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Reactivation of the Pleistocene trans-Arabian Wadi ad Dawasir fluvial system (Saudi Arabia) during the Holocene humid phase

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ABSTRACT

The Wadi ad Dawasir fluvial system in central Saudi Arabia is investigated using remote sensing and sedimentology, in combination with bio-proxy analyses (molluscs and ostracods). Age control is provided by radiocarbon as well as luminescence dating, using both quartz and feldspar grains. It is shown that the fluvial system was active from the Asir Mountains across the partially sand-covered interior of the Arabian Peninsula to the Arabian Gulf during the Holocene humid period. Sedimentology and faunal analysis reveal the presence of perennial streams and a permanent freshwater lake in the distal reach of the Dawasir system that are synchronous with fluvial accumulation in the headwaters of its major tributary, Wadi Tathlith. The increased runoff during the Holocene led to a re-activation of streams that largely followed pre-existing Late Pleistocene courses and eroded into older sediments. The absence of Holocene lakes in most of the Rub' al-Khali implies that trans-Arabian rivers were mainly fed by precipitation in the Asir Mountains. Monsoonal rainfall was apparently stronger there as well as in the northern, south-eastern and southern part of the Arabian Peninsula (southern Yemen and Oman), but it apparently did not directly affect the interior during the Holocene. The palaeoenvironmental reconstruction shows a narrow trans-Arabian green freshwater corridor as the result of phases of sustained flow lasting up to several centuries. The permanent availability of water and subsistence for wildlife provided a favourable environment for human occupation as documented by Neolithic stone tools that are found all along Wadi ad Dawasir.

1. Introduction

Four major sand seas (Ar Rub' al-Khali, Ad Dahna, Al Jafura, and An Nafud) cover an area of 765,000 km^2 on the Arabian Peninsula (Wilson, 1973), by this comprising 36% of the territory of the Kingdom of Saudi Arabia. They are the most prominent evidence of the present arid to hyper-arid climate, with rainfall of $<$100 mm a^{-1} in the interior of the peninsula. Higher rainfall levels are restricted to the Hijaz-Asir Plateau and the Yemeni highlands (Almazroui et al., 2012). This pattern is tied to the Hadley cell circulation and its local manifestation, the monsoon system, which are key components responsible for the climate of Arabia (Webster, 2005). At present, the source of rainfall reaching SW Arabia and the coast of Dhofar is the African summer monsoon rather than the Indian Ocean Summer Monsoon as previously assumed (Fleitmann et al., 2007; Bosmans et al., 2014; Enzel et al., 2015; Jennings et al., 2015). The winter months are characterized by a stable high pressure system, clear skies and mild temperatures. During this time of the year Mediterranean cyclones track across the Arabian Peninsula and reach as far as Oman, giving rise to low levels of rainfall.

Little palaeoclimate research was carried out in Saudi Arabia until recently, although the joint mapping project of the Kingdom of Saudi Arabia and the U.S. Geological Survey revealed compelling geomorphologic evidence of much wetter episodes during the Quaternary (Brown et al., 1989). A fluvial-style drainage network with large gravel accumulations east of the Hijaz-Asir Mountains (Holm, 1960) and lake deposits within the dunes of the Rub' al-Khali and the Nafud were investigated subsequently in detail by McClure (1976, 1984) and Schulz and Whitney (1986), respectively. The observation of gravel plains and aquatic molluscs in the lower reaches of Wadi ad Dawasir had already led Philby (1933) to conclude that this river system and possibly others had reached the Arabian Gulf. Brown (1960) argued that gravel terraces 20 to 60 m above the present thalweg of Wadi Sahba and Wadi Batin represent remnants of approximately 1 km wide Pleistocene river

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courses. Despite their low gradient of about 1 m km^{-1}, these rivers transported coarse clasts indicating a high stream power. For example, Holm (1961, cited in Edgell, 2006) reported quartzite boulders measuring up to 25 cm in size in a palaeochannel of Wadi Sahba ca. 95 km from the coast, i.e. about 600 km downstream of the source terrain in the Arabian Shield. Furthermore, these palaeorivers built-up conglomerate megafans before entering the Arabian Gulf (Hötzl et al., 1978a; Edgell, 2006). Based on K-Ar ages of two basalt flows encasing a gravel layer in the Wadi ad Dawasir, Anton (1984) argued that the major trans-Arabian wadis depicted in his palaeohydrological map were incised between 3 and 1 million years ago.

