Available online at www.sciencedirect.com
ScienceDirect
Quaternary International 198 (2009) 234–245

Aeolian dust in Europe: African sources and European deposits

Jan-Berend Stuut[a,*], Ian Smalley[b], Ken O'Hara-Dhand[b]

[a]*MARUM—Center for Marine Environmental Sciences, University of Bremen, P.O. Box 330440, 28334 Bremen, Germany*
[b]*Giotto Group, Waverley Materials Project, Nottingham Trent University, Nottingham NG1 4BU, UK*

Available online 30 October 2008

Dedicated to Prof. Dr. D.H. Yaalon
Recollecting Dust, Loess & Deserts

Abstract

A conceptual model is presented for the provenance and dispersal patterns of small dust that falls on Europe. Generally its sources are in North Africa, and it is distributed across all Europe. Several key sources can be distinguished: 'Sahelian' dust comes largely from the old Lake Chad region—this is a clay-rich unimodal material. 'Saharan' dust comes from the great sand sheets—it contains small monomineralic particles and may have a bimodal size range. Three simple deposition zones can be recognised; a D1a zone where sufficient dust is deposited to form a discrete soil layer (not well classified as a Rendoll), in the extreme south of Europe; a D1b zone where the airborne dust simply provided a silty admixture to soil systems—across Middle Europe; and a northern zone D1c where the dust is a fugitive cloud, but very occasionally forms noticeable deposits. Two particle formation methods can be noted. Particle control in Sahelian dust is via the sedimentation in the original lake. This gives an open structure which can be modelled using a simple Monte Carlo approach. The open structure ensures that only small particles are produced; size control is via particle packing. A chipping mechanism can produce fine quartz particles from sandy deserts. The aeolian energy is, by and large, not sufficient to cause major impact fracturing but small mineral chips can be produced in the small dust size (fine and very fine silt), which go into high-level suspension and travel to Europe and beyond. The Saharan material can have a wider, more variable size distribution than the Sahelian material. The Canary Islands 'loess' is largely Sahelian material; the Cape Verde Islands deposits, from the nearby sandy regions, are Saharan deposits. Large dust has fallen on Europe, and produced widespread loess deposits. Large dust is essentially an 'in-continent' deposit; small dust comes from outside—from Africa.

1. Introduction

Europe is not a particularly dusty continent, compared to Australia or Africa, but there is a dust history to be considered and widespread loess to be examined and explained. Furthermore, there is contemporary dust activity, mostly involving dust from North Africa. A continent wide study is mostly an exercise in simplification and generalization and this review will concentrate on the nature of dust materials associated with the European environment, their sources and transportation routes, their zones of deposition, and various consequences and palaeoclimatic implications.

Dust is defined as material transported in suspension in the atmosphere, and this is material, which, predominantly, falls into the silt category (2–63 μm). This study of airborne silt, follows Friedman and Sanders (1978) in recognising five silt categories, each separated by 1 phi (ϕ) interval (9–4ϕ; 2–63 μm). Although the authors do not support the phi (ϕ) system of measurement, it provides a convenient way of demarcating the silt range, and facilitating a discussion on dust.

A major size distinction is observed in the world of dust; crudely expressed as a division into large dust and small dust (see Livingstone And Warren 1996). Failure to appreciate this fundamental dichotomy has caused much confusion in the study of dust and loess. Large dust is

*Corresponding author. Tel.: +49 421 218 65657; fax: +49 421 218 65505.
E-mail address: jbstuut@marum.de (J.-B. Stuut).

1040-6182/$ - see front matter
doi:10.1016/j.quaint.2008.10.007

coarse silt (16–31 µm) and very coarse silt (31–63 µm), carried in suspension but usually only for relatively short distances and forms loess deposits. Small dust is fine silt (4–8 µm) and very fine silt (2 4 µm) that travels very efficiently in suspension, is often washed out by rains, and may form deposits and additions to soils far downwind of the original particle source. Particle source distinguishes large and small dust; the different particle sources establish the two distinctive particle populations, and this point needs to be continuously emphasized. In the European scenario large dust is produced ‘in continent’, moved about by rivers and deposited by aeolian action. At present dust in Europe is only formed in significant quantities in the Po valley in Italy (Husar et al., 2000). Small dust is produced externally and blown into the continental region. It is widely dispersed, and from particle production to deposition only one major event is involved. In Europe small dust is mostly moving north towards deposition, but large dust from northern Africa is moving essentially south and east, but with minor amounts going north and west. The movement of large dust, which is to become loess across Europe, is a complex matter still requiring final elucidation.

Apart from exceptional cases where Chinese dust makes it around the planet to the Alps (e.g., Grousset et al., 2003), and some local coarse dust (e.g., Franzén and Hjelmroos, 1988; de Jong et al., 2006) the major source of small dust material is in North Africa, in the old Lake Chad basin and the great sand seas (e.g., Goudie and Middleton, 2006). Most of this material is carried to the west and out over the Atlantic. Fig. 1 shows the general setting and attempts to indicate proposed source and deposition regions, and related features.

Some dust falls on the Canary Islands and forms the Canary Islands ‘loess’, which has a mode size of around 5 µm (Coudé-Gaussen, 1991; Torres-Padrón et al., 2002; Menéndez et al., 2007). Small dust material from Africa has been noted and studied in many European locations such as Crete (e.g., Nihlén and Mattsson, 1989), Spain (e.g., Rodá et al., 1993), Italy (e.g., Bergametti et al., 1989), UK, (e.g., Stevenson, 1969), the Alps (e.g., Ricq-de

