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The formation of the Namib Sand Sea inferred from the spatial pattern of magnetic rock fragments

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ABSTRACT

The Namib Sand Sea on the west coast of Namibia is one of the world's oldest desert region and based on cosmogenic dating it has likely existed since the earlier Pleistocene. Among the possible sand sources, geomorphological and petrographic evidence points towards the Orange River catchment as the most prominent one. Little is known about the dynamics of transport and mixing of the sand during the desert formation and this is because the information about the Namib Sand Sea generally rests upon study sites at its edges. Here, we present a statistical analysis of magnetic components in sand samples collected along a south to north transect through the desert and at two inland sites. The magnetic components are rock fragments mainly of basaltic origin. Their statistically uniform distribution in the Namib Sand Sea indicates no significant sand source other than the Orange River and thus a predominant northward direction of the sand transport. A northward transport and the absence of a magnetic trend along the transect suggests mixing of the sand prior to its deposition in the Namib Sand Sea, most likely during river transport and under high current conditions along the shoreline. Finally, the uniform magnetic pattern provides compelling evidence for a stable erosion regime in the Orange River catchment with a steady release of magnetic components at least since the Pleistocene.

1. Introduction

The Namib desert, which stretches about 1000 km along the coast of south western Africa, is a classical example of a costal desert (Laity, 2009). The Orange River is the largest river in southern Africa. It arises in the Drakensberg mountains in the Lesotho highlands and transports sediments over a distance of 2300 km to the South Atlantic Ocean. Since the Cenozoic era the Orange River and its tributary, the Vaal River, have formed the drainage system with the largest sediment discharge in southern Africa (e.g., Bluck et al., 2007). The Orange River has been considered to be the main sand source of the Namib Sand Sea, which is the central dune region of the Namib desert near the Tropics of Capicorn (e.g., Rogers, 1977; Lancaster, 1989). The Namib Sand Sea, also termed the Namib erg, covers an area of about 34 000 km^2 between Lüderitz in the south and the Kuiseb River in the north, having the Great Escarpment as its eastern margin (Fig. 1). It contains a variety of dune morphologies; these are mainly linear dunes, with star dunes on the eastern margin and crescentic dunes along the coast (Livingstone et al., 2010). The unconsolidated eolian sand of the Namib erg is termed the Sossus Sand Formation and lies separated by an unconformity on the Tsondab sandstone (Miller, 2008). This terrestrial sandstone formation is of Miocene age and consists of eolian dunes associated with fluvial and playa sediments (Ward, 1988). The deposition of the Sossus Sand Formation may have begun during the latest Pliocene about 2 million years ago (Goudie and Eckhardt, 1999). Fossil remains in the Tsondab sandstones, however, indicate that the desertification started before ≈16 million years ago (Senut et al., 2009).

Chronological control of the Sossus Sand Formation is challenging, because the dynamics of the sand transport and mixing can critically affect the results of the different dating methods. Optical stimulated luminescence data yielded variable dune deposition ages of about 10^4 yr and several 10^4 of years, suggesting that dunes in the Namib Sand Sea could be formed after the last global climate change in the latest Pleistocene (Bristow et al., 2007) or the Last Glacial Maximum (Stone and Thomas, 2013). In a recent paper, Vermeesch et al. (2010) have reported cosmogenic nuclei data and zircon U–Pb age spectra that confirm the Orange River catchment as the exclusive source for the near-coastal Namib erg and indicate a residence time of the sand of more than a million years.

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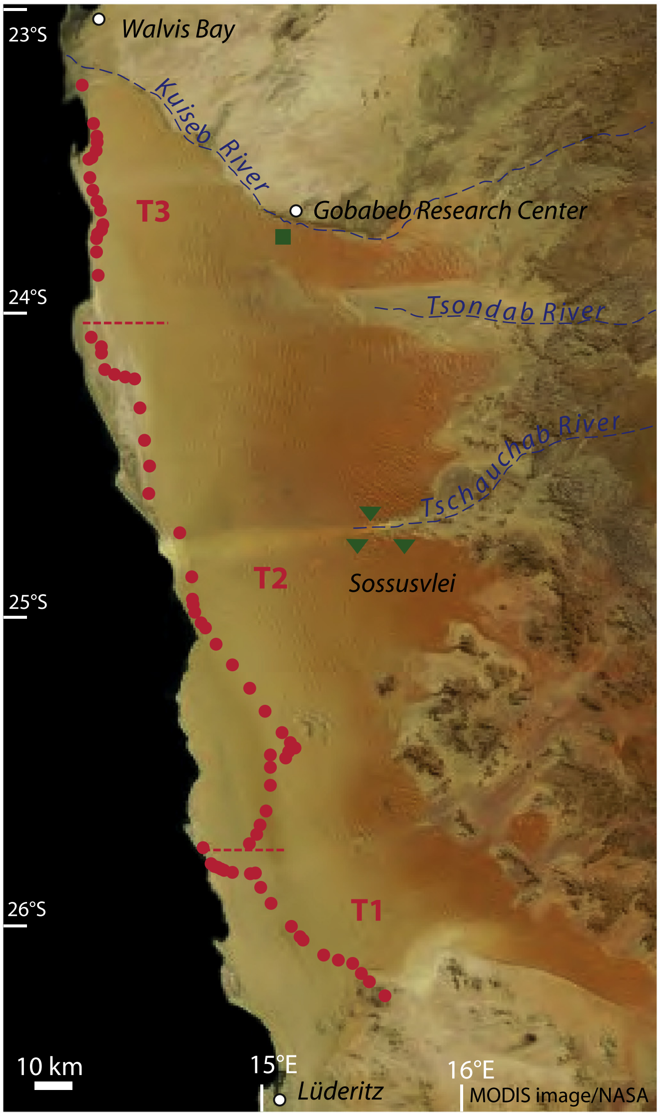

