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Chronostratigraphy and geomorphology of washover fans in the Exmouth Gulf (NW Australia) – A record of tropical cyclone activity during the late Holocene

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ABSTRACT

Washover fans typically form due to barrier overwash or breaching and coastal inundation and generally represent geomorphological and depositional evidence of intense storms. Few studies have investigated the chronostratigraphy of washover fans in order to infer magnitude/frequency patterns of extreme-wave events over longer time scales. Here we present new data on the chronostratigraphy of late Holocene washover fans in the Exmouth Gulf (Western Australia) by using ground penetrating radar and unmanned aerial vehicle (UAV) survey techniques, as well as geomorphological, sedimentological and chronological investigations. This study aims to (i) provide a detailed characterization of the washover fans' geomorphology and stratigraphical architecture; (ii) document depositional processes involved in their formation; (iii) establish a chronostratigraphy based on optically stimulated luminescence (OSL); and (iv) understand the significance of the washover fans for recording past tropical cyclone (TC) activity. The fans consist of multiple sequences of sand, shell debris and coral rubble comprising depositional units related to TC-induced inundation. The units are separated by palaeosurfaces with incipient soil formation, formed during periods of reduced depositional activity. In combination with the interpretation of a UAV-based high-resolution digital surface model, multiple phases of reactivation are inferred. OSL results allow the establishment of a local long-term TC record and suggest storm-induced deposition at ~170, ~360, ~850 and ~1300 years ago. Further units were dated to ~1950, ~2300, and ~2850 years ago. The chronology of TC events is consistent with other work relating TC activity with El Niño Southern Oscillation (ENSO) and sea surface temperature (SST) patterns, corroborating the regional palaeotempestological relevance of this unique geomorphological record.

1. Introduction

Washover fans represent unequivocal geomorphological evidence of barrier overwash or scouring and coastal inundation, caused by temporary super-elevations of the sea level relative to the barrier (Donnelly et al., 2006; Matias et al., 2008, 2010). Although storm-unrelated barrier overwash may occur during spring tide conditions along low-lying barriers (e.g., Morton et al., 2000; Matias et al., 2010), the formation of washover fans is usually driven by extreme sea conditions, which particularly occur during storms accompanied by high wind speeds, storm waves and storm surges. While most washover fans are thus induced by extratropical winter storms or tropical cyclones (TCs) (Donnelly et al., 2006), tsunami-induced washover fans are also described for Chile (Atwater et al., 2013) and Greece (May et al., 2012).

Storm-induced washover fans typically exhibit particular stratigraphical and geomorphological patterns, depending on the local geomorphological conditions and the environment (e.g., subaqueous, subaerial) they are deposited in (Schwartz, 1982; Sedgwick and Davis, 2003). Horizontal to sub-horizontal stratification generally dominates sandy fans or fan sections with subaerial deposition, while foreset stratification with steeply inclined sediment layers at

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the avalanching face is characteristic for subaqueous deposition, e.g. in a coastal lagoon. Further sedimentary characteristics include heavy mineral-rich planar lamination and sequences of mm- to cm-thick layers with both inverse and normal grading, as well as prograding delta-type depositional patterns and washover channels (Donnelly et al., 2006; Shaw et al., 2015). While barrier overwash and related disturbances of coastal barriers seem to be catastrophic on annual or decadal time scales, they belong to the inherent natural processes of barrier evolution (Matias et al., 2008).

However, most studies on washover fans focus on the documentation of stratigraphical patterns, shoreline changes, and the erosional and depositional legacy of modern events such as recent hurricanes and typhoons (Schwartz, 1982; Sedgwick and Davis, 2003; Wang and Horwitz, 2007; Phantuwongraj et al., 2013). Shaw et al. (2015) recently inferred hydrodynamic conditions during washover formation by Hurricane Ike in 2008. While some studies have shown that single washover sites may record multiple events (Switzer and Jones, 2008; Williams, 2011), and washover deposits have repeatedly been used to infer past storm recurrence (e.g., Liu and Fearn, 2000; Donnelly et al., 2004; Donnelly and Woodruff, 2007; Dezileau et al., 2011, 2016; May et al., 2013; Williams, 2013), to the best of our knowledge no previous study has investigated the chronostratigraphy of washover fans in high resolution in order to infer magnitude/frequency patterns of extreme-wave events over longer time scales.