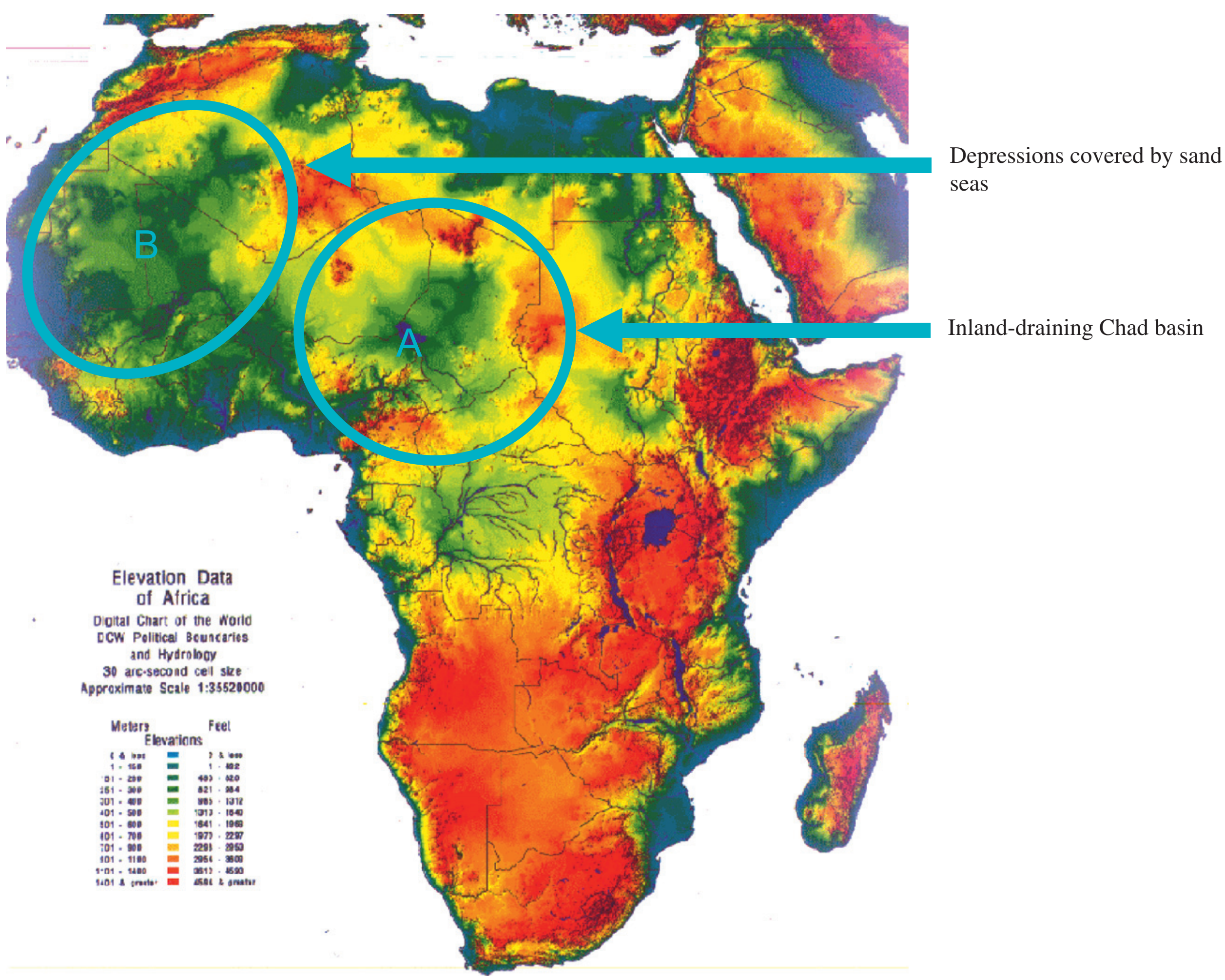

Fig. 1. Digital elevation model (DEM), illustrating the geomorphology of the main dust sources in northern Africa. (A) The Bodélé Depression in Chad surrounded on practically all sides by mountain ranges, (B) Several basins in northwest Africa are well-known sources of dust (e.g., Livingstone and Warren, 1996). DEM from USGS, Sioux Falls, South Dakota, USA.

Bouard and Thomas, 1972) Scandinavia (e.g., Franzén et al., 1994) and there is no doubt that in some places it has made a significant contribution to local soils. The Rendzinas in southern Spain are almost certainly the result of dust input from North Africa and the classic A–C horizonation suggests that no other explanation is likely (e.g., Danin et al., 1983), because the upper A-horizon is detached from the lower materials since it is made up of dust and the C-horizon contributes nothing in effect.

Much of the small dust that is delivered from Africa is old lake sediment particles, which are lifted as small aggregates of clayey material (e.g., McTainsh, 1985). The small dust size is controlled by the particle packing in the original lake sediment (Smalley, 1970). The particular geomorphology and recent geological history of the Lake Chad region ensures a continuing supply of this small dust material (e.g., Engelstaedter et al., 2006). Particle fragments produced by sand grain impacts in sandy desert regions contribute another set of small dust particles. It appears that small dust consists mostly of clay mineral aggregates and monomineral particle fragments. A dichotomy is suggested, into old dust; older lake-floor sediments, and new dust; fine material that is delivered by the active drainage systems. The new dust is small dust and the old dust is large dust.

To describe a sediment and to examine any aspect of the sedimentation process it is useful to look at the whole sequence of events/processes, which go to determine the position and nature of the eventual deposit. The PTD scheme (Smalley, 1966, see also Wright, 2001; Smalley et al., 2005) was an early attempt to define the events forming a sediment; the events are divided into P—particle formation events; T—transportation events, and D—deposition events. First devised to describe loess deposits there is inevitably some emphasis on clastic, particulate sediments. Although the basic idea is very simple, when applied to some complex loess deposits a remarkably detailed sequence of events can be revealed for study. It would appear that in the case of aeolian dust moving from Africa to Europe a very simple sequence is observed: P actions—particles are formed in the arid regions of north Africa; T actions—a long high transportation of fine particles in suspension, roughly from south to north; and D actions—deposition in various European environments. A PTD sequence for African dust has been attempted (Evans et al., 2004) and this will be developed in this paper. This study is mainly concerned with P and D events; the T events have received detailed attention—but the P and D events have been somewhat neglected, even though Morales (1979) directed specific attention to the importance of studying particle formation events, he proposed: "comprehensive studies to understand the production of fine particulate material by weathering and disintegration processes as a first *and important* (authors' emphasis) step in dust production" (Morales, 1979).

