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Monsoon triggered formation of Quaternary alluvial megafans in the interior of Oman

Ingo Blechschmidt [1], Albert Matter, Frank Preusser *, Dirk Rieke-Zapp

Institut für Geologie, Universität Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland

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ABSTRACT

A vast bajada consisting of coalescing low-gradient (<0.3°) alluvial fans exceeding 100 km in length formed along the southwestern margin of the Oman Mountains. It comprises an old fan sequence of inferred Miocene to Pliocene age termed Barzaman Formation, diagenetically highly altered to dolomitic clays, and a thin veneer of weakly cemented Quaternary gravels. A combination of remote sensing, lithological analyses and luminescence dating is used to interpret the complex aggradation history of the Quaternary alluvial fans from the interior of Oman in the context of independent regional climate records. From satellite imagery and clast analysis four fans can be discerned in the study area. While two early periods of fan formation are tentatively correlated to the Miocene–Pliocene and the Early Pleistocene, luminescence dating allows the distinction of five phases of fan aggradation during the Middle–Late Pleistocene. These phases are correlated with pluvial periods from Marine Isotope Stage (MIS) 11 through 3, when southern Arabia was affected by monsoonal precipitation. It is concluded that the aggradation of the alluvial fans was triggered by the interplay of increased sediment production during arid periods and high rainfall with enhanced erosion of hillslopes and transport rates during strong monsoon phases. However, the lack of fine-grained sediments, bioturbation and organic material implies that although the Quaternary fans are sourced by monsoonal rains they formed in a semi-arid environment. Thus, it appears that, in contrast to the Oman Mountains, the interior was not directly affected by monsoonal precipitation.

1. Introduction

Numerous geological records such as deep-sea sediments and polar ice cores document important changes in climatic conditions during the Quaternary. However, knowledge on the impact of this variability in environmental conditions on geological processes on the continents is still limited. This is particularly true for desert areas where terrestrial records are scarce, indeed a better understanding of the relationships between palaeoclimate variability and the hydrological cycle, groundwater recharge and geomorphic processes is essential in order to evaluate the possible impact of global change on society in these areas.

Terrestrial palaeoclimate information on the Quaternary evolution of southern Arabia has so far mainly been constrained by speleothems, aeolian sediments and lake deposits. All of these proxies monitor the effect of past climate variability on Earth surface processes in the area. While aeolian sediments record periods of aridity and, in particular, sediment availability (e.g., Goudie et al., 2000; Preusser et al., 2002; Radies et al., 2004), palaeolake deposits indicate pluvial periods (e.g., McClure 1976; Lézine et al., 1998; Radies et al., 2005). Oxygen-isotope ratios of ancient groundwater and speleothem-calcite combined with δD values of fluid inclusion water provide information on the isotopic composition of rainfall and thus changes of monsoon precipitation (e.g., Burns et al., 1998, 2001; Fleitmann et al., 2003, 2004; Weyhenmeyer et al., 2000).

The present climate of southern Arabia is arid and only the southern part of the region is influenced by the Indian Ocean summer monsoon. This is due to the location of the Intertropical Convection Zone (ITCZ) over the southernmost part of the Arabian Peninsula (Fig. 1). However, lake deposits and speleothems reveal that much larger areas of Arabia were repeatedly affected by monsoon-type climate in the past. These humid phases, triggered by a northward shift of the ITCZ and thus of the monsoon-belt, occurred at about 6–10.5 ka, 78–82 ka, 120–135 ka, 180–200 ka, and 300–325 ka according to uranium-series dated speleothem growth (Burns et al., 2001), hence, mainly during past interglacial times.

It has been assumed that the formation of the vast (ca. 40 000 km^2) braidplain (bajada), consisting of coalescing alluvial fans flanking the southern and western piedmont of the Oman Mountains, developed during such wetter phases (Beydoun, 1980; Maizels, 1987; Maizels and McBean, 1990). This assumption has, however, not yet been supported by any independent dating results. The bajada of the Oman Interior shows great lateral thickness variations from a few tens to

* Corresponding author.
E-mail address: preusser@geo.unibe.ch (F. Preusser).
[1] Present address: Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (NAGRA), Hardstrasse 73, 5430 Wettingen, Switzerland.

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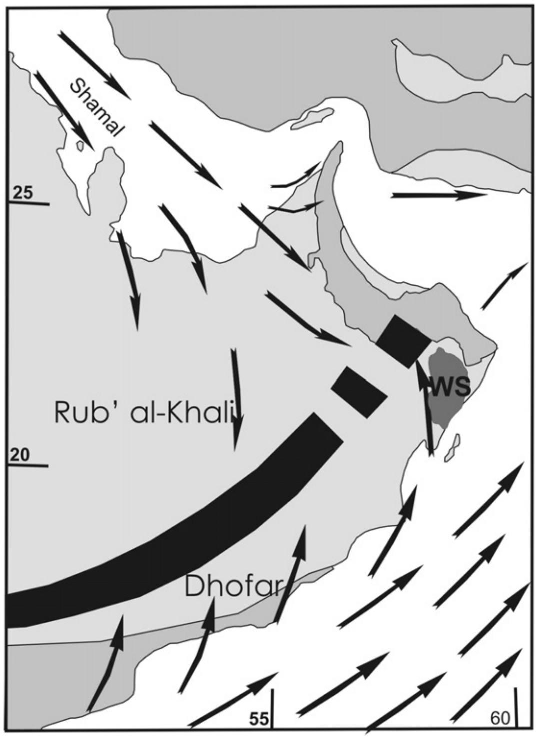

