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Geo-archaeological evidence for a Holocene extreme flooding event within the Arabian Sea (Ras al Hadd, Oman)

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A B S T R A C T

The Arabian Sea is regarded as one of the least studied regions in terms of coastal hazards such as tropical cyclones and tsunamis. Parts of the coastline are developing rapidly, especially in Oman. This calls for a proper understanding of the natural processes that act on and affect it. This can be done by investigating the magnitude and impact of past events, in particular on human settlements. By doing this, future risks may not only be scientifically predicted and evaluated, but the damage caused by future events might even be mitigated. Evidence of past extreme wave events is preserved in the onshore stratigraphic record. In addition to this, the coastal zone of Oman is rich in archaeological remains. Presented here are the results of comprehensive mapping and analysis of extreme wave deposits of an archaeological site near Ras al-Hadd, suggesting that the Early Bronze Age site HD-6 was inundated at 4450 cal. BP. An event layer is identified between two settlement phases within the archaeological excavation. A contemporaneous sand bed with a maximum thickness of 0.4 m was mapped in the vicinity of the settlement. Ground penetrating radar surveys allow measurement of the thickness as well as identification of the internal facies architecture of the deposit. A high resolution digital elevation model reveals the coastal geomorphology. It is concluded that the causative event must have been a tsunami that was most likely generated within the Makran Subduction Zone. This interpretation does however, remain tentative at the moment. Archaeological evidence indicates that the site was immediately re-occupied after the event, which attests to a certain resiliences of the Early Bronze Age coastal communities in the region.

1. Introduction

The world population is increasing, with a trend of urbanisation and concentration of settlements along coastlines (McGranahan et al., 2007). The coastal zone is a dynamic and rapidly changing environment where extreme marine flooding events have a huge economic and social impact. Coastal vulnerability assessment relies on knowledge of the maximum water level (worst case scenario) during marine flooding events, as well as their recurrence intervals (Eisner, 2005). Early warning as well as disaster mitigation is based on this input information. However, instrumentally recorded data regarding flood events is often not available for remote areas and where it is, has not been recorded for an extended period into the past. Statistical approaches to calculate recurrence intervals of tsunamis and storm surges are therefore hampered and may only be facilitated by the analyses of the coastal geomorphology and sediments left behind by past events (Jaffe and Gelfenbaum, 2002; Cunningham et al., 2011; Weiss and Bourgeois, 2012; Cheng and Weiss, 2013).

Geo-archaeological investigations offer the potential to (a) identify and evaluate past extreme events along the world's coastlines and (b) to analyse human adaptation strategies to such calamities. This context is well studied for palaeo-tsunami in the eastern Mediterranean Sea (e.g. Pirazzoli et al., 1999; Reinhardt et al., 2006; Pareschi et al., 2007; Bruins et al., 2008, 2009; Vött et al., 2008, 2011; Goodman-Tchernov et al., 2009; Dey and Goodman-Tchernov, 2010; Stiros, 2010; Papadopoulos et al., 2014). Several case studies reveal the relationship of coastal hazards (tsunami) and human adaptation strategies along the pacific coastline of Cascadia (e.g. Hutchinson and McMillan, 1997; Losey, 2005, 2007; Bornhold et al., 2007; Witter et al., 2009; Peterson et al., 2011). Goff and McFadgen (2003), McFadgen and Goff

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(2007), Hutchinson and Attenbrow (2009) and Goff et al. (2011, 2012) provide well documented geo-archaeological evidence for palaeo-tsunami along the shores of New Zealand. Local tsunami evidence within the archaeological record is reported by Dickinson et al. (1999) for Tonga, by Haslett and Bryant (2007) for Lisbon as well as Fitzpatrick (2012) for the Caribbean. Geo-archaeological proxies are applied to lake shores as well (Lake Geneva: Kremer et al., 2014). The early Holocene Storegga slide left archaeological traces in Norway (Bøe et al., 2007).

A multi-hazard national early warning system is currently being installed within Oman to mitigate the impact of future tsunamis and storm surges, including tropical cyclones. The instrumental as well as historic record is exceedingly short for the Northern Indian Ocean as well as for Arabia. With this paper we aim to delineate palaeo-floods by using geo-archaeological evidence, extending the record of extreme events within the Northern Indian Ocean. We apply a high resolution, trans-disciplinary approach. We expect the data to be useful to evaluate future risk by validating scenarios, which might help to mitigate damages caused by any future flooding event. The archaeological context of the findings allows us also to study the human response to natural hazards in the past.