2. Saharan dust in Europe

A comprehensive study of early reports on dustfalls in Europe was written by Free (1911) and followed by a very complete bibliography on the older dust literature by Stuntz and Free (1911), who report ancient descriptions of dustfalls dating back almost 3000 years; to the times of Homer, and Virgil and Livy. Fett (1958) described several studies of Saharan dust reaching Europe in the mid 20th century, and also how storm trajectories across the Mediterranean brought dust from Libya to Italy and occasionally across the Alps. Yaalon and Ganor (1973) also briefly discussed dust heading for Europe: "Sahara dust transported by cyclonic winds reaches Europe occasionally". The major scientific contributions on Saharan dust published in the seventies and eighties of the 20th century were the results of a number of workshops such as e.g., Morales (1979), Péwé (1984), Leinen and Sarnthein, 1989) and Guerzoni and Chester (1996). Essentially, it was concluded in these workshops that there is still a need for a better understanding of the localized factors, which influence dust generation and transport. In addition, there is a strong need for models that can simulate the dust generation and injection at the synoptic scale that can be used in mesoscale and global circulation models. The development of satellite imagery and the recognition (by e.g., the IPCC) that aerosols do affect global climate significantly have led to the appearance of a vast amount of dust publications in the last decade (e.g., Husar et al., 1997; Guerzoni et al., 1999; Chiapello et al., 2000; Husar, et al., 2000; Goudie and Middleton, 2001; Chiapello and Moulin, 2002; Pérez-Marrero et al., 2002; Ansmann et al., 2003; Chiapello et al., 2005; Mahowald et al., 2005; Stuut et al., 2005; Engelstaedter et al., 2006; Goudie and Middleton, 2006; Mona et al., 2006; Moreno et al., 2006).

3. Small dust in Europe

Most Saharan dust is deposited over the Mediterranean countries of southern Europe and has been reported since ancient times (e.g., Bücher and Lucas, 1984). Dust clouds originating from the Sahara are often observed in the Mediterranean countries typically as yellowish-brown clouds that are washed out by rains mostly against topographic barriers, which cause uplift of the dust-transporting air masses (e.g., Prodi and Fea, 1979; Nihlén and Mattsson, 1989). Occasionally, the dust particles travel further north; Pitty (1968) recorded the arrival of Saharan dust in London in July 1968, coming from the western Sahara along the east Atlantic coast, and small dust particles were also occasionally observed in The Netherlands (e.g., Reiff et al., 1986), Germany (e.g., Littmann and Steinrücke, 1989) and in Scandinavia (e.g., Franzén, 1989). There can be substantial dustfalls such as the one in early March 1991 that covered an area of at least 320,000 km^2 stretching from Sicily in the south to Sweden and Finland in the north (Burt 1991; Bücher and Dessens, 1992; Franzén et al 1995). Most of these small dust particles were carried North by anticyclonic cells (Wheeler, 1986) and washed out by rains, to be mostly seen as a thin veneer covering e.g., cars and bikes. The Saharan provenance of the material was supported by the exotic pollen that were found in local wind-blown deposits in Sweden (Franzén and Hjelmroos, 1988).

4. Large dust in Europe

Present-day large dust (16–62 μm) in Europe essentially means Saharan and Sahelian material crossing the Mediterranean and then being dispersed by variable winds across the continent and deposited by dry deposition (Guerzoni, et al., 1999). Huge amounts of dust are blown out of the Sahara towards the North, based on trace metals. Martin et al. (1989) estimated the input of red dust from the Sahara of the same order of magnitude as the annual downstream flow of rivers discharging to the western Mediterranean. Estimates of total Saharan dust production vary widely ranging from 130–460 (Swap et al., 1996) to 1400 million ton per year (Ginoux et al., 2004). d'Almeida (1989) argued that only about 12% of the total Saharan dust export is transported north, and calculated a total amount of about 80–120 million tons per year, which, considering the large spread of estimations (Goudie and Middleton, 2006) may well be an underestimation.

Where Africa and Europe are close, e.g., southern Spain, the contribution of African dust to soils is significant. In Spain, most of the dust-laden winds presently carry great numbers of large dust predominantly in the summer months, leading to dust concentrations in the atmosphere far exceeding the EU standards for air quality (e.g., Rodriguez et al., 2001). Large dust in the Mediterranean realm is also deposited with rain, leading to the so-called "red rains" or "blood rains" (e.g., Passerini, 1902; Avila et al., 1997; Avila and Peñuelas, 1999). Large dust has been observed on other relatively proximal deposition areas for Saharan dust such as Sicily (Corregiari et al., 1989), southern Italy (Molinaroli et al., 1993; Guerzoni et al., 1996), and Crete (di Sarra et al., 2002), although wet deposition seems to be the predominant sedimentation mechanism (e.g., d'Almeida, 1986; Rogora et al., 2004).

Fossil large-dust deposits present a fairly complex picture. Large dust (in the classic loess range 10–50 μm) was produced in Europe at various times in the Quaternary and has formed a range of loess deposits across the continent (e.g., Frechen et al., 2003; Haase et al., 2007; Rousseau et al., 2007). Of course for most of its history it is simply coarse or very coarse silt (e.g., Markovic et al., 2006) but it takes on the form of dust for the last deposition event, and this gives it the nature, structure and properties of loess. To find out why this silt/dust is concentrated in its particular size range requires consideration of the source of the material. The silt/dust itself largely consists of quartz particles and it appears that there are crystallographically controlled defects, possibly related to Moss defects (Moss and Green, 1975), in quartz particles which predispose the breakage product to be found in the 'loess' size range (e.g., Assallay et al., 1998). While the size control on small dust particles appears to derive mostly from the deposition mode in the early phase of wet deposition in the lake, the control is exercised on most large dust particles at the transition from sand to silt size. There are certain natural modes in the clastic universe; one gives quartz sand, and one gives quartz silt. Small dust largely escapes these controls.

5. Saharan dust in Europe; sources and distribution

Dobson (1781) was most likely the first to apply a simple triangulation method to determine the major source of Saharan dust and came very close to the Bodélé depression in former lake Chad, which is presently recognised as the single major source of Saharan dust (McTainsh and Walker, 1982; Prospero et al., 2002; Engelstaedter, et al., 2006; Koren et al., 2006). Since then, trajectory calculations helped many scientists to locate potential sources of dust deposited in Europe (e.g., Ganor and Mamane, 1982; Reiff, et al., 1986; Bergametti, et al., 1989; Franzén, et al., 1994; Avila, et al., 1997).

