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Testing foraminiferal taphonomy as a tsunami indicator in a shallow arid system lagoon: Sur, Sultanate of Oman

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ABSTRACT

The tsunami produced by the 1945 Makran Trench earthquake is considered to be the second deadliest in the Indian Ocean after the 26 December 2004 Indonesian event. The tsunami struck Iran, Pakistan, India and Oman; however, historical records outside of India and Pakistan are sparse due to limited populations in those regions and little communication with larger cities. Sur Lagoon, Oman, a small microtidal lagoon, contains stratigraphic evidence of the 1945 tsunami. The goal of this study is to test the utility of foraminiferal provenance and taphonomy as an indicator of the 1945 event and examine its potential in detecting older events in the geologic record. Foraminiferal (taxa and taphonomy) and high resolution particle size analysis show that high abundances of predominantly marine taxa (*Amphistegina* spp., *Ammonia inflata*, and planktics) associated with the tsunami bed indicate an outside marine origin for the sediment. Influxes of large test sizes and fossil specimens support a shallow marine provenance. Findings indicate that foraminiferal analysis, when combined with other proxies (e.g. mollusc taphonomy, particle size distribution), can be used to delineate tsunami units from normal background sedimentation in intertidal systems. This technique holds potential for detecting older events in Sur Lagoon which are documented in historical texts, but as of yet, have not been 'ground-truthed'.

1. Introduction

Most taphonomic studies of foraminifera focus on time-averaging or lateral transport of tests with only semi-quantitative observations on test condition (e.g. fragmentation and size; Hawkes et al., 2007; Kortekaas and Dawson, 2007). However, recent research has shown that test condition along with provenance assessment may provide useful environmental information and may help determine overwash events in coastal systems (e.g. Pilarczyk and Reinhardt, 2011). Here we present the second phase of a two part study that firstly examined recent taphonomic trends (test condition and provenance; Pilarczyk et al., 2011) in Sur Lagoon, Oman (Fig. 1) and now examines an inferred 1945 Makran Trench tsunami deposit. Documentation of recent events like the 1945 tsunami, often with written or oral accounts, is important for understanding overwash dynamics in coastal settings and interpreting older events in the stratigraphic record (e.g. lagoons or ponds; Satake and Atwater, 2007).

The 1945 tsunami deposit in Sur Lagoon was found to have a lateral, sheet-like geometry with distinctive bivalve shell taphonomy (shell condition and provenance), and with its shallow position in the stratigraphic record, was inferred to be from the 1945 event (Donato et al., 2008; Donato et al., 2009). The bivalve taphonomy proved very useful for identifying the event in trench sections where large exposures are possible, but its utility will be limited by sample size in core studies. This study examines the foraminiferal trends within this deposit for eventual application to older deposits deeper in the stratigraphic record within the lagoon.

1.1. The 1945 Makran Trench tsunami

Historical records mention several tsunamis that have impacted the coastlines of the Northern Arabian Sea (e.g. 325 B.C., 1483, 1765, 1851, etc.; Ambraseys and Melville, 1982; Heidarzadeh et al., 2008a, 2008b; Heidarzadeh et al., 2009 and references therein). Little is known about these events and details regarding the dates, coastlines impacted, wave heights, number of deaths and earthquake epicentres are often contradicted in the literature (see Heidarzadeh et al., 2008b). Several studies have reported upwards of ten tsunamigenic earthquakes originating from the eastern and western flanks of the MSZ since 325 B.C., however, this number may not be accurate since many tsunamis are not likely reported (Quittmeyer and Jacob, 1979; Ambraseys and Melville, 1982; Pararas-Carayannis, 2006; Heidarzadeh et al., 2008a). While often incomplete, the historical tsunami record for the Northern Arabian Sea documents at least six events that had a magnitude greater than 8.0 (e.g. 325 B.C., May 1008, 18 February 1483; May 1668; 1765; 19 April 1851; 28 November 1945). The oldest tsunami on record may have been responsible for destroying Alexander the Great's fleet on its way back to Mesopotamia in 325 B.C. (Pararas-Carayannis, 2006).

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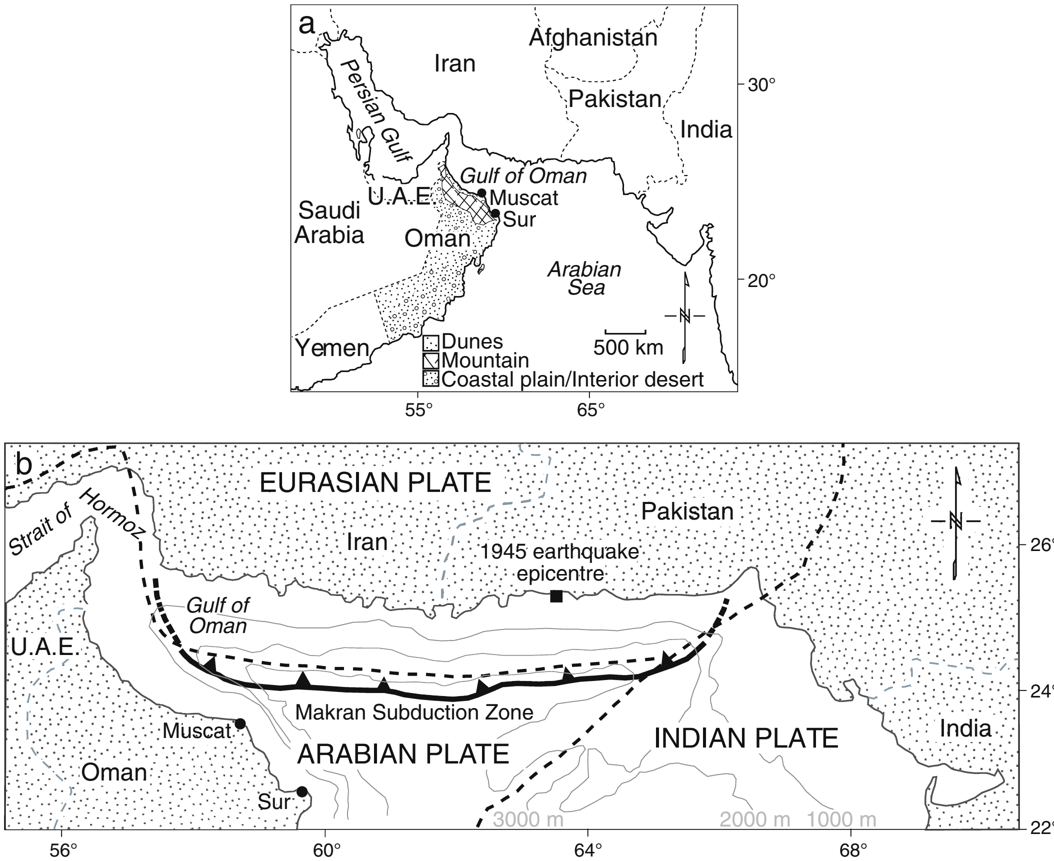


