegger, 2007) contributes to its distinct dominance in the VST samples compared to the bulk sample.

Another factor that may influence the transportability of the LBF species is the microstructures of the outer shell wall. The relatively smooth surface with scarce or no pustules of the deeper water morphotype of *O. ammonoides*, as used in this study, compared to the rounded or elliptic pustules completely covering the shell of *A. papillosa* (Hottinger et al., 1993) may also contribute to its efficient mobility. Calculated Reynolds number of 1 mm *O. ammonoides* and

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A. papillosa yielded a similar value of 100; however, the measured entrainment velocity of the latter was slightly higher than the former, on both smooth and rough surfaces (Yordanova & Hohenegger, 2007). In sharks, for example, surface structures aligned with the flow direction were identified to reduce skin friction drag (Dean & Bhushan, 2010), therefore this subject is difficult to resolve and requires further investigation.

**Bulk versus transported sediments**

The results of the multivariate analyses reveal the different character of the bulk sediments versus the VST samples, and the profound difference in transport patterns at different velocities (Fig. 8). At a flow velocity of 60 cm s\(^{-1}\), most of the sediments >250 µm were transported as bedload (see Fig. 6A and Fig. 11: bulk versus sample L1), which resulted in sediment composition similar to the original sample.

Sample L2 and the samples taken under conditions of 80 cm s\(^{-1}\) velocity show high similarity of 83.6% on average (Fig. 8). This means that the assemblage transported 2 to 3 cm above seafloor by the lower velocity has the same composition as the assemblage transported up to 9 to 10 cm above seafloor by the higher velocity (Fig. 11). This finding emphasizes the efficiency of the 80 cm s\(^{-1}\) current velocity to re-suspend and transport sediments above seafloor and to greater distances compared to the 60 cm s\(^{-1}\) velocity. Furthermore, the results show that small quantities of LBF shells winnowed from the coarse terrigenous fraction can be transported by lower velocities, such as 60 cm s\(^{-1}\), beyond the shelf edge. In the sedimentary record, the appearance of LBF shells with no coarse sediments may represent less vigorous transport events.

Indeed, Ash-Mor et al. (2017) identified two types of turbidites consisting either of 20 to 30% or >70% sandy sediments, compared to the pelagic sediments that consist of <20% (see fig. 6 in Ash-Mor et al., 2017), considering the limited source area for shelf originated sediments as the western continental shelf width is ca 600 m on average (Tibor et al., 2010). The experiment results suggest that turbidites that comprise large volumes of coarse sediments and LBF shells represent mass flow processes initiated by high current velocities (see turbidites in core MG10P27 in Fig. 1B). In contrast, turbidites with a minor amount of LBF shells (with little or no coarse sediments) in the sedimentary record were winnowed beyond the shelf edge and transported in lower current velocities during small-scale events.

The experimental flow velocities used in the present study examine the boundary conditions necessary for the initiation of sediment-transport processes at the deeper continental shelf and slope. At the western GEA, the gradient angles are 9° and 17°, respectively (Tibor et al., 2010; Fig. 1E). Once sediments pass the shelf edge, the current may accelerate due to the gravitational force down the steeper angle of the slope, as demonstrated by in situ measurements in submarine canyons at water depths >1000 m, offshore Zaire and Portugal that yielded current velocities faster than 1 m s\(^{-1}\) (Khripounoff et al., 2003; Talling, 2014; Maier et al., 2019). Nevertheless, the total amount of sediments, including LBF shells, transported beyond the shelf edge is controlled by the current velocity along the shelf probably generated by seismic triggers.

**Fig. 11.** Schematic illustration of the vertical distribution of 250 to 1000 µm *Operculina ammonoides* and *Amphistegina papillosa*, with different states of preservation, during 60 cm s\(^{-1}\) (A) and 80 cm s\(^{-1}\) (B) current velocity.
considering the lack of river outlets, low sedimentation rates and relatively stable sea-level during the occurrence of the Holocene GEA turbidites (Ash-Mor et al., 2017).

Shell damage during transport and loss of hydrodynamic properties

During transport, sediment particles, including LBF shells, may collide and erode in the turbulent flow. Sediments used in the experiment were sampled from the continental shelf, deeper than wave-base influence. The occurrence of 28% poorly preserved shells in the original sample is most likely the result of predation stress by fish, molluscs or echinoderms (Buzas & Carle, 1979; Lipps, 1988; Culver & Lipps, 2003; Goldbeck et al., 2005; Debenay et al., 2011; Guy-Haim et al., 2017).