A major source area for transport of dust to western Europe was identified in southernmost Algeria, between Hoggar and Adrar des Iforhas (d'Almeida, 1986). This is a high region, south of Mt. Tahat (9850 m). Another source, where material is particularly rich in palygorskite (Molinaroli, 1996) is in the region of Western Sahara and southern Morocco. These sources have been essentially confirmed by back trajectory analysis for dust deposited over northeastern Spain. Avila et al (1997)

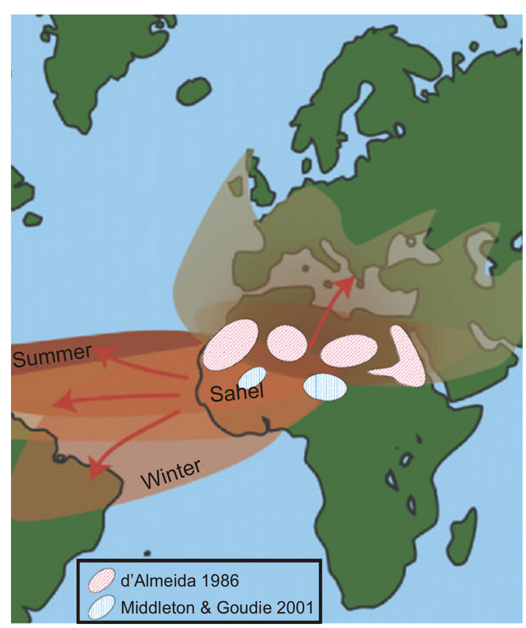

Fig. 2. Present-day active dust sources in the Saharan Desert (modified after Kellogg and Griffin, 2006, and incorporating d'Almeida, 1986; Middleton and Goudie, 2001; Engelstaedter and Washington, 2007).

traced deposition events back to three main areas: Western Sahara; Moroccan Atlas, and central Algeria. These source areas have also been identified for transport of dust to the British Isles (Tullet, 1978; Wheeler, 1986). A common trajectory for transport to Britain is over the Bay of Biscay, in mid-tropospheric winds skirting an anticyclone over western Europe.

Less commonly, dust is transported from Algerian sources over the Mediterranean and France in association with a low-pressure system centred over the Bay of Biscay (Wheeler 1986, Coudé-Gaussen et al., 1998).

A graphical summary of the major sources recognised by d'Almeida (1986), Middleton and Goudie (2001), Blanco et al. (2003) and Engelstaedter and Washington (2007) is provided in Fig. 2. Goudie and Middleton (2006) state that the problems with source identifications may have to do with the fact that different methods and definitions are used. Nevertheless, roughly four dust sources can be identified (after d'Almeida, (1986) and Molinaroli (1996)), from west to east: (1) Morocco to north Mauritania, (2) south Algeria, (3) south Libya and Chad, and (4) Egypt and north Sudan. By monitoring dust observations on the island of Corsica for a year, Bergametti et al., (1989) mapped out three different sources of Saharan dust from 20 events, originating from eastern Algeria, Tunisia, and western Lybia (sector 1), Morocco and western Algeria (sector 2), and "south of 30 °N", called the Sahelian source by Littmann (1991). Two additional sources were proposed by Middleton and Goudie (2001) in north Mali, after Kalu (1979) and central Chad. The use of back trajectory models (e.g., Draxler and Rolph, 2003) and satellite imagery (e.g., Prospero et al., 1970) has brought a major step forward to the provenance of the dust outbreaks.

A further complication of this observation is the fact that the aerosol at any one point can be a complicated mixture