However, systematic knowledge about these obvious palaeoenvironmental changes resulted from studies carried out mainly in the adjacent countries (Oman, United Arab Emirates, Yemen) on stalagmites (Burns et al., 2001; Fleitmann et al., 2003a, 2003b, 2004, 2005, 2007, 2011; Neff et al., 2001), lake sediments (Parker et al., 2004, 2006; Lézine et al., 1998; Radies et al., 2005; Petit-Maire et al., 2010; Rosenberg et al., 2011a; Catlett, 2014), aeolian dunes (e.g. Juyal et al., 1998; Goudie et al., 2000; Preusser et al., 2002; Radies et al., 2004) and fluvial deposits (Blechschmidt et al., 2009; Berger et al., 2012; Hoffmann et al., 2015; Parton et al., 2015). Advances in geochronology, especially Optically Stimulated Luminescence (OSL) and Uranium-Thorium ($^{234}U/^{230}Th$) methods, now permit dating these archives beyond the dating limit of radiocarbon and, hence, reconstruction of the temporal and spatial framework of the environmental history. The climate record derived from the previously mentioned archives reveals significant hydrological changes with pronounced humid periods in southern Arabia during Marine Isotope Stages (MIS) 1, 5a, 5e, 7 and 9, and further though less well-documented humid phases during MIS 3 and 11. It is assumed that high summer insolation during these periods strengthened the monsoon and pulled the associated rainfall belt northward into the interior of Arabia. ^{18}O data from stalagmites suggest that the highest precipitation levels occurred during MIS 5e and the lowest during MIS 1 (Fleitmann et al., 2011).

In the past decade, the number of studies on the palaeoenvironment of Saudi Arabia has increased markedly due to a more open political situation allowing access to remote areas such as the Rub' al-Khali. Many of these studies have been carried out in the context of investigating the human dispersal Out-of-Africa models because knowledge of the palaeohydrology and the timing of humid phases is essential for understanding the migration of anatomically modern humans (AMH) into Arabia and beyond (e.g. Petraglia et al., 2011). This range expansion was only possible when the Arabian deserts, which represented a barrier for AMH, turned into a 'Green Arabia' with sufficient surface water and nutrition available during pluvial phases. Research has focused mainly on palaeolakes in the Rub' al-Khali (Rosenberg et al., 2011b; Crassard et al., 2013; Matter et al., 2015; Groucutt et al., 2015), the Nafud (Petraglia et al., 2012; Rosenberg et al., 2013; Hilbert et al., 2014; Scerri et al., 2015; Stimpson et al., 2015) and Tayma (Ginau et al., 2012; Engel et al., 2012), whereas only two modern studies have dated stalagmites and fluvial deposits, respectively. The stalagmites of central and northern Saudi Arabia turned out to be 400 ka old or older, indicating that rainfall was too low or sporadic to allow growth of stalagmites in the past 400 ka (Fleitmann et al., 2004). The first luminescence-dated fluvial sediments in the headwaters of Wadi as Sahba were interpreted to reflect humid events at ca. 54 ka, ca. 39 ka (corresponding to MIS 3), and ca. 0.8 ka (McLaren et al., 2009).