The transport of LBF of both well and poorly preserved shells is more efficient in the higher current velocity, as shown by their high occurrence throughout the water column (Fig. 5). At both experimental velocities, lower abundance of poorly preserved shells was detected in almost all the VST samples compared to the bulk sediments, meaning that fragmented shells were not resuspended as much as the preserved ones. Sample L1 is characterized by approximately two times more poorly preserved shells than sample H1 (Fig. 7A ‘a’ and 7B ‘a’). However, above the flume base, the ‘H’ samples consist on average of 25% more poorly preserved shell than the ‘L’ samples (Fig. 5A and B), emphasizing that hydrodynamic properties are significant, especially in the lower transport velocities, and influence the mobility and destruction of such shells.

The significance of hydraulic properties is further emphasized in the results of shells >250 µm. Sample L1 contains up to three times more well and poorly preserved LBF shells than H1, although both samples contain a similar abundance of 150 to 250 µm sized shell (compare Fig. 9A ‘b’, sample L1 with Fig. 9B ‘b’, sample H1 and Fig. 7A ‘b’, sample L1 with Fig. 7B ‘b’, sample H1). The flow patterns generated by both velocities promote the suspension of the smaller size fraction equally throughout the water column. However, in the lower velocity the importance of hydrodynamic properties for the resuspension (for example, higher cavity %, smooth edges and discoid shape) of the larger size shells is emphasized.

The differences between the two flow velocities in relation to the hydraulic properties of the shells are also demonstrated from the analysis of O. ammonoides shells larger than 1 mm, both well-preserved and poorly-preserved (Figs 7A ‘e’ and 9A ‘e’ compared to Figs 7B ‘e’ and 9B ‘e’). Operculina ammonoides larger than 1 mm are too heavy to be resuspended by the 60 cm s⁻¹ flow velocity despite its hydrodynamic properties, especially the poorly preserved shells, which have a lower hydrodynamic shape. These results strengthen the conclusion that a minimum current velocity of ca 80 cm s⁻¹ was required in order to transport large quantities of specimens of this size beyond the GEA shelf edge and down the continental slope. Indeed, O. ammonoides specimens >1 mm are highly abundant in the medium-scale and large-scale turbidites found in the GEA slope (Ash-Mor et al., 2017). Although higher velocities eventually wane as well, the initial amount and grain size of the material carried by such a current is greater and has the potential to travel farther down slope. In this study, it was impossible to quantify breakage caused by collision during transport at different velocities because shells erode during the experiment, and therefore shift to smaller size fractions. In addition, shells with originally small size may have eroded to <150 µm, a size fraction not analyzed in this study. In addition, shell erosion is time-dependent and will further deteriorate as flow duration continues. This experiment was designed to understand sediment transport processes in the GEA where the transport distance from the source (shelf) to the deposition sites (continental slope) ranges between ca 0.75 to 3.7 km (Ash-Mor, et al., 2017). However, turbidity currents can occur as a single event or several subsequent events that last from an hour to several days. The transported sediments may travel for distances of a few kilometres to more than 1000 km and deposit as layers <1 mm to a few metres thick, depending on sediments availability and slope angle (Khripounoff et al., 2003; Xu et al., 2004; de Stigter et al., 2011; Talling et al., 2013). Previous experiments simulating turbidity flow distance of ca 550 to 1570 m and 1641 to 3801 m (time lapse of 24 h and 72 h, respectively) showed the outer shells of Palaeonummulites venosus (2 to 3 mm) eroded by up to 25% and 50%, respectively (Beavington-Penney 2004). In the present experiment the shorter duration of flow and smaller shell sizes suggest that the change in shell preservation is minor. However, the high concentration of poorly preserved shells in sample...
L1 may be related to increased shell damage caused by the bedload flow, which resulted in their low suspendibility and buoyancy.

**Implications for understanding transport processes from larger benthic foraminifera assemblages in turbidites**

Description of turbidity current event records are mostly studied from the deposits they leave behind, because direct measurements from sediment traps are rare (e.g., Sumner & Paull, 2014). An extensive array of moorings along Monterey Canyon sediment suggested that grain size is a complex proxy for understanding down-canyon changes in maximum flow speeds, although seabed deposits appear to faithfully record the sand component that is transported in the water column during sub-annual turbidity currents (Maier et al., 2019). Turbidites deposited at the upper part of the submarine canyons off the Atlantic coastline of Portugal show that the grain size larger than 100 µm consisted of more than 85% lithogenic particles. At deeper water depths, the deposits are composed of <80% lithogenic particles (meaning that the relative biogenic fraction increased) with grain size of ca 10 µm (de Stigter et al., 2011). These findings are in accordance with the results of the present study that show that the lighter biogenic particles are resuspended in the water column. Although the transport distances in the GEA are much shorter, the biogenic particles are transported further and deeper than the lithogenic sediments and, therefore, compose a higher percentage of the deposited sediments in relation to their source origin on the shelf (Ash-Mor et al., 2017). Further examination of the benthic fauna, particularly foraminifera, of the Atlantic margin turbidites may shed additional light on the source area, current velocities at the source, and transport and deposition patterns at the termination site.