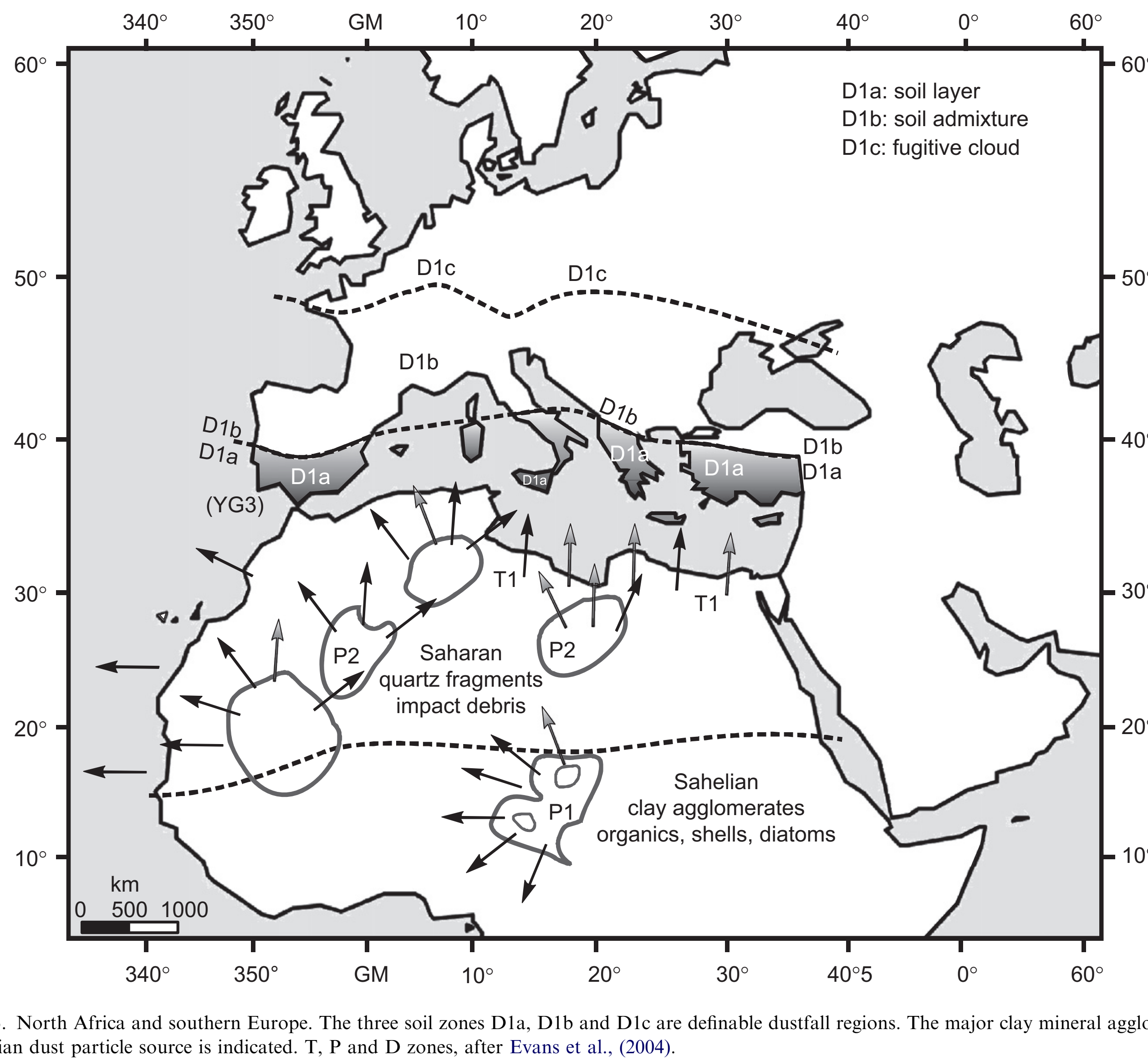

Fig. 3. North Africa and southern Europe. The three soil zones D1a, D1b and D1c are definable dustfall regions. The major clay mineral agglomerates Sahelian dust particle source is indicated. T, P and D zones, after Evans et al., (2004).

of particles lifted at different times and different places (Westphal et al., 1988). Westphal et al. (1988) observed bimodal size distributions in their modelled aerosols that developed when dust was mobilized within a dust plume that was generated on a different consecutive days in the source area.

Koopmann (1979), and based on his data Weltje and Prins (2003) and Holz et al. (2004) demonstrated a gradual downwind decrease in the size of Saharan dust deposited in the north equatorial Atlantic Ocean. Similar size, flux- and compositional-gradients exist in the Mediterranean Sea, observed by a number of authors (e.g., Chester et al., 1984; Tomadin et al., 1989; Guerzoni et al., 1997). Two main geological processes were discerned: input of dust to the Mediterranean deep-sea sediments, acting as nutrients for marine life and as an archive for climate change (e.g., Loÿe-Pilot et al., 1986; Bergametti, et al., 1989; Tomadin and Lenaz, 1989), and as a source for the formation of the *terra rossa* soils in southern Europe (e.g., Yaalon and Ganor, 1973; Macleod, 1980; Rapp, 1984; Nihlén and Mattsson, 1989; Rapp and Nihlén, 1991). These soils are the D1a deposits in Fig. 3; the classic Rendzina or A–C soils where the upper horizon is obviously detached from the lower materials because, as we hypothesize, it is made up of dust. No simple horizonation can be observed here, the upper material is delivered from outside the immediate pedological environment—in this case small dust is delivered from African sources. The D1a deposits are the most obvious manifestations of the delivery of small dust from Africa to Europe. The D1b material, travelling further north is incorporated seamlessly into the soil systems and serves only to increase the fine silt content; there are no horizonation effects.

Middleton and Goudie (2001) observe that dust transport to southern Europe occurs frequently, as one would expect. Their analysis of TOMS satellite data for 1999 shows that dust penetrated the troposphere over the Mediterranean on more than 60% of days throughout the months of March–September, with Mediterranean dust outbreaks recorded on 100% of days in June and August. In the western Mediterranean, there was an input of Saharan material as far north as Sardinia on 43% of days in June and 60% of days in August. The most frequent source for dust reaching Sardinia was central southern Tunisia and adjacent areas of eastern Algeria, an area of salt pans shown by Dubief (1953) as generating more than 40 sand-blowing events each year. Morocco/western Algeria was an occasional source of dust reaching Sardinia according to the 1999 TOMS data, as was northeastern Libya—which was not mentioned by Bergametti et al. (1989) in their Corsican work. Analysis of meteorological station data by Middleton (1986) shows a broad area across eastern Algeria and western Libya with more than 15 dust storm days a year on average and three stations in northeastern Libya with a long-term (1956–1977) mean of more than 10 dust storm days per year.

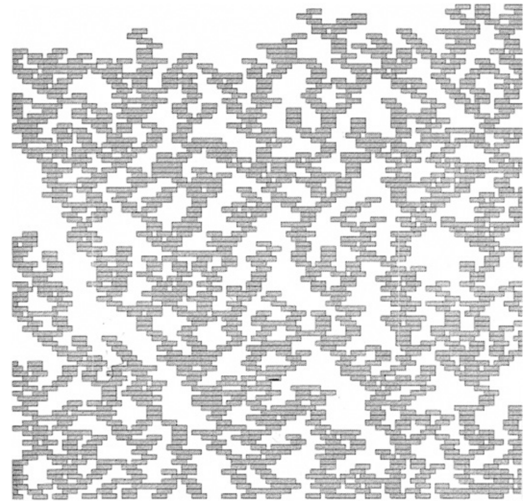

Fig. 4. The packing structure for a lake sediment. Small particles detached from this packing form CMA particles. The packing structure determines particle size, no large aggregates are formed.

6. Particle formation (P) actions

Several monitoring projects have been carried out to study dust moving to Europe (e.g., Littmann and Steinrücke, 1989; Pye, 1992; Avila et al., 1997; Moulin et al., 1997; Rodriguez, et al., 2001). During their observational period from October 1987 to April 1989, Littmann (1991) recorded nine depositional events of African dust in Bochum, between Essen and Dortmund, in Germany. He reported on the mineralogy and size distribution of the dust. Two types of size distribution were observed which he called a unimodal type and a bimodal type. His unimodal distributions had median grain sizes in the fine silt 2–4 μm size range and appear to represent classic 'small' dust. His bimodal distributions had a mode of 2–4 μm but also a peak at around 20 μm—a characteristic particle size for 'large' dust. In his conclusions he noted that dust from a single source shows a unimodal grain size distribution and the dominance of either Sahelian or Saharan diatom species. Dust from multiple sources is most likely from a Sahelian dust plume recharged over the Sahara; it shows a bimodal grain size distribution and the presence of both Sahelian and Saharan diatom species.