Fig. 1. Overview map of the Arabian Peninsula showing generalised modern, summer surface wind pattern, approximate present position of the Intertropical Convergence Zone (ITCZ). WS = Wahiba Sands.

more than one thousand metres. It consists, according to Béchennec et al. (1993), of two distinct units; the Miocene–Pliocene Barzaman Formation forming the bulk of the bajada and thin Quaternary gravels. Rodgers and Gunatilaka (2002) interpret the bajada as a deposit on the distal Oman Mountains forebulge. The length of the exposed relict alluvial fans exceeds 100 km and may be up to 250 km and their longitudinal gradient is less than 0.3°, i.e. much flatter than classical alluvial fans. Their distal parts are covered by the Rub al-Khali and Wahiba Sand seas (Rodgers and Gunatilaka, 2002; Radies et al., 2004). The megafans show a complex pattern of superimposed sinuous conglomeratic ridges representing exhumed palaeochannel thalwegs rising 5 to 20 m above the plain (Glennie, 2005). Decreasing sinuosity from older meandering to the younger braided channels is interpreted by Maizels and McBean (1990) to reflect reduction of continental pluviality through time associated with a change from possibly perennial to ephemeral stream flow. This change in palaeohydraulic conditions is further supported by the oxygen isotopic composition of early carbonate cements in the alluvial conglomerates. The earlier palaeochannel generations have more negative values than later generations suggesting, based on the inverse relation between $\delta^{18}O$ and rainfall amount, decreasing monsoon intensity (Burns and Matter, 1995). However, in the absence of geochronological data, except for a few initial luminescence ages (Juyal et al., 1998), the link between palaeohydrology, channel styles, geomorphological evolution of the alluvial fans and palaeoclimatic phases remains to be proven.

In this paper we firstly discriminate different fans and their channel generations from satellite images using superimposition and intersection as main criteria. Secondly, we analyse clast composition of individual fans and, thirdly, present a geochronology of palaeochannel generations and identify phases of fan formation based on the results of luminescence dating. Palaeodrainage systems respond most sensitively to changes in climate, which affect precipitation, runoff and fluvial styles and vegetation. The ultimate aim therefore, is to reconstruct the relationships between the geomorphological evolution of the Quaternary alluvial fans and the palaeoclimate of southern Arabia in a geochronological framework.

2. Materials and methods

2.1. Remote sensing and field analyses

The different alluvial fan systems and their spatial extent and the morphology of palaeodrainage networks have been investigated using satellite images. The main focus of these investigations was to identify the morphological characteristics, the spatial arrangement and relative age relationships of different channel systems. The contributing upland area draining towards the fans in modern times was calculated in a geographic information system (GIS). The GIS analysis was based on digital elevation data collected during the Shuttle RADAR Topography Mission (SRTM; Rabus et al., 2003). SRTM data are provided to the public by the United States Geological Survey for download (http://edcsns17.cr.usgs.gov/EarthExplorer/). Gaps in the data were filled with elevation data from other sources, i.e. topographic maps, or were filled by interpolation to create a consistent Digital Elevation Model (DEM) of Northern Oman with a cell size of 90×90 m^2. Flow direction and flow accumulation within the DEM were calculated in order to delineate the drainage basins. Channels were derived from the flow accumulation data and match with channels that can be identified on satellite imagery of the same area. A contributing drainage area threshold of 16.2 km^2 was found appropriate.

Sedimentary characteristics were determined on 20 measured outcrop sections. Clast analyses (size, roundness, major composition) were performed on a randomly chosen 1.0×1.0 m surface by counting all components, generally about 400, with the long axis >2 cm. Five lithological groups were distinguished: cherts, ophiolites (harzburgite, dunite, gabbro, peridodite, basalt), limestones, siliciclastics and whitish-pink, fine-grained, dolomitic and clay-rich rocks termed barzamanite by Maizels (1987).

2.2. Luminescence dating

2.2.1. Samples and laboratory procedures

Luminescence dating of sediments uses a light-sensitive signal in quartz and feldspar grains that is zeroed by daylight during sediment transport and accumulates during burial, when the grains are sealed from daylight (cf., Aitken, 1998; Duller, 2004; Preusser et al., 2008). For dating, the dose accumulated by the grains during burial (equivalent dose—D_e) and the amount of natural radioactivity within the sediment (dose rate—D) have to be determined. The alluvial sediments from interior Oman are a special challenge in this context. First, sand layers that are suitable for luminescence dating are only rarely found within the usually coarse-grained gravel. Secondly, the sand layers bear only small amounts of quartz grains needed for dating due to the abundance of limestones and ophiolites in the catchment area. This forced us to sample large amounts of sand (several kilograms) at the few suitable locations. Due to the moderate cementation of the sand, massive blocks were recovered from the outcrops during two field surveys.

All preparation work for D_e determination was carried out under subdued red-light conditions in the laboratory. The outer light-exposed part of the sand blocks was first carefully removed using a water-cooled rock saw. The removed material was used for dose rate determination. From the remaining material carbonates were dissolved using hydrochloric acid that caused a volumetric reduction of up to 90% in the sample material. The dried material was sieved and a Frantz magnetic separator was used to extract the non-magnetic minerals (i.e. quartz). Quartz was separated using heavy liquids and subsequently etched by 40% hydrofluoric acid to remove plagioclase and the outer part of the quartz grains that is affected by external alpha radiation. D_e measurements were made on small aliquots (some