Fig. 1. Moderate Resolution Imaging Spectroradiometer (MODIS) image of the Namib erg. Red dots represent sampling sites along the transect between Lüderitz and Walvis Bay, subdivided into the three subgroups T1, T2, and T3. Green squares and triangles mark the inland sites near the Gababeb Research Center and at Sossusvlei.

These authors have suggested two possibilities to explain the discrepancy of the time constraint of the Namib erg. First, the dunes were active throughout this time and the sand grains have been recycled many times on their journey to the north. Alternatively, the sand was buried for an extensive period of time during which relatively humid conditions alternated with dry conditions that fostered increased dune mobility and sand mixing.

A striking characteristic of the Namib erg is its color gradient from whitish and yellow-brownish near the coast to much redder sand on the eastern edge (Fig. 1). A magnetic study showed that this variation originates from fine grained secondary iron oxides, such as goethite and/or hematite, associated with clay coatings of the sand grains (Walden et al., 2000). Detailed sand color analysis along a west-east profile in the northern part of the Namib erg, using a combination of remote sensing and laboratory measurements on sand samples, has provided evidence that the sand arises from the mixing of at least two distinct sources (White et al., 2007). Generally, three sand sources have been considered: (i) reworked Tsondab sandstone, (ii) river-transported material from the Great Escarpment, and (iii) wind-derived material from the Orange River delta (e.g., Stone, 2013, and references therein). It has been argued that the redness of inland dunes is caused by reworked material from the Tsondab sandstone (e.g., Besler, 1996). A magneto-mineralogical study on sand samples from a reddish inland dune at the Sossusvlei site showed that the magnetization of the sand material is carried by the high susceptibility minerals magnetite and maghemite in basaltic fragments (Gehring et al., 2009). Rock fragments are generally valuable indicators for the provenance of the sand, and they are independent of the dune colors (e.g., Garzanti et al., 2012). Consequently, the spatial distribution of magnetic rock fragments could provide constraints for the interplay between source, transport and mixing of eolian sands during the formation of the Namib erg. Here we report the statistics of the magnetic pattern of sand samples from a south-to-north transect and from two inland sites of the Namib erg in order to test this assumption.

2. Methodology

The south-to-north transect through the Namib Sand Sea in this study follows the predominant wind trajectories, and, therefore, the major directions of sand transport (Lancaster, 1989). This sampling disposition provides a continuous spatial record that complements magnetic, petrographic, and geochemical data collected from the edges of the Namib Sand Sea (Walden et al., 2000; Vermeesch et al., 2010; Garzanti et al., 2012).

A set of 113 sand samples were collected in 250 ml plastic flasks in roughly equal intervals along a transect between Lüderitz and Walvis Bay (Fig. 1). The sampling sites were determined by passages through the desert and are independent of the type, height, size and shape of the dunes. Sampling position within the dune was not specially considered. Thus, the samples represent a random collection in a south-to-north spatial frame. In addition, sand samples were taken at two inland sites near the Gobabeb Research Station and at the Sossusvlei including dune 45, respectively (Fig. 1). It is worth noting that the accessibility of the Namib desert permits no E to W sampling, i.e., from the coast to the inland, in a similar spatial resolution as for the S to N transect.

The magnetic content of the samples was determined by susceptibility measurements using an AGICO KLY-2 Kappabridge on 3.2 cm^3 material taken from each flask. The ordering temperatures of the magnetic carriers of a total of 12 samples throughout the transect and 6 samples from the inland sites were determined on magnetic separates with the Kappabridge coupled to a thermoelement. The average heating/cooling rate was 12 °C min^{-1} and the sample was kept in a steady argon gas flow to prevent oxidation during the measurements. In addition mineralogical and morphological properties of magnetic separates were investigated by powder X-ray diffractometry (XRD: Bruker D8, θ–θ geometry, Lynxeye stripe detector (PSD), CuKα radiation) and scanning electron microscopy (SEM: FEI Quanta200FEG instrument). Backscatter electron (BSE) images were obtained at analytical conditions of the SEM with a working distance of 10 mm (Gehring et al., 2009).

The collected sand samples were divided into five groups, according to their geographic location: the first three groups were the southern, center, and northern thirds of the transect (termed T1, T2, and T3) and were used to test for north-south trends in the magnetic susceptibility. The fourth and fifth group, respectively, consisted of samples from the Gobabeb and the Sossusvlei sites and were employed to compare inland locations with the coastal transect. The grouping is shown in Fig. 1. To assess the degree of mixing in the Namib erg, two null-hypotheses pertaining to the geographically defined groups were statistically tested: (1) the magnetic susceptibility variation is the same for all groups, and (2) the average magnetic susceptibility is the same for all groups. For the statistical evaluation the test by Brown and Forsythe (1974)