Fig. 1. a. Location of Sur, Oman. b. Makran Subduction Zone (MSZ), broad-scale plate tectonics and the 1945 earthquake epicentre are indicated (after Donato et al., 2009 and Heidarzadeh et al., 2008a).

On 28 November 1945 a M_w 8.1 subduction zone earthquake located approximately 300 km west of Karachi, Pakistan resulted in a tsunami with wave heights ranging from 2 to 13 m and was reported to have killed over 4000 people (Fig. 1b; Ambreseys and Melville, 1982; Byrne et al., 1992; Pararas-Carayannis, 2006). Debate exists over the exact location of the epicentre of the 1945 tsunamigenic earthquake. Byrne et al. (1992) argue that the rupture occurred on a 5° dipping thrust plane extending 70–90 km inland and 10–30 km offshore (25.15°N, 63.48°E). Similarly, Ambraseys and Melville (1982) report the epicentre to be located at 25.02°N and 63.47°E. In contrast to the single rupture hypothesis maintained by Byrne et al. (1992) and Ambraseys and Melville (1982), Okal and Synolakis (2008) simulated a multiple simultaneous rupture scenario along three known fault zones within the Makran Subduction Zone (MSZ) and then compared it to a more speculative scenario involving another 450 km of rupture to include a 'probable' fault zone. It was found that maximum wave amplitude between the two simulations did not vary significantly, however the wave generated by the additional 'probable' fault expressed trapping inside the Gulf of Oman. Other models show that the 1945 tsunami propagated to the south (Dominey-Howes et al., 2007) impacting the eastern corner of the Arabian Peninsula (Heidarzadeh et al., 2008b), and suggests that the observed tsunami was too large to be attributed to a single rupture and may have been the result of a submarine landslide (Ambraseys and Melville, 1982; Dominey-Howes et al., 2007). Bilham et al. (2007) support this idea, arguing that submarine landslides triggered by the earthquake damaged underwater phone lines. The apparent discrepancy over the origin of propagation is likely due to a lack of understanding concerning earthquake generation, since it is not known whether single or multiple ruptures occurred. Okal and Synolakis (2008) and Ambraseys and Melville (1982) also simulated two additional Makran earthquakes (e.g. 1765, 1851) but conclusions remain speculative.

The lack of eyewitness accounts for the 1945 event has hampered our understanding of the earthquake and tsunami. At that time, most Arabian Sea coastal areas had low populations consisting of isolated fishing villages, and survivors are becoming aged and increasingly difficult to find. Recent interviews (2008) of a resident of Sur, who was a child in 1945, described tsunami flooding reaching ~3 m at Sur (Donato et al., 2009).

Geological evidence of the 1945 tsunami is also sparse. Compelling evidence of the 1945 tsunami was found in Sur Lagoon (Fig. 2) in 2006 and is discussed in detail in Donato et al. (2008, 2009). The inferred tsunami bed (5–25 cm thick) has high concentrations of angular shell fragments, articulated bivalves (out of life position) from lagoon and offshore provenance, is laterally extensive and covers an area of at least ~1 km^2 (Figs. 3 and 4). The bed thins progressively in a western and southern direction, and becomes finer grained, better sorted and skewed with increasing distance from the entrance channel. The sheet-like shell bed was deemed to be tsunamigenic (vs. a storm) due to the unique character of the shells which indicate offshore scour of the substrate with landward transport and deposition inside the lagoon (Morton et al., 2007).

2. Regional setting

2.1. Sur Lagoon physiography

Sur Lagoon, a small (~12 km^2) tidally dominated (mean tidal amplitude ~1.2 m), lagoon, is situated approximately 100 km south of the capital Muscat on the eastern coast of Oman (Figs. 1 and 2). The lagoon can be divided into a Distal (average elevation = 0.6 ± 0.5 m.s.l.) and Main Lagoon Basin (average elevation = 0.3 ± 0.6 m.s.l.) and communicates with the Shallow Marine Area (average elevation = −0.8 ±