The Littmann mineralogy was not well defined but he reported dominant quartz, with some carbonates; small amounts of feldspars were present, with the clay mineral fractions dominated by mixed-layer illite and chlorite. Basically monomineral particles and clay mineral agglomerates are the products of the dominant P actions in arid North African regions.

We consider these P actions at some length; a satisfactory discussion of dust particle origins, transportation and deposition has to begin with a careful consideration of the mechanisms of particle production (as Morales required). Monomineralic fragments and clay mineral aggregates arise from different regions and are produced by widely differing processes.

7. Clay mineral agglomerates (CMA)

An ideal example of a particle consisting of a clay mineral agglomerate (CMA) might be a cluster of several clay mineral particles with a nominal diameter of about 4 μm. It was formed somewhere within the extent of the old Lake Chad, say in the Bodélé depression. It has been picked up by the wind and moved north (with possible digressions) and has found its way into a Littman sample. He classifies it as a 'Sahelian' particle—and it does indeed come from the borders of the Sahel. This will be the archetypical Sahelian clay particle. It is possible to describe a mechanism which accounts for its formation, and for the size constraints that determine the particle size distribution in Sahelian material.

Evans et al. (2004) described the formation of Sahelian dust material and we essentially follow their approach (Figs. 3 and 4). It is important to realise that the process of sedimentation of clay particles in the old widespread Lake Chad formed a sedimentary structure, which subsequently determined the nature of the airborne dust particles which the dried lake bed so abundantly supplied (and is supplying). These are Littmann's Sahelian particles. 'Sahelian' may not be an ideal term but it serves to distinguish CMA particles from mineral fragments. The sedimentation process can be modelled by a very simple Monte Carlo model which produces an ideal lake sediment structure (Fig. 4). Smalley et al., (2005) demonstrated that by a simple modelling exercise that allows free falling particles in a computer model, an ideal open random structure is formed, which models a typical loess deposit, and perhaps surprisingly, also a lake deposit of clay-size particles. This structure shows immediately why CMA particles are found in the fine and very fine silt ranges. The Monte Carlo packing does not produce any large aggregates, the obviously detachable particles are all agglomerates of a small number, say 2–6, particles.

8. Monomineralic fragments

There are two major types of dust particle; the CMA particle and the monomineralic fragment. A typical fragment might be a quartz chip of about 4 μm in nominal diameter, derived from the sandy areas of North Africa. Fig. 5 shows the Livingstone and Warren (1996) map of sand seas and it is these that provide much of the dust material that blows out of North Africa. The TOMS data (see Middleton and Goudie, 2001) seems to suggest that the Lake Chad region is the most effective generator of dust and this implies that most dust is of the CMA variety, but records of dustfall indicate that mineral fragments do form a significant contribution to dust clouds. The location of sand seas in the western part of Africa suggests that the material falling on the nearby Cape Verde Islands (Rognon et al., 1996) might be largely fragment material.

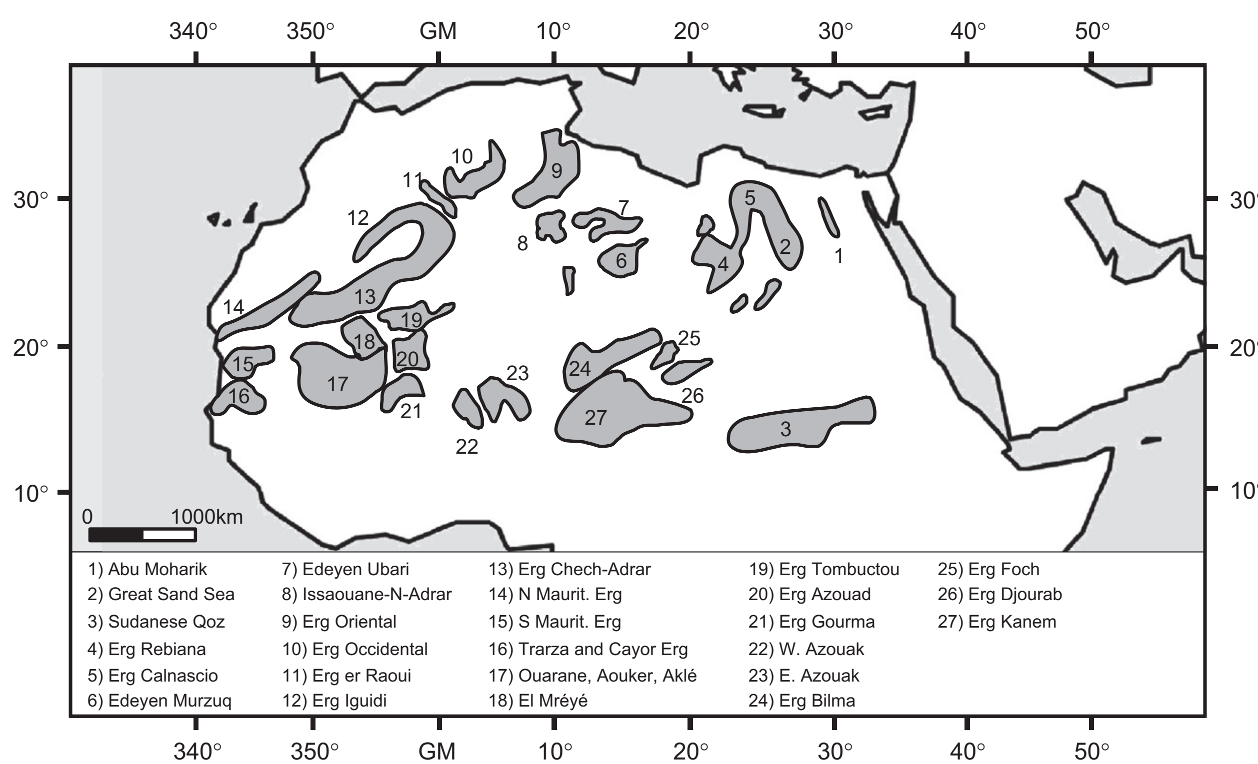

Fig. 5. Sand seas in North Africa, based on the map by Livingstone and Warren (1996). Sand seas produce monomineralic fragments.

