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Ground penetrating radar facies of inferred tsunami deposits on the shores of the Arabian Sea (Northern Indian Ocean)

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ABSTRACT

The occurrence of tsunami waves that affected the shores of the Arabian Sea including the Gulf of Oman coastline has been proven by historical reports and sedimentological investigations. The damaging effect of such extensive events should not be underestimated in this region. In our study we present an investigation of coarse- to fine-grained, marine tsunami deposits in the vicinity of Fins, Sultanate of Oman, using ground penetrating radar (GPR). The sedimentary setting along the beach section preserves evidence (boulder & block deposits as well as trenching results) for possible high-energy wave impacts. The investigated area's environment is representative of conditions which lead to the best possible GPR data quality: arid conditions, no interference due to electrical power lines, and an elevated study area (~5–10 m a.m.s.l.) which eliminates the low-frequency noise of the ground and the possibility of salt water in the GPR data. 3D visualisation of GPR results from four study areas show e.g. wedging out of sediments and fining inland features, as well as several erosion features at the base of the deposit. These findings corroborate the hypothesis of inferred tsunami deposits. Furthermore, the presented GPR investigation technique provides new insights regarding the spatial distribution and internal architecture of (palaeo-) tsunami deposits in comparable tsunami prone regions worldwide.

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1. Introduction

Recent tsunamis in various oceans throughout the world revealed the vulnerability of coastal areas to these extreme wave events. Research efforts on devastating palaeo-events concentrate on the description and reconstruction of recent and past coastal inundations. Historical (Soloviev, 1990; Baptista and Miranda, 2009; Goff and Dominey-Howes, 2009; Ambraseys and Synolakis, 2010; Goto et al., 2010), archaeological (e.g. Bruins et al., 2008; Vött et al., 2011) and geological (Goff et al., 2001; Dawson and Stewart, 2007; Reicherter et al., 2010a, 2010b; Goto et al., 2010, 2012; Hoffmann et al., 2013a) data are used to assess the susceptibility of a specific coastal area. This allows the historical record to be extended far into the past and eventually forms the statistical background needed to calculate recurrence intervals, model run-up heights (Baptista et al., 1998; Heidarzadeh et al., 2008b, 2009; Reicherter et al., 2010a; Kaiser et al., 2011; Muhari et al., 2011; Cheng and Weiss, 2013; Rodriguez et al., 2013) and finally to improve the assessment of risk throughout these regions (Jaffe and Gelfenbaum, 2002); the recurrence interval of tsunami events is a hugely significant factor needed to mitigate against the loss of life and property in tsunami prone areas (e.g. Nott, 2003; Eisner, 2005).

The major obstacle in palaeotsunami research remains how to differentiate between storm and tsunami deposits (Tuttle et al., 2004; Goff et al., 2006; Morton et al., 2007; Atwater et al., 2012; Phantuwongraj and Choowong, 2012; Ramírez-Herrera et al., 2012; Shanmugam, 2012). Various proxies are used to reveal the geological record. The most common diagnostic criteria focus on the sedimentology (Dawson and Smith, 2000; Scheffers and Kelletat, 2003; Peters et al., 2007; Srinivasalu et al., 2007; Donato et al., 2009; Vött et al., 2009a, 2009b, 2011; Reicherter et al., 2010a, 2010b; Bahlburg and Spiske, 2012; Goto et al., 2012; Switzer et al., 2012; Szczuciński et al., 2012), stratigraphy (e.g. Bruins et al., 2008; Reicherter et al., 2010b), boulder deposits (Whelan and Kelletat, 2005; Goff et al., 2010; Goto et al., 2010; Nandasena et al., 2011; Engel and May, 2012; Hoffmann et al., 2013a), (micro-)palaeontology (Mamo et al., 2009; Vött et al., 2009a; Pilarczyk et al., 2011, 2012; Pilarczyk and Reinhardt, 2012), anisotropy of magnetic susceptibility (e.g. Wassmer et al., 2010; Chagué-Goff et al., 2011), geochemistry (e.g. Chagué-Goff, 2010), electrical resistivity tomography (e.g. Vött et al., 2008, 2009a, 2009b, 2011; Hadler et al., 2013) or x-ray computer tomography (e.g. Vött et al., 2009b). To our

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knowledge the capacity of ground penetrating radar (GPR) to reveal the internal facies architecture of tsunamigenic sediments has rarely been utilised in palaeotsunami research with only a small number of authors having published on this subject:

Switzer et al. (2006) studied a large wash-over fan at the southeastern Australian coast. Their GPR data show an erosional contact between the washover and the pre-event dunes. It remains unclear if these deposits are tsunamigenic or storm related.

Vött et al. (2009b) describe their findings from Lake Voulkaria (Greece) where three generations of tsunami deposits are preserved. A basic investigation of electrical resistivity tomography (ERT) and GPR was done to detect geomorphological features and the stratigraphy of the subsurface. The presented GPR profile in this study proves the trend of the upper boundary and partly the lower boundary of the investigated deposits.

Koster et al. (2013) describe the general use of GPR on tsunami deposits in combination with sedimentological analyses. The study was carried out in two different study areas in Europe (southern Spain and Greece). It deals with opportunities and challenges of this geophysical method with regard to tsunami detection. The authors highlighted that GPR measurements help improve spatial distribution models and identify the stratigraphical architecture (e.g. erosion features) of tsunamites.

With this paper we aim to demonstrate the possibilities and limitations of this non-invasive and time efficient geophysical tool. The facies architecture and spatial distribution of the deposits of inferred tsunamigenic origin are investigated. We focus on four field sites along the Sultanate of Oman's coastline. These sites all face the Arabian Sea which is part of the northern Indian Ocean.