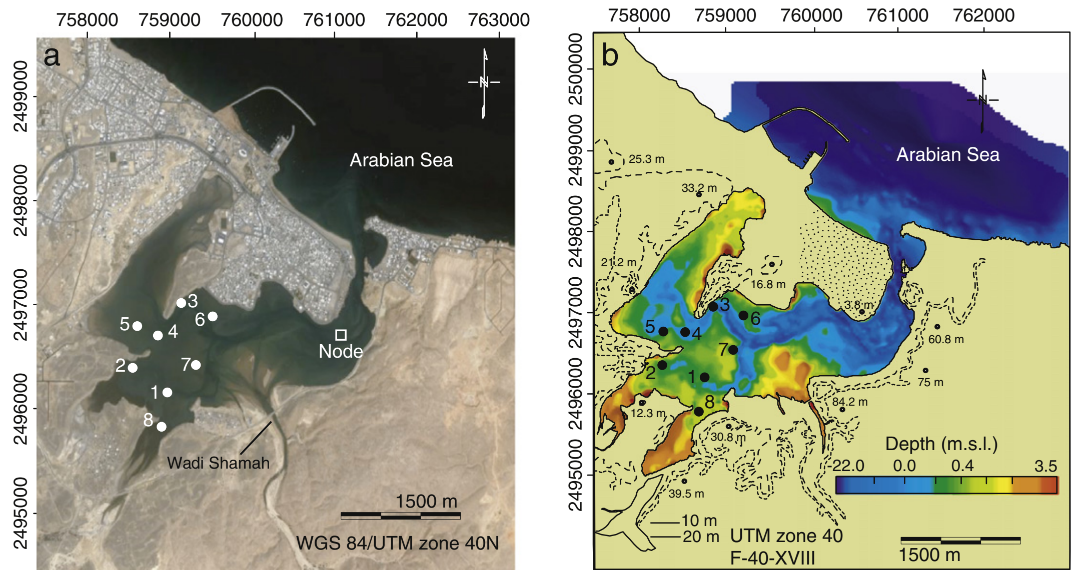


Fig. 2. a. Google Earth image of Sur Lagoon indicating the lagoon entrance, tidal channels, Wadi Shamah and location of Cores 1–8 (circles). The node used to measure core distances from the lagoon entrance is indicated by a square (Fig. 6). b. Digital Elevation Model (DEM) of Sur Lagoon.

1.1 m.s.l.; Pilarczyk et al., 2011). Communication with the Gulf of Oman is through a narrow (103–209 m wide) entrance channel at its north-eastern corner, which connects a 2.5 km network of tidal channels (Fig. 2). The lagoon is bordered by Paleocene-Eocene aged highlands and is restricted on its north-eastern margin by a low lying sand spit (~2–3 m.s.l; Fig. 2b). The lagoon basin experiences minimal wave action and contains a network of intertidal sand and mudflats which are exposed through diurnal tides. Low density mangrove patches fringe most of the lagoon except along the NE tip of the Distal Lagoon Basin and the SW section of the Main Lagoon Basin where high density mangroves are present. Sand texture within the lagoon becomes finer with increasing elevation and distance from the marine source (see Fig. 3 in Pilarczyk et al., 2011). The high energy Shallow Marine Area outside of the lagoon has a narrow shelf which abruptly drops to depths in excess of 200 m after ~5 km (Szuman et al., 2006).

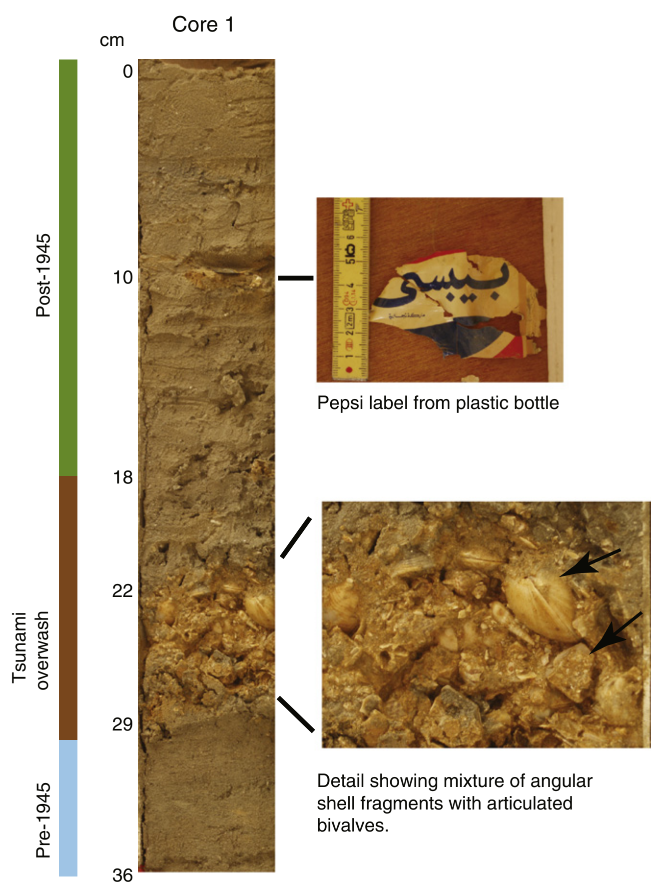


Fig. 3. Photographic record of Core 1 showing the stratigraphic units designated by bivalve taphonomy and particle size data as shown in Donato et al. (2009). Details of the tsunami unit show articulated bivalves out of life position with angular fragmented shells. Note the red-orange color of the shell unit vs. the sand above and below. A recent Pepsi bottle label was found in post-1945 sediments which shows reworking of the upper sediments. Compare exposure with trench section in Fig. 4d.

2.2. Recent cyclonic activity

Cyclone activity in the northern Arabian Sea is rare and is generally characterized by small cells that dissipate quickly. For a complete list of cyclone tracks in the northern Arabian Sea see Knapp et al. (2009). Cyclones Gonu (2007) and Phet (2010) are the exception and represent the most 'severe cyclonic storms' to have ever impacted the Arabian Peninsula in recorded history (Fritz et al., 2010). Cyclone Gonu in 2007, the most intense storm on record in the Arabian Sea (Category 5), resulted in ~50 deaths and $4 billion in coastal damage (JTWC, 2007; Dube et al., 2009; Fritz et al., 2010). On 1 June 2007, Gonu began as a depression over the eastern Arabian Sea and within hours of it moving west towards Mumbai, India it had intensified into Tropical Storm Gonu. By 4 June 2007 the storm reached Category 5 status with wind speeds in excess of 240 km/h reported 475 km east of Masirah Island, Oman. As the cyclone tracked northwest towards Oman, cooler sea surface temperatures and drier air caused it to gradually weaken before it made landfall at Ras al-Hadd (easternmost point on the Arabian Peninsula, ~30 km ESE of Sur) on 5 June 2007. Despite the reduction in wind speed (e.g. >240–164 km/h), Cyclone Gonu's strike at Ras al-Hadd marked the most severe storm ever recorded on the Arabian Peninsula. After it made landfall, Gonu tracked to the north-northwest where it downgraded to a tropical storm and made landfall on Iran's Makran Coast on 7 June 2007.