Its relatively large particle size (median perhaps at 20 μm) contrasts with the 5 μm material which comprises the Canary Islands loess (e.g., Coudé-Gaussen, 1991). The Canary Islands material could be Sahelian clay particles carried to the west.

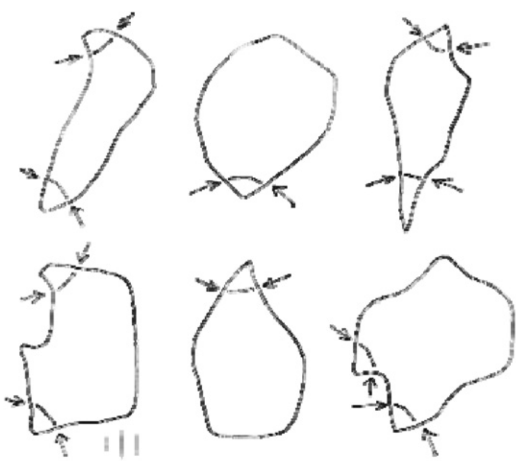

Fig. 6. Fine quartz particle production by particle impact. Quartz sand results from weathered granite; speculative impact breakages are shown. Small dust particles produced, based on Smalley and Vita-Finzi (1968).

The proposed chip-forming mechanism is very simple; it was outlined by Smalley and Vita-Finzi (1968) and requires high energy impact between quartz sand particles. Enough energy is available to produce chipping (Fig. 6)—not enough energy is available to produce large-scale fracture. The impact mechanism does not produce large dust particles, which is why the Sahara lacks a surrounding zone of typical loess. Impact does, however, produce small dust and this contributes to the European dust clouds.

9. Particle deposition (D) actions

The airborne dust particles move north over Europe, and some eventually settle. We hypothesize that close to Africa there is a high concentration of deposited material and this diminishes as distance increases. There is one boundary or division that needs to be noted, and it is neither firm nor distinct. Close to Africa the particle concentration is hypothesized to be sufficient to cause an identifiable deposit, an aeolian sediment, an airfall soil (the D1a region). To the north of this area is the region where the silt fall does not form a distinctive deposit but is simply incorporated into existing soils, it becomes an admixture rather than a deposit (the D1b zone).

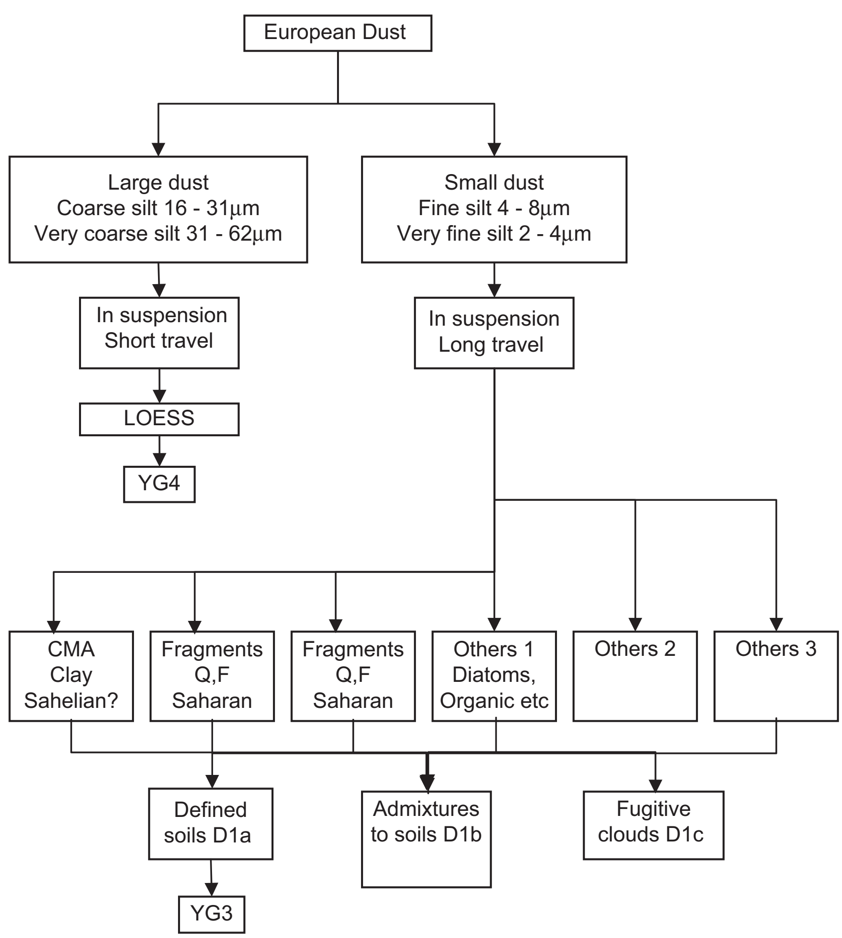

Fig. 7. Aeolian dust in Europe. The chart shows the two basic types of dust; large and small, and deposition types and regions.

Yaalon and Ganor (1973) produced a classification for such deposits/soils; they proposed a fourfold grouping:

YG1—soils in which accession of atmospheric dust has acted as a modifying agent;
YG2—soils in which accretion of atmospheric dust has proceeded simultaneously with the process of soil development, and where it has significantly affected the nature of the soils;
YG3—soils which have received a thin surface aeolian layer, which is thinner than the depth of the solum; and
YG4—soils formed from thick aeolian sediments.

Soils formed in loess would be expected to fall into the YG4 category, the other three categories should apply to small dust falling on Europe such as e.g., the terra rossa that is found in Spain, Italy and Greece (Macleod, 1980; Jackson et al., 1982; Bellanca et al., 1996; Durn et al., 1999). YG1 might correspond to D1b but it is doubtful whether the dust fall has *significantly* affected the nature of the soils. YG2 will not apply to any real extent; most North African dust arriving in Europe is relatively recent material, arriving after main soil-forming activity has occurred. YG3 might correspond with the obvious deposits of D1a, but that depends to some extent on the definition of 'solum'. In simple classical terms the A, E and B horizons are collectively known as the solum or 'true soil'. But E and B horizons could be lacking in a D1a soil; however, we shall identify D1a as a YG3 soil. In real terms, YG3 and YG4 are the significant aeolian soils.