2. Study area

2.1. General setting

The Sultanate of Oman is located on the north-eastern part of the Arabian Plate. The northern boundary forms a convergent continental margin with the Eurasian Plate and is marked by the Makran Subduction Zone (MSZ) in the east (Fig. 1) and the Zagros Fold and Thrust Belt in the west. The velocity of the northward movement of the Arabian Plate is given as 20 mm/a (DeMets et al., 2010). The Owen Fracture Zone (OFZ) marks the India–Arabia plate boundary and is developed as a dextral strike-slip fault system (Rodriguez et al., 2012). The climate setting is arid to semi-arid with a mean annual precipitation in the range of 50–100 mm. The Arabian Sea is characterised by a mixed semidiurnal tide cycle with a tidal range of 1.0–2.5 m. The study site is located close to the city of Ras al Hadd at the easternmost tip of the Arabian Peninsula (Fig. 1). Here, the coastline turns from NW–SE to NE–SW and is characterised by a very productive marine ecosystem (Currie, 1992; Murtugudde and Busalacchi, 1999). Marine resources are easy to exploit as a consequence of upwelling cold and nutrient rich thermocline waters that appear in late spring and peak during the summer (Izumo et al., 2008). This marine protein source has been intensively exploited by humans since at least the Early-Holocene (Lézine et al., 2010). The continuity of occupation results in numerous archaeological sites (Berger et al., 2005). The coastline is characterised by several intertidal lagoons, separated from the open sea by sandy Holocene beach ridges. Some of the lagoons show a landward transition into sabkhas. Here, seasonal streams terminate. Locally, the lagoonary loam facies interwedges with talus deposits from the surrounding hills which are made up of Palaeocene to Eocene dolomitised white chalk and wacke- and packstones of the Jafnayn Formation (Peters et al., 2001). Parts of the coastline are rocky with cliff heights of up to 50 m above mean sea level (msl). Here, block- and boulder deposits are observed which are interpreted as either storm- or tsunami related (Hoffmann et al., 2013a). Differential crustal movement has been observed along the coastline of Oman (Hoffmann et al., 2013b). However, based on geomorphological analyses, the coastal setting under study is regarded as tectonically stable.

2.2. Coastal hazards and vulnerability

The coastlines of the Arabian Sea are among the least studied regions in terms of hazard assessment as field data are poor in the area. The Sultanate of Oman is located in the eastern part of the Arabian Peninsula bordering the Northern Indian Ocean (Arabian Sea) and the Gulf of Oman, which connects to the Persian Gulf via the Strait of Hormuz (Fig. 1). Modelling approaches of tsunami propagation within the Arabian Sea (e.g. Dominey-Howes et al., 2007; Heidarzadeh et al., 2007, 2008a,b; 2009; Okal and Synolakis, 2008; Jaiswal et al., 2009; Heidarzadeh and Kijko, 2011; Neetu et al., 2011) need to be validated by field data. Of equal importance here is information on possible tsunami run-up heights as well as recurrence intervals. The statistics improve the more palaeo-events are known. Considering both, field data and modelling results will improve the evaluation of future risk and allows the refinement of risk and hazard assessments. The data will

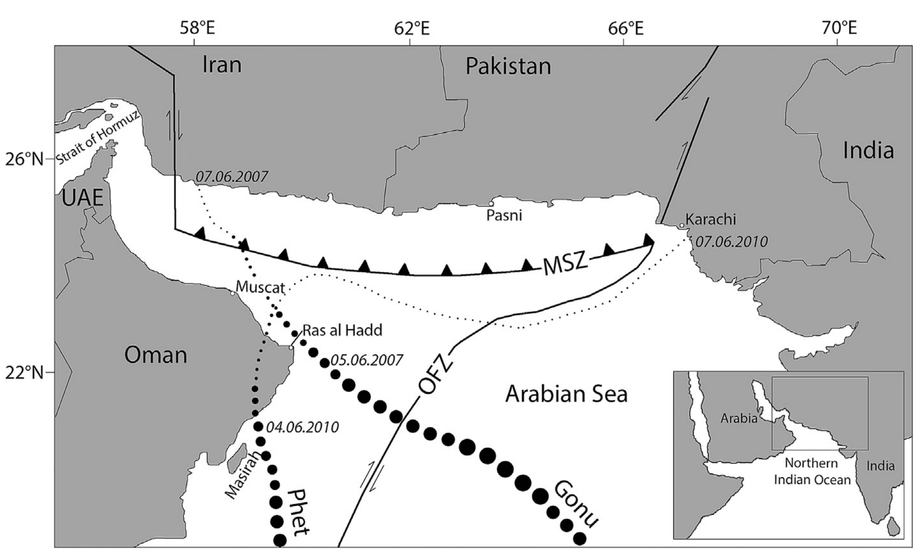

Fig. 1. Overview of the Northern Indian Ocean. The map illustrates the plate tectonic setting as well as the tracks of the tropical cyclones Gonu and Phet. The dot thickness corresponds to the Saffir–Simpson hurricane wind scale. Only cyclone Gonu reached category 5 in modern times. The study site is located near Ras al Hadd on the easternmost tip of the Arabian Peninsula. (MSZ: Makran Subduction Zone, OFZ: Owen Fracture Zone, UAE: United Arab Emirates).

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