Fritz et al. (2010) reported greatest damage at Ras al-Hadd with a 5 m storm surge that destroyed wall structures 200 m inland, and a marked decrease in high water marks with increasing distance from the initial strike location. Muscat was impacted by a 3 m storm surge that caused severe coastal erosion and road damage. A field survey at

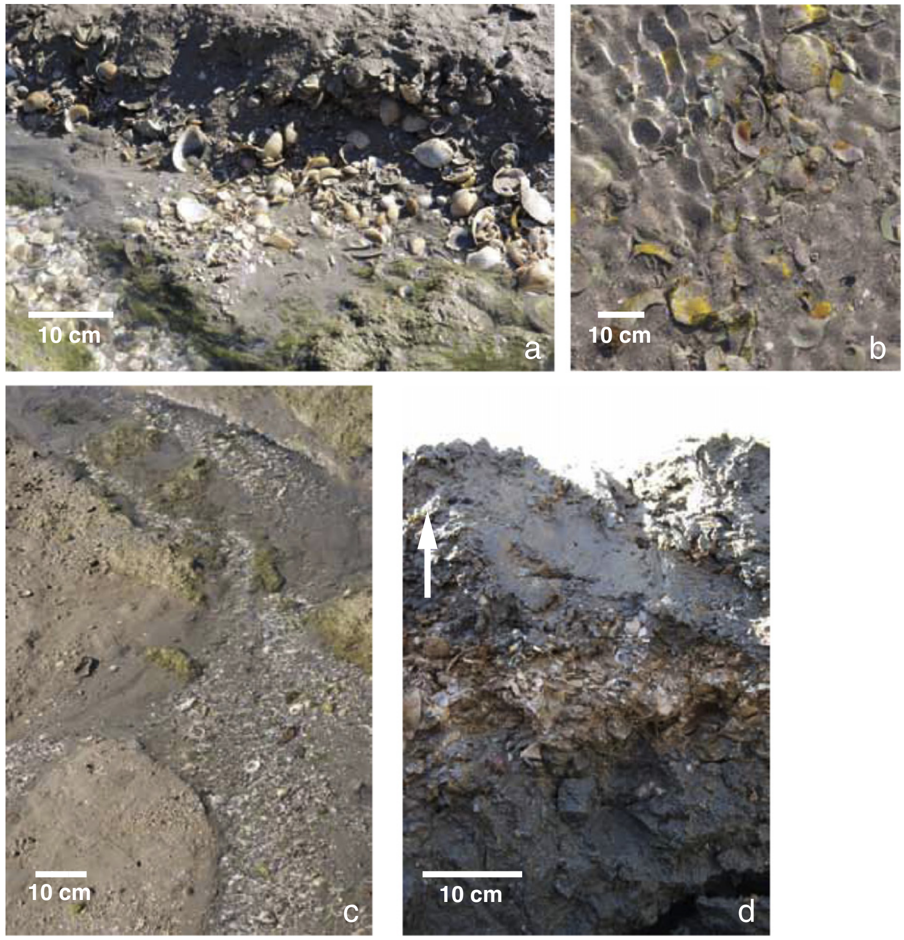


Fig. 4. a. Tidal channel erosion of the tsunami shell unit (plan view). b. Shells exposed in tidal channel become edge rounded, bioeroded (microboring) and encrusted (plan view). c. Accumulation of shells at the bottom of tidal channels (plan view). d. Exposure of the tsunami shell unit in a trench section close to Core 1.

Sur in November 2007 showed that Gonu's intense rain (>610 mm) and resultant flow through Wadi Shamah eroded the small delta and washed away the bridge (Donato et al., 2009). Despite the estimated storm surge of 2.6 m (Dube et al., 2009), a survey of the lagoon after the event found no record of overwash or shells (Donato et al., 2009).

More recently, on 2 June 2010 Cyclone Phet skimmed parallel to Oman's coast. It began as a Category 3 on 2 June 2010 with sustained winds of greater than 210 km/h. It lashed Oman's eastern region with hurricane-strength winds through to 4 June 2010 before moving northeast towards Karachi, Pakistan. Sur was closest to the path of the storm and was hit quite hard. Phet was not expected to make landfall on Oman, however it did hit Ras al-Hadd, Oman dumping 152 mm of rain within 24 h. Damage from the storm has not been assessed although this storm was less intense than Cyclone Gonu three years earlier, which did not produce a shell accumulation.

2.3. Arabian Sea environments as tsunami recorders

Arid Arabian Sea coastlines are difficult to work with as there is a lack of environments to act as tsunami recorders. Overwash onto terrestrial surfaces has low preservation potential since the sand sheet dries quickly and then is blown away. A body of water is needed to preserve the overwash event, yet there are few suitable coastal lagoons or estuaries. The majority of previous overwash studies have been conducted in temperate or tropical environments where terrestrial areas, coastal ponds, marshes and estuaries have proven useful (e.g. Goff et al., 2000; Luque et al., 2002; Cisternas et al., 2005; Rajendran et al., 2006; Kortekaas and Dawson, 2007). However, most of the lagoons or estuaries on the eastern coast of Oman, are barrier choked wadis (khors) that occasionally flood, eroding any accumulated sediment. Sur is somewhat unique in that it has one major wadi (Wadi Shamah) that occasionally floods (e.g. during Cyclone Gonu), but the flow by-passes the lagoon and flows out to sea allowing for the preservation of sand or shell sheets within the basin.