2. Study area

The survey-sites are located along the coastline of Oman within the southeastern part of the Arabian Peninsula, located on the western shores of the Northern Indian Ocean (Arabian Sea, Gulf of Oman; Fig. 1A). The tectonic setting is dominated by the Makran Subduction Zone (MSZ) located in the north of the Arabian Sea. This represents the plate boundary between the Arabian and Eurasian plates. The Owen Fracture Zone (OFZ) – a right-lateral transform fault – defines the boundary between the Arabian and Indian plate and is located off the Oman coast in the northwestern Indian Ocean.

Hoffmann et al. (2013c) reported differential land-movement along the coastline of Oman, where coastal areas have undergone either subsidence or uplift. The coastline under investigation here is considered to be located in an area of uplift, which is clearly evidenced by raised marine terraces; uplift rates are around 1 mm/a (Hoffmann et al., 2013c). The study sites are situated in the vicinity of the small village Fins, located halfway between Quriat and Sur. The coastline is characterised by small sandy pocket beaches and cliffs not exceeding 10 m in height. In some places the coast is characterised by wadis, which lead straight to the ocean (see Fig. 1C). The dominating lithologies are folded and faulted marly Palaeogene limestone, raised Quaternary coral reefs and beachrock.

The climate is arid with average annual precipitation around 60 mm. Tropical cyclones occur but are infrequent. Wave heights exceeding 6 m were reported for a cyclone in 1890 (Membery, 2002). Cyclone Gonu, which tracked along the north-eastern coastline of Oman in 2007, is the most intense cyclone on record in the Arabian Sea with wave heights in excess of 9 m (Dibajnia et al., 2010). The shore parallel track of this cyclone resulted in severe erosion; however, wash-over fans or boulder displacements were not observed in the study region (Hoffmann et al., 2013a). The most recent cyclone occurred in 2010 called cyclone Phet. This cyclone affected the northwestern coast of Oman, but the geomorphological characteristics of the study region were not affected. This included no block or boulder displacements (Hoffmann et al., 2013a).

2.1. Tsunami history in the Northern Indian Ocean

Part of the Northern Indian Ocean is located at the boundary between the Indian, Eurasian and Arabian Plates. Large submarine slides are recorded along the Owen Fracture Zone (OFZ) and a local tsunami risk is inferred (Rodriguez et al., 2013). The 2004 Indian Ocean Tsunami, generated in the Sunda trench, was recorded along the southern shores of Oman where Okal et al. (2006) report a run-up height of 3.25 m at Salalah (40 Q 190,000 E 188,3000 N) and negligible effects towards Masirah Island (40 Q 676,000 E 2,248,000 N) in the north. The maximum observed inundation is 447 m at Al Labki (40 Q 4,541,000 E 2,016,660 N; Okal et al., 2006).

The largest tsunami hazard source within the Northern Indian Ocean is the Makran Subduction Zone (MSZ), which has an along-strike extension of approximately 900 km and is divided into a western and eastern part (Kukowski et al., 2000; Smith et al., 2012). The Arabian Plate is being subducted at an angle of 5° below the Eurasian Plate (White and Ross, 1979) at a rate of around 40 mm/a (DeMets et al., 1990). The sediment thickness of the incoming plate is large (Kopp et al., 2000) resulting in one of the largest accretionary wedges observed at convergent margins (Smith et al., 2013).

The seismicity of the MSZ is comparatively low and the historic record is fragmented and incomplete (Byrne et al., 1992). The recurrence interval of large tsunamigenic earthquakes ($M_w > 8$) is, therefore, unknown. Heidarzadeh et al. (2008b) listed thirteen earthquake events since 326 BC along the MSZ, four to five of which potentially triggered tsunami waves. There are also historical records of earthquakes and tsunamis from 326 BC to AD 2005 listed by Rastogi and Jaiswal (2006). Modelling results by Heidarzadeh et al. (2009) suggest that local run-ups of more than 15 m can occur along the coastline of Oman. This is further constrained by analyses of the seismogenic potential of the MSZ; Smith et al. (2013) conclude that potential earthquake magnitudes (M_w 8.69 up to M_w 9.22) are larger than any recorded historical event (e.g. 1945 earthquake: M_w 8.2).

The only instrumentally recorded tsunami triggered by an earthquake within the MSZ occurred on 28th November 1945 (Pendse, 1946, 1948). The impact of this event along the coastlines of the Arabian Sea is described and reconstructed in detail by Hoffmann et al. (2013b), and Rajendran et al. (2008) numerically modelled the wave propagation affecting the coastlines of the Arabian Sea and Indian Ocean. The coastlines of northern Oman were affected by waves with maximum heights of 3 m. A near-surface shell bed (within 50 cm below ground surface) in Sur lagoon has been interpreted as being tsunamigenic and the 1945 event has tentatively been assigned as the time of deposition (Donato et al., 2008, 2009; Pilarczyk et al., 2011; Pilarczyk and Reinhardt, 2012). It remains unclear whether blocks and boulders were transported by this event (see discussion in Hoffmann et al., 2013a).

3. Methods

3.1. GPR

GPR is a non-invasive, fast, low-cost, and precise investigation technique that uses reflected electromagnetic waves (Bristow and Jol, 2003; Neal, 2004). During the last years it has shown its potential for detecting stratigraphic architecture, layer boundaries, and sand-body geometry (e.g. in coastal, fluvial, lacustrine/limnic or aeolian environments), and also to locate and correlate sedimentary structures (e.g. bedding, faults, joints & folds in sediments; cf. Bristow and Jol, 2003; Neal, 2004). A dense grid of GPR data allows calculating pseudo 3D-subsurface data (e.g. Pedersen and Clemmensen, 2005; Bersezio et al., 2007), and

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