Note that a similar phenomenon was described in a nearshore environment after the 2004 tsunami in Thailand. Foraminiferal assemblages in backwash deposits at 30 m water depth included *Ammonia beccarii* and *Rosalina vilardeboana* (= *Discorbis vilardeboanus* after Hayward et al., 2019) living at shallower depths of 5 to 10 m. In contrast, larger and less hydrodynamic species which occupy the same habitat, for example, *Elphidium depressulum* (evolute form with a rough surface) and *Ammobaculites vilosus* (rod form agglutinated species), were barely transported (Sugawara et al., 2009). Further examination of foraminiferal assemblages along the deeper shelf and continental slope in tsunami affected regions may reveal the

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**Fig. 12.** Schematic illustration of the sediment mass-transport process along the bathymetry profile, with distance from shore (X axis) and increasing water depth (Y axis): (A) natural conditions prior to the event; (B) re-suspension and transport during the triggering event; (C) deposition of larger benthic foraminifera (LBF) assemblages according to their hydrodynamic properties following the event. See Fig. 10 for the legend on different states of preservation of the LBF shells.
characteristics of tsunami deposits in deep environments.

The present study demonstrates the influence of LBF shell dimensions and inner structure on their resuspendibility and transport in the flow. Therefore, it is proposed that during mass transport events buoyant species are transported farther and deeper down the continental slope, while less buoyant species accumulate at shallower water depths. (Fig. 12).

Operculina ammonoides dominated turbidite assemblages found in core MG10P27, taken from the GEA at 532 m water depth, whereas A. papillosa dominated the assemblages in core MG10P22 at 316 m water depth (see Fig. 1A and E for core locations). These differences in dominance were suggested to represent different ecological niches (Ash-Mor et al., 2017). However, the results herein suggest that the difference in species dominance can be attributed to the difference in transport distance and deposition depth as well, because both species inhabit the same water depth range at the GEA outer shelf (Reiss & Hottinger, 1984; Perelis-Grossowicz et al., 2008). Further examination of shallower depths along the transport pathway of core MG10P27 may reveal the dominance of the less buoyant A. papillosa, and deposits from deeper depths on the western slope, seaward from core MG10P22 may contain LBF assemblages dominated by O. ammonoides, which were probably transported and deposited farther down slope.

It is finally stressed that O. ammonoides was found to dominate the outer northern shelf of the GEA, while the western outer shelf consists of similar values of both species to slightly more A. papillosa (compare ‘bulk’ in Fig. 6A ‘a’ and Perelis-Grossowicz et al., 2008). The dominance of each species in the turbidite deposits, derived from the continental slope at each environment (submarine canyon versus western slope), may be preserved. However, it is suggested that the ratio between both species in the turbidites along the slope may change as the sediments move down slope and particles are deposited according to their hydrodynamic properties.

CONCLUSIONS

This study represents a new approach analyzing symbiont-bearing larger benthic foraminifera (LBF) characteristics in an experiment simulating high velocity sediment transport. Sediments from the Gulf of Elat/Aqaba (GEA) outer shelf, dominated by Amphistegina papillosa and Operculina ammonoides, were used for the experiment, and LBF assemblages, shell dimensions, inner structure and state of preservation prior and during transport were used for estimating their transportability, and to discuss their implications for understanding sediment transport.

Foraminifera shells carried by 60 cm s\(^{-1}\) current velocity were mostly winnowed at the sediment–water boundary, while 80 cm s\(^{-1}\) current velocity efficiently distributed the shells in the water column above the simulated sea floor, including poorly preserved shells.

The 80 cm s\(^{-1}\) current velocity is estimated as a minimum threshold velocity required in order to produce transport events of large quantities of sediments and shells from the shelf to the deep sea, which are triggered by medium-scale and large-scale seismic events in the GEA that resulted in turbidite deposition. Lower velocities may result in the transport of the more buoyant LBF shells without the terrigenous coarse sediments and can be associated with smaller-scale seismic events.

The experiment also showed that the inner structure of LBF can affect the transport distances, changing the assemblage composition deposited along the transport pathway. Flatter shape and higher cavity volume in O. ammonoides shells increase their buoyancy, compared to A. papillosa, and transport them to greater depths. Furthermore, small-size juvenile specimens were homogenously transported by both velocities and are suggested to deposit at the later stages of the flow and to dominate the assemblage at the deepest and latest deposit of a turbidite unit.

The experiment in this study, which was conducted for the first time, demands further investigation with longer duration periods of transport in a flume system to examine the changes in shell preservation, and therefore buoyancy, with increasing travel distance under different transport conditions. Such experimentation will enable studying additional settings such as open sea passive and active shelf margins and submarine deep fan deltas and turbidity channels.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

REFERENCES


Experimental transport of foraminifera


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Supporting Information

Additional information may be found in the online version of this article:

Data S1. Foraminifera count.

Data S2. SIMPER.

Data S3. Generalized additive model.

Data S4. Generalized additive model plots.