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Particle-size distribution of inferred tsunami deposits in Sur Lagoon, Sultanate of Oman

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The sedimentary characteristics of shell beds within an interpreted tsunami deposit from Sur Lagoon, Oman were examined using shell taphonomy and high-resolution particle-size analysis. The tsunami bed was deposited by the 28 November, 1945 tsunami generated by the Makran subduction zone. Q-mode cluster analysis of particle-size data was evaluated as a means of discriminating individual tsunamite shell layers from lagoonal intertidal deposits. Results showed that the tsunami shell bed was more poorly sorted, and heterogeneous (in both the digested and undigested samples) than the background lagoonal sediments. The tsunami bed thickness correlated generally with the thickness of the shell-bed, however, cluster analysis extended the tsunami unit several centimeters above or below the shell bed in some cores. The particle-size analysis also showed subtle textural trends in the tsunami unit, suggesting that the tsunami bed was deposited in several distinctive phases during tsunami incursion into Sur Lagoon. The findings indicate that cluster analysis of particle-size data can be used to identify tsunami beds in intertidal environments and holds potential for identifying paleotsunami deposits in sediments from embayed intertidal–subtidal siliciclastic systems where obvious sedimentary structures may be absent.
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1. Introduction

The northeastern coast of Oman is located within ~120–170 km of the seismically-active Makran subduction zone (Fig. 1). On 28 November,1945 a large thrust earthquake (M_w 8.1) epicentered on the eastern portion of the subduction zone off the modern coast of Pakistan, produced a large tsunami that impacted coastlines along India, Pakistan, Iran, and Oman (Byrne et al., 1992). Historical records detailing the tsunami and its impact on the Omani coast are limited, but the event was recorded in Indian news reports (Ambreseys and Melville, 1982). Recently, Donato et al. (2008) identified and described thick, laterally extensive bivalve-rich shell beds deposited by the 1945 tsunami in Sur Lagoon ~500 km from the epicentre on the eastern margin of Oman (Fig. 1). In this paper, we further test the tsunami origin of the deposit by using Q-mode cluster analysis of high-resolution particle-size data. Our results demonstrate that cluster analysis is an effective method for recognizing subtle textural changes within the tsunami bed and for discriminating tsunami from lagoonal inter-tidal deposits.

1.1. The 1945 tsunami event

Historical records documenting tsunami impacts along the Oman coastline are lacking due to a sparsely-populated coastline and limited communication with larger centres (i.e. Muscat). Records have proven elusive in Oman for the tsunami generated on 28 November 1945. The epicentre was located on the seismically-active eastern portion of the Makran subduction zone (Fig. 1; Byrne et al., 1992). Details of this event were well documented by Indian and Pakistani media and meteorological services, as the earthquake and tsunami caused over 4000 deaths and extensive damage along the coastlines of Pakistan, Iran, western India, and Oman, with Pakistan recording a run-up height of 13 m (Pararas-Carayannis, 2006). Tsunami damage and casualties were reported in Muscat ~200 km north of Sur (Pararas-Carayannis, 2006, p. 362), although no supporting references were provided to substantiate the claim. However, a recent interview (May 21st, 2008) by Dr. Abdulrahman A-Harthi (Sultan Qaboos University-Dept of Geology) and Dr. Emile Okal (Northwestern University, Department of Earth and Planetary Sciences) provide some corroborating information. Mr. Ahmed M.J. Al-Alawi (approx. 85 yrs old) who was living at Sur during 1945, witnessed the event and recalled the flooding and a tsumani water level rise of ca. 3 m above mean sea-level (msl). More interviews need to be conducted to corroborate this water level estimate, but it does indicate that the tsunami had some effect at Sur.

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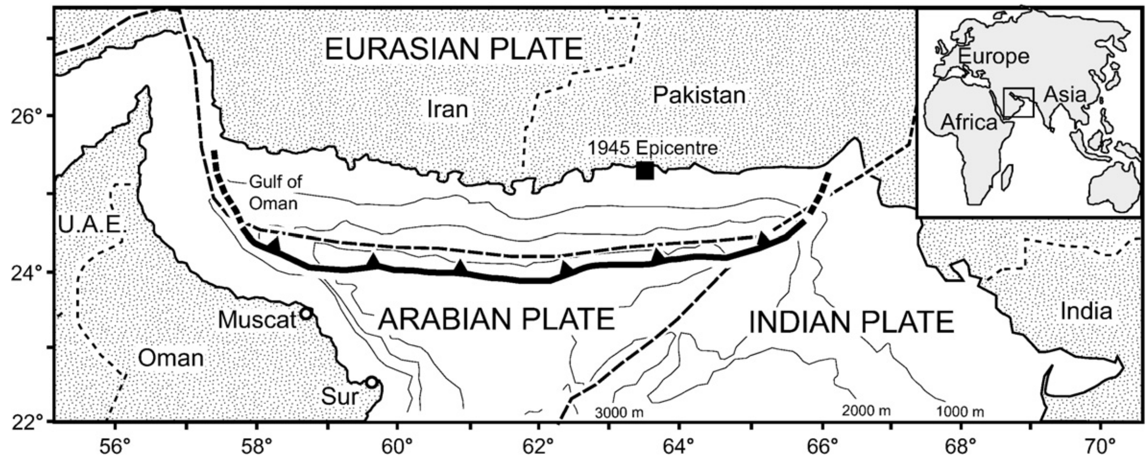

Fig. 1. Location of Sur Lagoon, Oman. Location of Makran subduction zone and 1945 earthquake epicentre indicated (after Byrne et al., 1992 and Okal and Synolakis, 2008).

