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Discriminating dusts and dusts sources using magnetic properties and hematite:Goethite ratios of surface materials and dust from North Africa, the Atlantic and Barbados

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ABSTRACT

Magnetic measurements and Diffuse Reflectance Spectroscopy are used in an attempt to differentiate dusts and dust sources in North Africa, over the Atlantic and in Barbados. Special attention is paid to dusts and to lacustrine clay and diatomite samples from the Bodélé Depression, in view of its alleged importance in trans-Atlantic and global dust generation. The results indicate that dusts from the Bodélé Depression can be distinguished from other dusts and potential sources in Niger, Chad, Burkina and Mali on the basis of their magnetic properties, notably their low magnetic concentrations, negligible frequency dependent magnetic susceptibility and distinctive IRM demagnetization characteristics. Dust from over the Atlantic and from Barbados, obtained from meshes in the 1960s and '70s have high frequency dependent susceptibility values, are quite distinctive from the Bodélé Depression samples and are more closely comparable to samples from elsewhere in the Sahara and especially the Sahel. The Diffuse Reflectance Spectroscopy data, though of limited value here, are not inconsistent with the inferences based on the magnetic measurements. Overall, the results obtained point to a wide range of sources for dusts both over North Africa itself and across the Atlantic. They do not offer support to the view that dusts from the Bodélé Depression have dominated supply across the Atlantic over the last five decades.

1. Introduction

Over the last decade and especially in the wake of the BodEx campaign in 2005 (BodEx, 2005), the role of the Bodélé Depression as a possible major, global dust source has received much attention. The east–west trending depression, some 500 km by 150 km, lies along the northern edge of the former mega-lake Chad which, at its greatest extent during the early –mid Holocene covered at least 350,000 km^2. Within the depression, the sediments susceptible to deflation comprise mainly diatomites (Bristow et al., 2009). From a combination of modeling (Tegen et al., 2006), meteorological observations and remote sensing (Washington et al., 2003, 2005; Washington and Todd, 2005), claims have been made that the Bodélé Depression may be the most important single source of dust in the atmosphere on a global scale (Washington et al., 2009). Moreover, aerosol trajectories (Ben-Ami et al., 2010) and geochemical analyses (Bristow et al., 2010) have been used to suggest that it may be a dominant source of dust and nutrients to Amazonia, mainly as a result of transport during winter months (Koren et al., 2006; Lovett, 2010). The study by Engelstaedter and Washington (2007) also reinforces the view that the Bodélé Depression is a significant hotspot for dust generation, alongside a wider range of sources in West Africa, which they claim are most active in June. Claims for the unique significance of the Bodélé Depression in dust generation have been contested recently by Crouvi et al. (2012), whose results show that dust sources in North Africa are much more widespread and diverse. They suggest that the extensive areas of mobile dunes are the dominant dust source, more important overall than the Bodélé Depression. At least one study, combining data from

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Meteosat-8 and surface measurements, documents a major Saharan storm drawing dust from a wide area over the Sahara and Sahel under the influence of northerly winds in March 2006 (Slingo et al., 2006). Moreover, Williams (2008) shows that satellite observations using the TOMS remote sensing instrument, data from which has been crucial in highlighting the outstanding significance of the Bodélé Depression as a dust source, are limited through blocking by upper level cirrus clouds, leading to a failure to capture the importance of dust outbreaks from the Sahel through the action of 'haboobs', intense dust storms carried on gravity currents mainly during summer months.

Relatively little research has been focused on establishing the extent to which the characteristics of the Bodélé Depression dust sources can be used to distinguish them from other North African dust sources and from dusts collected beyond the limits of the Depression. However, Abouchami et al. (2014), using geochemical and isotopic data, show that the Belterra Clays of the Amazon basin, considered by some to be derived from eolian dusts are clearly distinguishable from material from the Bodélé Depression. Instead, they appear to have been derived from in situ weathering. The sediments of the Bodélé Depression include extensive areas of exposed diatomites. Recognizable diatom frustules have been recovered from dusts over the Atlantic (e.g. Ehrenberg, 1849; Delaney et al., 1967; Romero et al., 1999). Diatomites, however, are not confined to the Bodélé Depression. Several studies (Gasse, 1987,2002; Servant and Servant, 1970) confirm how widespread and diverse are the diatom assemblages in sediments from the numerous lake basins in the Sahara-Sahel.

Previous studies confirm the value of magnetic measurements in discriminating dust sources globally (Maher, 2011), across North Africa (Lyons et al., 2010, 2012) in the North Atlantic and in Barbados (Oldfield et al., 1985). In the present paper we explore the role of magnetic measurements and Diffuse Reflectance Spectroscopy (DRS) in (i) discriminating a range of dusts and potential dust sources across the Sahara and Sahel regions, including the Bodélé Depression, (ii) allowing comparisons between the characteristics of these potential sources and those of dust samples taken from North Africa, the mid-Atlantic and Barbados and (iii) assessing the extent to which comparisons between the measured properties of the material from the Bodélé Depression and those from elsewhere are consistent with the suggestion that the Depression has been a dominant source of the dusts deposited elsewhere in N Africa, over the Atlantic and beyond.