3. Methods

In 2006, eight trench sections and corresponding short cores were collected in the Main and Distal Lagoon Basins and are the same cores used by Donato et al. (2008, 2009). A Digital Elevation Model (DEM) was created by walking a Trimble R3 differential GPS unit in north–south transects spaced 100 m apart, and east–west lines at 300 m spacing (Fig. 2b; Donato et al., 2008, 2009). Submerged locations of the lagoon and Shallow Marine Area were surveyed using a single-beam echo sounder. Data was processed with Geosoft Oasis TM software to create a DEM and was levelled to a mean sea level datum (see Donato et al., 2008).

Samples were selected based on facies designations derived from shell taphonomy and particle size data as described by Donato et al. (2008, 2009). Approximately 1 cm^3 samples were sieved (>63 μm) and examined for foraminiferal analysis using a binocular microscope. A total of 22 foraminiferal taxa (for plates see Pilarczyk et al., 2011) were identified using the taxonomy of Hottinger et al. (1993) and Hayward et al. (2004). Individual specimens were categorized using the same taphonomic criteria defined in Pilarczyk et al. (2011). These include: unaltered, fragmented, corraded (combined influence of corrosion and abrasion) and sediment in-filled tests (e.g. fossil; see

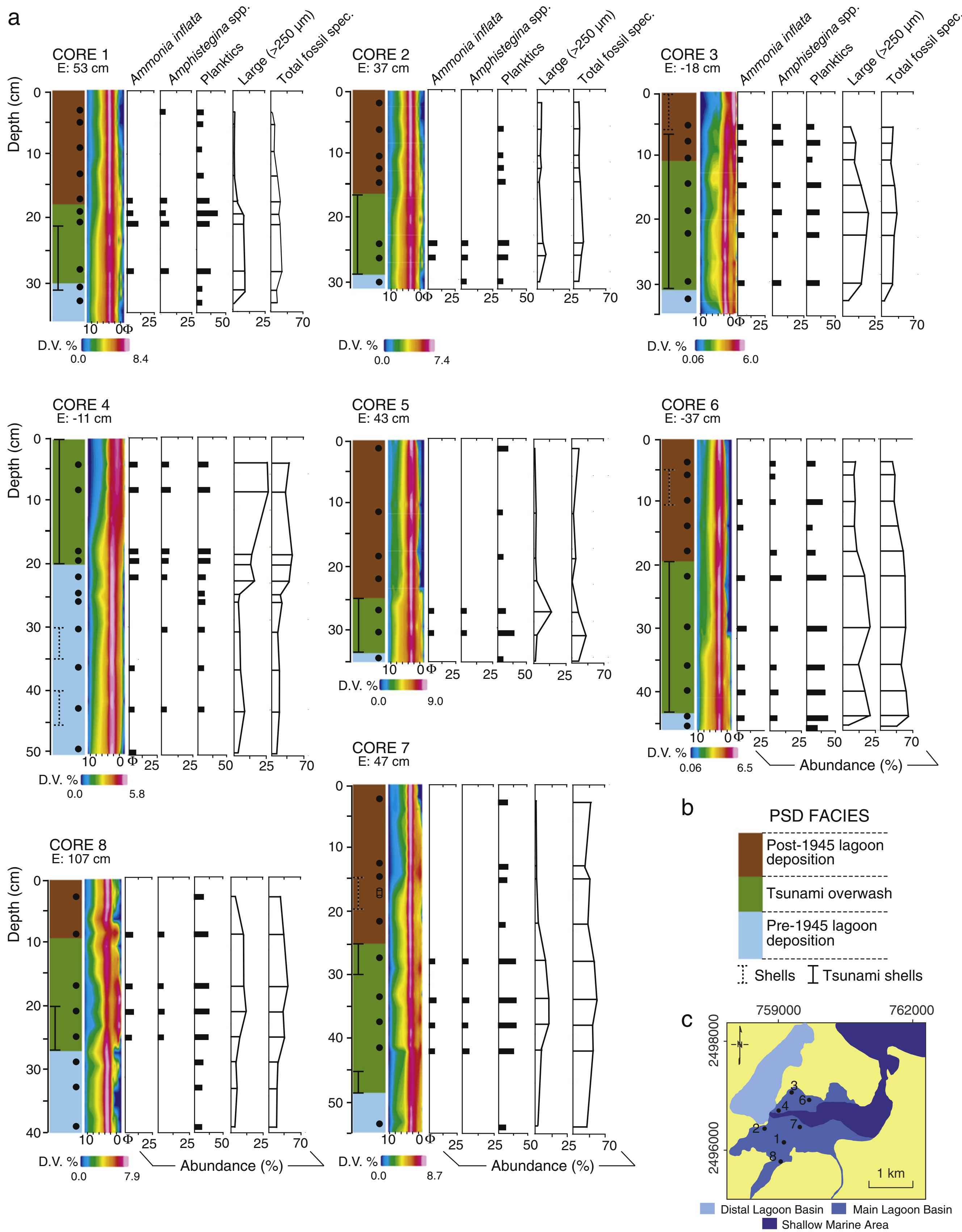


Fig. 5. a. Lithologic (PSD), shell and foraminiferal data for Cores 1 – 8. Foraminifera and taphonomic characters that best reflect tsunami overwash are indicated. For all taxonomic and taphonomic data see Online Figs. 1–5. Tsunami and lagoon units are based on PSD and shell taphonomy evidence (Donato et al., 2008; Donato et al., 2009). b. PSD facies. c. Core locations within Sur Lagoon.

Plate II in Pilarczyk et al., 2011). In addition, specimens were categorized into small (<150 μm), medium (150–250 μm) or large (>250 μm) test sizes (Figs. 5 and 6; Online Figs. 1–5).

4. Results

4.1. Previous shell and particle size results

Facies were defined through shell bed and particle size results and are summarized here from Donato et al. (2008, 2009). Pre-1945 lagoon deposition is dominated by brownish-grey structureless fine sands with low abundances of lagoon mollusc taxa typical of arid intertidal environments (e.g. *Hiatula ruppelliana, Marcia mamorata, Marcia opima, Protapes* sp.; Donato et al., 2008). Although rare, organic material (fragments of mangrove roots, leaves, and seeds) were also found. In Cores 1–8, the pre-1945 lagoon unit is ~2–15 cm thick and likely extends downward in the substrate.