This study presents a multidisciplinary approach to understand and unravel the stratigraphic architecture and chronostratigraphy of large washover fans located at the south-western coast of the Exmouth Gulf, Western Australia (WA). Even though the area is highly vulnerable to both tropical cyclones and tsunamis, the geological imprint of extreme-wave events in north-western WA is clearly understudied. To date only deposits of a mid-Holocene extreme wave event have been reported from the north-western part of the NW Cape, and mid- to late Holocene events have been inferred from marine organisms found up to 1 km inland and/or attached to wave-emplaced coarse clast deposits (Nott and Bryant, 2003; Scheffers et al., 2008; May et al., 2016). Since multidisciplinary approaches are imperative for a thorough understanding of complex sediment archives, the surface and subsurface anatomy of the washover fans was investigated using unmanned aerial vehicle (UAV) survey and digital photogrammetry (Structure-from-Motion, SfM) techniques, ground penetrating radar (GPR), as well as geomorphological and sedimentological data, complemented by optically stimulated luminescence (OSL) and radiocarbon dating. We aim at (i) providing a detailed characterization of the washover fans' geomorphology and stratigraphical architecture; (ii) documenting the depositional processes involved in the formation of the fans; (iii) establishing a consistent chronostratigraphy based on OSL spanning the last ~3000 years; and (iv) understanding the significance of the washover fans for recording past TC activity. Thereby, we ultimately aim at reconstructing late Holocene TC activity, data that is much needed for coastal hazard assessments as well as a better understanding of atmosphere-ocean interactions and their relation to TC occurrence on Holocene time scales (e.g., Denniston et al., 2015).

2. Regional setting

2.1. Geologic and geomorphologic setting

The Exmouth Gulf is part of the Paleozoic-Cenozoic Carnarvon Basin (Hocking et al., 1987). While extensive longitudinal dunes and dune networks dominate the Ashburton plain along the Gulf's eastern margin, it is bordered by the NNE-SSW striking Cape Range anticline of the NW Cape (also Cape Range Peninsula) to the west (Fig. 1a). The Cape Range anticline is formed by folded mid- to late Tertiary limestones (Collins et al., 2003) surrounded by four Pliocene-Pleistocene terraces and raised reefs (Wyrwoll et al., 1993; Orpin et al., 1999; Twiggs and Collins, 2010). Minor parallel-striking anticline structures (Rough Range, Giralia Range; Fig. 1a) stretch into and characterise the southern coast of the Gulf. Towards the coast, the mostly calcarenitic rocks are covered by alluvial and colluvial deposits of varying composition which are in turn overlain by late Pleistocene and Holocene dune and beach deposits at many places (Wyrwoll et al., 1993; Collins et al., 2003; Scheffers et al., 2008). Between approximately 7000 and 6000 years BP, post-glacial relative sea level is thought to have reached a highstand of 1–2 m above present (Lewis et al., 2013). Since 6000 years BP, a phase of marine regression (Lambeck and Nakada, 1990; Lewis et al., 2013) followed, which is responsible for discontinuities in or the absence of coastal sedimentary records of mid- to late Holocene age.

As part of Western Australia's mesotidal north-western coast (Fig. 1a), the mean tidal range in the Gulf increases southwards from 2.1 m at Learmonth to 2.6 m along the southernmost coast (Short, 2005). Characterised by water depths of <20 m (e.g., Orpin et al., 1999), the inner part of the Exmouth Gulf experiences mean significant wave heights of <1 m (Fig. 1a) during the austral winter. This is in contrast to 2–3 m along the exposed Ningaloo Reef at the western coast of the NW Cape. However, at the entrance to the Gulf, wave heights may exceed 5 m during TC conditions (Eliot et al., 2012). Along the western coast of the Exmouth Gulf, in the northern part of a SSW–NNE-oriented headland between the Bay of Rest and Point Lefroy, lobate washover fans (F1 and F2; Fig. 1a–c) stretch southwards into a low-lying supratidal mud plain. Similar E–W oriented washover structures are found along the opposite, western margin of the Bay of Rest, just ~5 km to the south-east of Learmonth Airport (F3; Fig. 1a,d).

2.2. Climatic setting and past tropical cyclones

The northern Carnarvon coast and thus the Exmouth Gulf have a tropical, arid climate with hot and humid summers and warm, dry winters (Semeniuk, 1996). Moderate southerly winds prevail during summer, changing to predominantly northerly winds during winter (BoM, 2016a). Large parts of the fluvial discharge and associated sediment supply to the Gulf and the coastal lowlands occur during surface discharge events triggered by heavy and sustained convective rains, which particularly occur in connection with TC events (Orpin et al., 1999; Twiggs and Collins, 2010; Dare et al., 2012).

Since TC formation is generally favoured by high sea surface temperatures (SST) (Emanuel, 2005), the north-western part of Australia is one of the most TC affected coastlines of the world (Fig. 1; Lough, 1998; Short and Woodroffe, 2009), exhibiting a slightly increased TC frequency during La Niña conditions (Nicholls, 1984; Kuleshov et al., 2008; Chand et al., 2013; Denniston et al., 2015). While present inter-annual TC activity seems to be largely controlled by the El Niño Southern Oscillation (ENSO) at a global scale (Camargo et al., 2007; Nott and Forsyth, 2012), the relationship of ENSO and TCs remains ambiguous over prehistoric time scales, at least for the tropical Pacific, Indian and Australian regions (Denniston et al., 2015). However, TCs potentially influence regional hydroclimates (Dare et al., 2012; McGrath et al., 2012) and entail temporarily high fluvial, aeolian and, in combination with related storm surges, littoral morphodynamic activity, causing major coastal changes such as beach and foredune erosion, washover deposition and/or sediment redistribution (Semeniuk, 1996; Nott and Hubbert, 2005).

Ten TCs with notable damages in the Exmouth region are listed