Models for the 1945 event show the tsunami predominantly directed to the south (Dominey-Howes et al., 2007) but also show it impacting the eastern corner of the Arabian Peninsula (Heidarzadeh et al., 2008b). The simulations, using the fault parameters of Bryne et al. (1992) showed that the observed tsunami was too large to be explained by the proposed source mechanism. Other possible mechanisms include a submarine landslide (Dominey-Howes, Cummins and Burbidge, 2007; Ambraseys & Melville, 1982) and large displacements on splay faults (Heidarzadeh et al., 2008a). Heidarzadeh et al. (2008a) concluded that the Makran Trench has the potential for generating tsunamis with considerable run-up heights in far-field areas. Additional simulations have been made for two hypothetical Makran earthquakes (1765, 1851) larger than the one in 1945 but data regarding the size and location of the events are scarce (Quittmeyer and Jacob, 1979; Okal and Synolakis, 2008; Ambraseys & Melville 1982).

1.2. Tsunami shell taphonomy

Donato et al. (2008) identified the shell bed in Sur lagoon as a tsunami deposit due to its distinctive shell taphonomy, shell provenance, thickness and wide lateral extent in the lagoon. The taxonomic composition (and habitat) of the bivalves in the shell layers varied due to proximity to source areas (e.g. lagoon vs offshore) but the abundance of whole, articulated specimens and angular fragments in the layer was very distinctive. These consistent taphonomic characters were found from core to core (n=8) over a wide area (>1 km^2) and at a similar depth (20–40 cm below modern surface) indicating a singular, large-scale event. The shell taphonomic traits indicate live transport of the articulated shells, breakage of the shells through turbulent flow and burial without subsequent reworking. A similar shell deposit in the Mediterranean (Caesarea, Israel) with near identical taphonomic characters was ascribed to an older tsunami (115 A.D.; Reinhardt et al., 2006). The Sur deposit was attributed to the 1945 tsunami based on its shallow depth below the sediment surface as no direct dating evidence was found (^{210}Pb dating proved ineffective; Donato et al., 2008).

Alternate interpretations on the origin of the shell unit at Sur relate to tidal channel migration and storm deposition, which can be rejected (or minimized) based on the documented taphonomic characters. The shell bed was not deposited as a channel lag as shell concentrations in such contexts do not contain articulated specimens and the shells are often heavily bioencrusted, bioeroded and rounded (e.g. Meldahl and Cutler, 1992). Articulated bivalves left exposed in tidal channels disarticulate through tidal reworking and have little chance of burial with both valves together.

Similarly, the distinctive taphonomic characters and the extensive sheet-like distribution of the bed in the lagoon were used to argue against a storm origin. The presence of many articulated offshore and lagoonal bivalve species out of life position (along with angular fragments) is more consistent with rapid (minutes) deposition and burial by a tsunami event rather than more prolonged storm deposition over several hours. The exhumation of offshore and lagoonal bivalves accompanied with suspended load transport and deposition of shells in a massive, sheet-like geometry does not appear to be typical of storm deposition (e.g. see taphonomic characters described by Boyajian and Thayer, 1995; Meldahl and Cutler, 1992). Storm shell concentrations tend to form in more localized units or lenses (often shore parallel; Meldahl and Cutler, 1992) rather than extensive sheet-like beds and often have a biofabric (shells are nested, imbricated and size-sorted; eg. compare with Meldahl and Cutler, 1992 and see Brett, 2003 for a summary).

1.3. Sedimentological indicators

Tsunami deposits are difficult to identify in arid siliciclastic sandflat coastal settings due to numerous erosive post-depositional processes acting on the sediment. The action of daily tides, wind-driven waves, storm waves, and even localized processes such as bioturbation can potentially erase traces of these events from the sediment record in short periods (i.e. 10 years or less, Dominey-Howes et al., 2006). In arid terrestrial settings, the deposits are further threatened by wind erosion, deflation and fluvial sheet-wash erosion during high-discharge flood events.

Perhaps due to the perceived lack of preservation potential, there have been few attempts to identify tsunami deposits in arid environments outside the Mediterranean (e.g., Scheffers and Kelletat, 2003; Scheffers and Kelletat, 2005; Scheffers and Scheffers, 2007). Consequently, most of the diagnostic characteristics used to identify tsunami deposits globally have been derived from temperate climates with terrestrial deposits, coast proximal lakes, marshes and estuaries being the favored environments (Atwater et al., 2005). Most of this previous work has relied on the presence of intrusive marine sediment layers (sand sheets, gravel, etc.) as tsunami indicators, however, storms can also produce these deposits and recent research has tried to develop a criteria for separating the two (eg. Goff et al., 2004; Kortekaas and Dawson, 2007; Morton et al., 2007). Tsunami deposits are typically produced through suspended load transport and often display one or more of the following characteristics: laterally extensive and thickly-bedded sand sheets (often structureless) showing landward thinning, normal or inverse grading, and presence of marine microfossils and macrofauna (Dawson and Smith, 2000; Goff et al., 2001; Tuttle et al., 2004; Morton et al., 2007). In contrast, storm deposits typically are produced through bedload transport and

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