The tsunami unit ranges in thickness from 10 to 40 cm and is characterized by a slight coarsening to heavily oxidized (red-orange in color) structureless medium sand, which is largely shell material (Fig. 4d). Particle size analysis was performed on the <2000 μm fraction, omitting the coarse shells. Differences in the undigested vs. acid digested particle size data illustrate the dominance of shelly material in the sediment (note: in Fig. 4 of Donato et al., 2009 digested (D) and undigested (UD) labels are erroneously labelled). The shell concentration consists of abundant offshore (e.g. *Anadara uropigimelana, Tellina palatum*, and *Glycemeris* sp.) and lagoon mollusc taxa with unique taphonomy (i.e. articulation and angular fragmentation). Shell concentrations were very distinct in the stratigraphy and were used to define the tsunami unit, but subsequent particle size results extended its range to include sandy intervals above the shells (Cores 3 and 8).

Post-1945 lagoon sedimentation is similar in character to pre-1945 lagoon sedimentation except in some cores where there are thinner shell units that do not have the characteristics of the tsunami shell unit. These thinner beds represent erosion and reworking of the shell bed through tidal channel migration observed in several locations within the lagoon. Shells, once eroded, are concentrated at the bottom of tidal channels and subsequently become bioencrusted and bored losing their previous taphonomic character (Fig. 4a–c). Sediment texture is similar to the pre-1945 sediments as well, and is reflected by a brownish-grey structureless fine-sand (Donato et al., 2009). Abundances of organic material are slightly higher than pre-1945 sediments, but overall low. Recent debris is also found in the upper sand indicating erosion and re-sedimentation events (Fig. 4a–d).

4.2. Previous foraminiferal results from surface samples

Foraminiferal analysis of surface samples in Pilarczyk et al. (2011) found three biofacies within Sur Lagoon that were largely defined by geographic areas: 1) the subtidal Shallow Marine Area (−1.9 to 0.3 m.s.l.) with higher wave energy; 2) the mostly intertidal Main Lagoon Basin (−0.3 to 0.9 m.s.l.) with moderate wave energy, and 3) the dominantly intertidal Distal Lagoon Basin (0.1 to 1.1 m.s.l.) characterized by very low wave energy. The biofacies had very similar assemblages and were defined largely by the presence/absence of a few key species that were either low, or moderate in abundance (*Ammonia inflata, Amphistegina* spp., *Elphidium advenum* and planktics). The taphonomic characters did not show any strong correlation with position in the lagoon although abundance of fossil specimens and test size did show some trends.

4.3. Foraminiferal character of the tsunami unit

Overall, there is not a great difference in the foraminiferal assemblages, with similar taxa found in all stratigraphic units. The assemblage is dominated by miliolids and *Ammonia parkinsoniana* with *Ammonia tepida, Elphidium craticulatum, Elphidium gerthi, Peneroplis planatus* and *Porsonion granosa* present in smaller abundances (Fig. 5; Online Figs. 1–5). The Shannon Diversity Index (SDI) also does not vary between the units; pre-tsunami (2.0 ± 0.1), tsunami (2.0 ± 0.1) and post-tsunami (1.8 ± 0.2; Online Figs. 1–5) all have similar values.

However, there are some important differences in minor but important taxa in the tsunami unit that are very diagnostic (Pilarczyk et al., 2011). These include *A. inflata, Amphistegina* spp. and planktics, as well as taphonomic characters consistent with the modern Shallow Marine Area (i.e. large specimens, fossil specimens; Figs. 5 and 6). In all cores *A. inflata* abundances are highest in the tsunami unit (e.g. 4% ± 1); although, small amounts (<2%) are also present in pre-1945 sediments in Cores 3, 4, 5 and 6. In post-1945 sediments, abundances of *A. inflata* from cores taken closest to the entrance channel (Cores 6, 7 and 3) are high (Cores 6, 7 and 3; 1–4%), but still less than abundances within the tsunami unit (3–5%). *Amphistegina* spp. follow a similar trend where abundances within the tsunami unit are higher (4% ± 1) than the other units (pre-1945 is <3%; post-1945 is <2% except at Core 3 where it is 5%); but also, in post-1945 lagoon sediments, abundances show a decrease with distance away from the lagoon entrance (Fig. 6a). Planktics are also slightly higher in some tsunami units, but in most cores the abundances are not significantly different than the pre- or post-1945 sediments (Fig. 5). Overall, *A. inflata* and *Amphistegina* spp. are the best indicator species since sediments above and below the tsunami unit contain lower abundances and it was a consistent trend.