Breeze et al. (2015) demonstrated the potential of combined remote sensing and geographic information system (GIS) techniques to map palaeodrainage networks and palaeolakes across vast areas in much greater detail and with improved accuracy compared to earlier palaeodrainage maps of Anton (1984) and Edgell (1990, 2006). Furthermore, climate model simulations provide useful information when validated against field data to better understand the functioning of climate change. The results of a set of simulations carried out by Jennings et al. (2015) confirm that the Arabian Peninsula was wettest during MIS 5e and that lesser amounts of precipitation occurred during MIS 5c and MIS 3. Moreover, they support the results of earlier simulation experiments by Herold and Lohmann (2009) that the African monsoon rather than the Indian Summer Monsoon was the source of higher rainfall. This is in accord with the spatial and temporal distribution of lakebeds in southern Arabia. The fact that Pleistocene but no Holocene palaeolakes occur in the interior of the Rub' al-Khali suggests that the monsoonal rainfall belt migrated farther onto the Peninsula in the Pleistocene than during the Holocene (e.g. Rosenberg et al., 2011b; Matter et al., 2015). Enzel et al. (2015) challenge this interpretation based on a reanalysis of published Holocene lacustrine records. They argue that: a) the palaeolakes represent marsh environments requiring a much lesser annual rainfall to be sustained than open lakes, and b) the intensification of rainfall is not related to a northward shift of the Intertropical Convergence Zone (ITCZ) and the Indian Summer Monsoon but to a slight landward expansion of the African Monsoon across the Red Sea with uplift of the moist air over the Yemeni – Asir highlands associated with modest rains feeding the downstream wetlands. If this was the case, then the drainage systems must have experienced a major reactivation.

In this study, we investigate this hypothesis using a multi-proxy approach to reconstruct the evolution of the palaeodrainage of Wadi ad Dawasir, one of the major trans-Arabian wadis. As palaeodrainage systems respond sensitively to climate changes that affect precipitation, runoff and fluvial style, we first determine the catchment area and reconstruct the drainage pattern by remote sensing techniques. In order to get a more complete view of the area, the adjacent Wadi as Sahba system is included in the analysis. We then investigate selected sedimentary sections in the proximal and distal reaches of the Wadi ad Dawasir system and determine their facies, fossil content (molluscs and ostracods), and age (radiocarbon and luminescence dating). The ultimate goal is to establish a relationship between geomorphology, facies and runoff within a robust geochronological framework. With the above, we aim to better understand the environmental conditions in the central part of the Arabian Peninsula, for which very little information is available at the moment. The newly gathered information will be crucial for cross-checking atmospheric circulation models as well as for better characterization of past environments as important in the context of early human habitation and dispersal through the region.

2. Methods

2.1. Remote sensing and field methods

A GIS environment was implemented to analyse the Wadi ad Dawasir and Wadi as Sahba palaeodrainage systems and related catchment areas. ArcGIS 10 was applied for geospatial analyses of digital elevation models (DEMs) and to analyse multispectral data for further mapping. Digital elevation data from the Shuttle Radar Topography Mission (SRTM; Farr and Kobrick, 2000; Rabus et al., 2003; Farr et al., 2007) with a resolution of 3 arc-second (~90 m at the equator) are provided by the Global Land Cover Facility (GLCF) for download. SRTM 2.1 data were used as base data to create a DEM mosaic of the Arabian Peninsula with a cell size of 90 × 90 m (Fig. 1A). During processing, SRTM data voids were filled with elevation data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2) (Abrams et al., 2010, 2015; Tachikawa et al., 2011). To avoid possible discontinuous drainage networks in the following processing steps, all sinks within the resulting DEM were removed to get a DEM without depressions. Flow direction and flow accumulation were then derived using the eight-direction (D8) flow model by Jenson and Domingue (1988). A drainage network was delineated by applying a threshold value to the flow accumulation raster that defines a minimum required contributing upstream area of a cell as a stream. With regard to the large area of interest (Fig. 1B), a contributing catchment area of 150 km^2 was found appropriate to show