Even where, as is often the case, it has been impossible to quantify mineral contributions from magnetic measurements, they have often proved valuable in discriminating materials on the basis of their provenance, especially where the measurements are diagnostic of distinctive environmental processes or sources (Liu et al., 2012). DRS also has been used successfully for characterizing soils and sediments and linking them to environmental processes (Ji et al., 2001; Hao et al., 2009). From Liu et al. (2011), it is clear that quantitative determination of concentrations using DRS is likely to be unreliable where the forms, sources and degree of substitution and grain sizes are, as is likely to be the case here, very diverse. Use of DRS has therefore been limited to estimating the ratio between hematite and goethite in view of the likely link between the ratio and different environmental contexts and weathering regimes (Schwertman and Taylor, 1989). Goethite and hematite play an important role in controlling the colour and reflectance of potential dust sources and the dusts themselves.

2. Samples of surface materials and dusts

The total sample set upon which the present study is based comprises 245 surface materials and dusts in the following groups:

1. Surface materials collected during three field trips between 2006 and 2010. These comprise samples along transects in Mali, Niger, Burkina Faso and Chad ($n = 146$). Of these, 12 (Group 1a) are from the region to the east of 12°E and north of 18°N, from the most northerly and arid parts of Niger. These surface samples are also paired with the subset of dust samples from the same locations (Group 2a below). Samples from the field sampling in 2010 include 8 from the Bodélé Depression (Group 1b) as well as 13 samples from Chad (Group1c) that span the arid zone to the north and south of the Depression.
2. Dusts, including 34 collected along the first broadly north–south Niger transect between July and September, 2007, mainly obtained by brushing exposed, elevated surfaces on old buildings. These integrate dust fall from unknown and variable periods of time. Of these, 12 are from the most arid region of N Niger (2a). In addition, 7 samples were collected between 15.11.2007 and 14.10.2008 from Niamey, most from a previously cleaned radar dome that integrated dust fall over 3 years (2b). Dusts were also collected in 2010 from sites in Niger and Chad (2c). These comprise four that represent dust accumulation over a period of at least several months, as well as one sample (Lab. No. 88) taken during a Harmattan dust storm during the winter 2009–2010.
3. Surface materials and dusts from the Bodélé Depression collected during the BodEx campaign in 2005 ($n = 18$). The mass of many of these samples is <0.5 g.
4. Dust samples from Barbados and mid-Atlantic ($n = 33$). 15 of the samples from Barbados were taken between October 1966 and July 1969 by means of nylon mesh panels and are among those included in Oldfield et al. (1985) and referred to below as group 4a. They include both red 'summer' dusts and grey 'winter' dusts. An additional mesh sample was taken in July 1970 and this was the only sample from Barbados available for inclusion in the suite of measurements upon which Fig. 9 is based. All but one of the remainder come from two sets of dusts obtained from mesh samplers on board ship. One set is referred to in Oldfield et al. (1985) and the other was provided by R. Chester for which precise location other than 'mid-Atlantic' can no longer be established. Both were obtained during the 1970s and, along with an additional mesh sample taken on the Glomar Challenger in March 1975, constitute group 4b.

The samples from North Africa (Groups 1–3) are associated with a marked range of climatic settings with a gradation of weathering regimes. This mainly relates to the strong, broadly north-to-south rainfall gradient across North Africa. Rainfall ranges from <30 mm/yr in the hyper-arid north of Niger and Chad to around 1000 mm/yr in southern Niger and Mali. In general, rainfall increases sharply south of ~15°N where the climate is influenced by the West African monsoonal rains, which are driven by the annual migration of the Intertropical Convergence Zone (ITCZ) (Hastenrath, 1985). Surface samples are mostly associated with Quaternary playa deposits, dunes and laterites (Schlüter, 2006).

Surface deflation and dust production are driven by two dominant wind systems–the north easterly winter Harmattan winds and the south westerly summer monsoon winds (Hastenrath, 1985). The Harmattan winds typically occur from October to April and transport vast quantities of mineral dust southwest from the Sahara towards the Gulf of Guinea and across the Atlantic (McTainsh and Walker, 1982). Summer winds, which also have the potential to transport vast quantities of material, commonly precede the onset of westward moving storms (Drees et al., 1993).

Fig. 1 shows the location of the sampling sites in N Africa.

Samples in groups 1 and 2 include some that form part of the data upon which previous publications by Lyons et al. (2010, 2012) are based. Those from Chad, including the Bodélé Depression