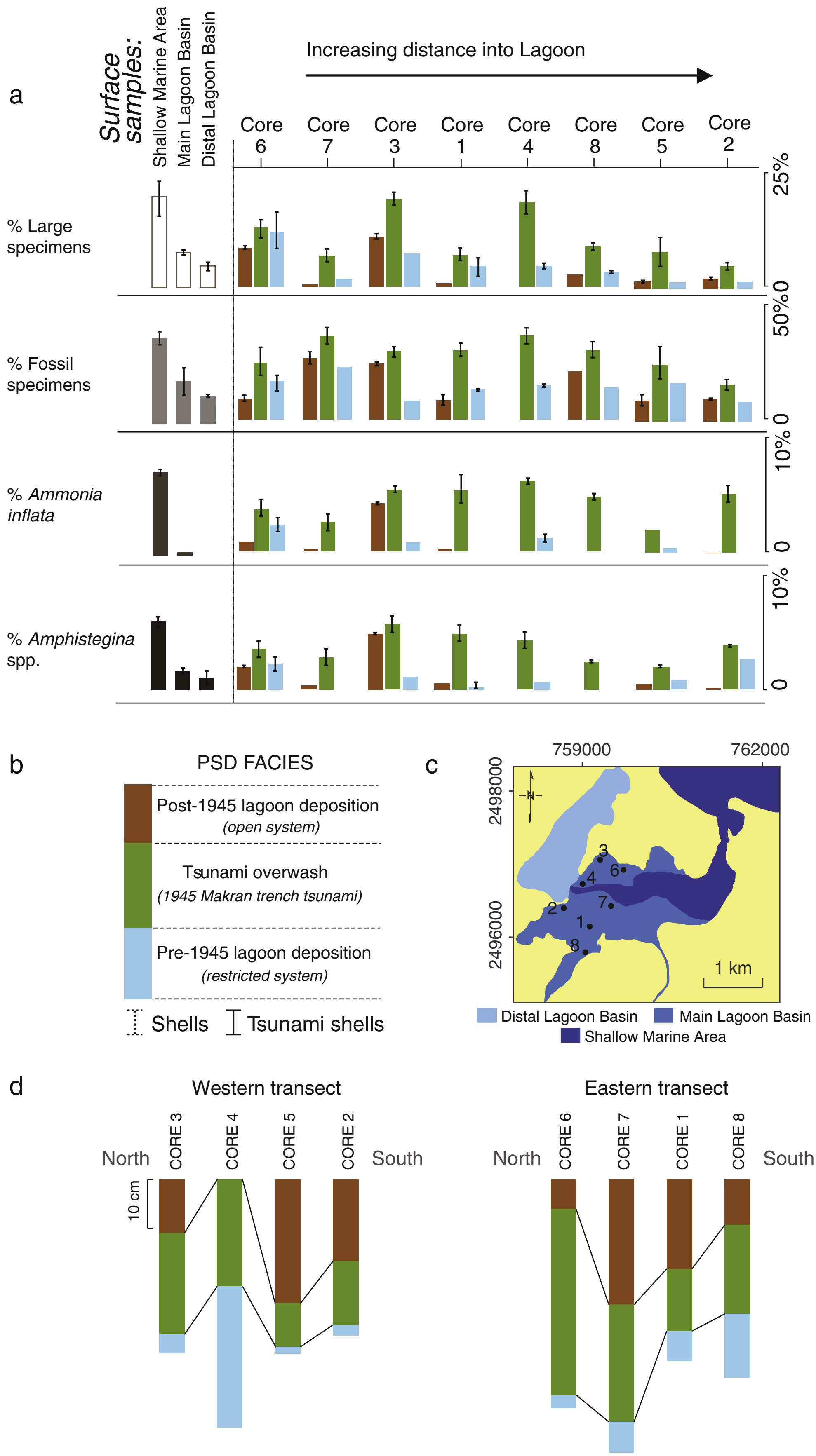
The tsunami unit also has higher abundances of large (>250 μm), and fossil specimens (31% ± 8). Large tests and fossil specimens were previously shown to be associated with modern Shallow Marine Areas (Pilarczyk et al., 2011). Fragmented individuals are higher in some of the tsunami units, but the trend is not consistent throughout the cores. Similarly, abundances of total individuals per 1 cm^3 are quite variable and only in Cores 1, 3, 6 and 7 do they peak in the tsunami unit (Online Figs. 1–5).

5. Discussion

Foraminiferal analysis was able to distinguish the tsunami unit as discerned through shell taphonomy and particle size analysis. This is largely accomplished with two allochthonous species, *Amphistegina* spp. and *Ammonia inflata*, with the number of large specimens and to a lesser extent, fossil taxa also defining the unit in the cores. However, the abundance of these indicator species is very low (<5%) and the overall taphonomic character was not significantly different in the tsunami unit compared with pre- and post-1945 sediments (Figs. 5 and 6). There was little to no overprinting (fragmentation) of the foraminiferal tests through the process of tsunami transport and deposition vs. the bivalves which showed distinctive features (Online Figs. 1–5). Only the proportions of large tests and fossil specimens increased in the tsunami unit, which can be explained by sorting that occurred with transport and deposition during the event.

5.1. Allochthonous tests and size-sorting

Hawkes et al.'s (2007) analysis of deposits from the 2004 Indian Ocean tsunami were able to resolve distinct episodes of deposition by the presence of offshore radiolarians in uprush phases and mangrove foraminifera dominating backwash phases. Donato et al. (2009) alluded to multiple tsunami incursions into Sur Lagoon, however, shell taphonomy and particle size evidence was not enough to support any conclusion. Likewise, there does not seem to be any systematic trend in the foraminiferal data; however, subtle changes may not be evident due to lower sampling resolution. In addition, as pointed out in Pilarczyk et al. (2011), the biofacies/taphofacies within the lagoon are very homogeneous, and changes in test character may be hard to identify.


a
Surface samples:
Shallow Marine Area
Main Lagoon Basin
Distal Lagoon Basin
Increasing distance into Lagoon
Core 6
Core 7
Core 3
Core 1
Core 4
Core 8
Core 5
Core 2
% Large specimens
% Fossil specimens
% Ammonia inflata
% Amphistegina spp.
25%
0
50%
0
10%
0
10%
0
b
PSD FACIES
Post-1945 lagoon deposition
(open system)
Tsunami overwash
(1945 Makran trench tsunami)
Pre-1945 lagoon deposition
(restricted system)
Shells
Tsunami shells
c
759000
762000
2498000
2496000
N
1 km
Distal Lagoon Basin
Main Lagoon Basin
Shallow Marine Area
d
Western transect
North
CORE 3
CORE 4
CORE 5
CORE 2
South
10 cm
Eastern transect
North
CORE 6
CORE 7
CORE 1
CORE 8
South

Changes in test size and concentrations of planktic foraminifera have also been used to determine pre- and post-tsunami sediments from the 2004 Indian Ocean event (Hawkes et al., 2007). Results indicated that test size was a useful taphonomic character; medium sized tests (<200 μm) dominated the pre-tsunami sediment while the tsunami unit tended to have larger tests (>200 μm). In addition, test concentrations increased moving up the unit (Hawkes et al., 2007). The results from Sur mostly mirror these findings where the 1945 tsunami unit is shown to contain a predominance of larger tests, and in some instances shows increases in planktic foraminifera and concentration of tests, however this is not displayed in all cores. The most important indicators are the robust *Amphistegina* spp., *Ammonia inflata* and in some instances, fossil specimens which indicate a Shallow Marine Area provenance for the sediment. As would be expected, certain taxa will be more useful than others depending upon geographic location, type of coastal recorder and the characteristics of the tsunami itself. As pointed out previously, identifying the useful taxa and their taphonomic trends should be conducted to properly assess the stratigraphic record (Mamo et al., 2009; Pilarczyk et al., 2011).

5.2. Fragmentation

The lack of an increase in fragmentation of recent (vs. fossil) specimens in the tsunami unit seems unusual (Online Figs. 1–5). Increased fragmentation is present in some of the cores (e.g. Core 2) but it is not a distinctive feature and was not different than what was observed in pre- and post-1945 sediments. Kortekaas and Dawson (2007) described increased fragmentation in their tsunami unit in Portugal, but it was documented with qualitative observation, so the results are difficult to assess. Satyanarayana et al. (2007) reported a lack of fragmented foraminifera within the 2004 Indian Ocean tsunami deposit in India. Unusually high abundances of preserved delicate species were present and interpreted to be the result of wave scour followed by suspension prior to deposition. In the case of Sur Lagoon, fragmentation is not a dominant feature, and contrasts with the bivalve taphonomy which shows extensive angular fragmentation (Donato et al., 2008). However, it is unclear that a tsunami would in fact cause increased foraminiferal fragmentation and we do not seem to have that effect represented here. It is thought that the high degree of angular fragmentation associated with larger shells maybe due to the type of coastline (Reinhardt et al., 2006; Donato et al., 2009; Massari et al., 2009). Rocky shorelines provide a hard substrate for shell collision and fragmentation vs. soft sediment shorelines where fragmentation might be less. Even though there is a rocky shoreline at Sur which, likely produced the bivalve fragmentation during the 1945 tsunami, it does not seem to have taphonomically overprinted the foraminiferal tests (e.g. Reinhardt et al., 2011).

5.3. The potential for documenting older events

Mapping indicator species laterally and vertically in cores will be important for documenting bed geometry (e.g. sheet-like) and distinguishing a tsunami or storm origin (Morton et al., 2007). The foraminiferal results agree well with the shell designation of the tsunami unit (see Fig. 4 in Donato et al., 2009), but correspond better with PSD data (i.e. Cores 1, 2, 4, 5, 8). As discussed in Donato et al. (2009), the PSD data corresponds well with the base of the shell unit, but the upper boundary in several cores extends into the overlying sand (Cores 1, 3, 8; Fig. 5). The extension of the boundary is due to the abundance of small shell fragments in the sand which have PSDs that are similar to the shell unit. Foraminiferal evidence also corresponds with the base of the shell concentration, but better matches the PSD data for the upper boundary. It is unclear whether this upper shell fragment-rich sand is from the tsunami or reworking of the boundary with subsequent storms or tidal channel migrations (Donato et al., 2009; Fig. 5). This blurring of the top boundary (i.e. time-averaging) is expected to be more pronounced with the smaller foraminifera than with the shells (see Fig. 3). Contributions to this effect may also be from crab burrowing, which was observed to bring shell material and sediment from the tsunami unit to the surface (McLachlan et al., 1998).

In Donato et al. (2009), Core 7 was found to be problematic as there was a lack of thick shell beds to determine the extent of the tsunami unit (Fig. 5). In this case, the foraminiferal records better indicate the overwash interval. Based on its stratigraphic position and correlation with the other shell beds , a more confident interpretation can be made on its origin (Pilarczyk and Reinhardt, 2011; Reinhardt et al., 2011). This will be particularly important in future core studies.

Using the 1945 tsunami deposit as a reference, foraminiferal provenance and taphonomy can be used as a tsunami indicator for older geologic deposits. Previous foraminiferal studies did not use taphofacies analysis, however, based on this study, it may provide an enhanced understanding of tsunami deposition (see Mamo et al., 2009 and references therein). At Sur Lagoon, shelly sand sheets containing influxes of predominantly offshore taxa (*Amphistegina* spp., *Ammonia inflata*, and planktics), larger test sizes and fossil specimens are likely to be the result of tsunami deposition rather than storm. Preliminary work shows a series of such beds in long cores taken from the lagoon. Ascribing either a storm or tsunami origin to these beds will help to qualify risk assessment for the Omani coastline, which to date remains undocumented.

6. Conclusions

The combined use of foraminferal provenance and taphonomy was effective in identifying the 1945 Makran Trench tsunami at Sur Lagoon and will likely be a good indicator of older events at this location. High abundances of predominantly marine taxa (*Amphistegina* spp., *Ammonia inflata*, and planktics) coupled with high abundances of large test sizes, fragments and fossil specimens were found to be associated with tsunami deposition. At Sur Lagoon, most sedimentological tsunami criteria (e.g. grading) did not apply to the 1945 tsunami bed. Bivalve taphonomic analysis conducted previously however, provided evidence of a tsunami through the presence of articulated bivalves and angular fragments from offshore provenance. Both PSD and foraminiferal analysis support this tsunami interpretation and hold the added benefit of delineating older deposits where shell quantities are limited (e.g. cores). Although successful in detecting the 1945 tsunami deposit, foraminiferal analysis on its own would only be effective in documenting a marine incursion and should be combined with other proxies when ascribing an event origin.

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Fig. 6. a. Foraminiferal data from surface samples (after Pilarczyk et al., 2011) and major stratigraphic units in Sur Lagoon. Core locations are arranged in order of increasing distance into the lagoon. Percentages on the y-axis reflect relative abundances. b. A generalized stratigraphic section indicating an older more restricted lagoon system evolving into a more open system by way of tsunami inundation. c. Core locations within Sur Lagoon. d. Correlation of cores through two north–south transect lines (eastern and western) indicating a slight thinning trend in tsunami bed thickness.

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