10. Conclusions

There are conclusions relating to perception, and conclusions relating to mechanism. We need to be aware of the distinction between large dust and small dust; this is a very crude distinction but it is absolutely necessary to establish the division between loess (travelled over short distances) and aerosolic (travelled over long distances) dust. The table in Fig. 7 attempts to set out the participants in the dust scenario. We would like to identify major particle-forming mechanisms, in particular for small dust. Particle formation for large dust also known as loess has been extensively discussed elsewhere. We propose a simple classification for small dust falling on Europe and becoming involved in soil systems.

Middleton and Goudie (2001) wrote that one of the most important needs in furthering our understanding of the Saharan production of dust is to identify the major source areas. If we can identify the various types of small dust and determine the formation mechanisms for the particles this may aid in identifying source areas. The simple dichotomy of 'Sahelian' and 'Saharan' dust points to sources in old lake beds and current sand seas. With sufficient knowledge of the particle-formation mechanism, mineralogical compositions can be used to trace the provenance of the dust.

Acknowledgements

We thank the creators and organisers of the Bibliography of Aeolian Research (BAR) for their sterling efforts in codifying the vast literature on airborne dust and related topics and making the tasks of interested scholars so much easier and more pleasant. We also thank the organisers of the Novi Sad '06 meeting of the INQUA Loess Sub-Commission, which set in train the discussions that led to this paper. We thank the Loess Letter Archive for supplying ancient material. Dan Muhs and Slobodan Markovic are thanked for their critical reviews, which strongly improved the manuscript. JBS is funded through the DFG-Research Center/Excellence Cluster "The Ocean in the Earth System".

References

Ansmann, A., Bösenberg, J., Chaikosvky, A., Comerón, A., Eckhardt, S., Eixmann, R., Freudenthaler, V., Ginoux, P., Komguem, L., Linné, H., López Márquez, M.A., Volker, M., Mattis, I., Mitev, V., Müller, D., Music, S., Nickovic, S., Pelon, J., Sauvage, L., Sobolewsky, P., Srivastava, M.K., Stohl, A., Torres, O., Vaughan, G., Wandinger, U., Wiegner, M., 2003. Long-range transport of Saharan dust to northern Europe: the 11–16 October 2001 outbreak observed with EARLINET. Journal of Geophysical Research 108 (D24), 4783.

Assallay, A.M., Rogers, C.D.F., Smalley, I.J., Jefferson, I.F., 1998. Silt: 2–62 μm, 9–4ϕ. Earth-Science Reviews 45, 61–88.

Avila, A., Peñuelas, J., 1999. Increasing frequency of Saharan rains over northeastern Spain and its ecological consequences. The Science of the Total Environment 228 (2–3), 153–156.

Avila, A., Queralt-Mitjans, I., Alarcon, M., 1997. Mineralogical composition of African dust delivered by red rains over northeastern Spain. Journal of Geophysical Research 102 (D18), 21977–21996.

Bellanca, A., Hauser, S., Neri, R., Palumbo, B., 1996. Mineralogy and geochemistry of terra rossa soils, western Sicily: insights into heavy metal fractionation and mobility. Science of the Total Environment 193 (1), 57–67.

Bergametti, G., Gomes, L., Remoudaki, E., Desbois, M., Martin, D., Buat-Ménard, P., 1989. Present transport and deposition patterns of African dusts to the north-western Mediterranean. In: Leinen, M., Sarnthein, M. (Eds.), Palaeoclimatology and Palaeometeorology: Modern and Past Patterns of Global Atmospheric Transport (NATO ASI Series. Series C, vol. 282). Kluwer Academic Publishers, Dordrecht, pp. 227–252.

Blanco, A., Tomasi De, F., Filippo, E., Manno, D., Perrone, M.R., Serra, A., Tafuro, A.M., Tepore, A., 2003. Characterization of African dust over southern Italy. Atmospheric Chemistry and Physics 3, 2147–2159.

Bücher, A., Dessens, J., 1992. Poussières sahariennes sur la France et l'Angleterre, 6–9 March 1991. Journal of Meteorology 17, 226–233.

Bücher, A., Lucas, G., 1984. Sedimentation éolienne intercontinentale, poussières sahariennes et géologie. Bulletin des Centres de Recherches Exploration–Production ELF Aquitaine 8, 151–165.

Burt, S., 1991. Falls of dust rain within the British Isles. Weather 46, 347–353.

Chester, R., Sharples, E.J., Sanders, G.S., Saydam, A.C., 1984. Saharan dust incursion over the Tyrrhenian Sea. Atmospheric Environment 18 (5), 929–935.

Chiapello, I., Moulin, C., 2002. TOMS and METEOSAT satellite records of the variability of Saharan dust transport over the Atlantic during the last two decades (1979–1997). Geophysical Research Letters 29 (8), 1176.

Chiapello, I., Goloub, P., Tanré, D., Marchand, A., Herman, J., Torres, O., 2000. Aerosol detection by TOMS and POLDER over oceanic regions. Journal of Geophysical Research 105 (D6), 7133–7142.

Chiapello, I., Moulin, C., Prospero, J.M., 2005. Understanding the long-term variability of African dust transport across the Atlantic as recorded in both Barbados surface concentrations and large-scale Total Ozone Mapping Spectrometer (TOMS) optical thickness. Journal of Geophysical Research 110 (D18S10).

Corregiari, A., Guerzoni, S., Lenaz, R., Quarantotto, G., Rampazzo, G., 1989. Dust deposition in the central Mediterranean (tyrrhenian and Adriatic Seas): relationships with marine sediments and riverine input. Terra Nova 1, 549–558.

Coudé-Gaussen, G., 1991. Les pousières sahariennes. J. Libbey Eurotext, Paris, 485pp.

Coudé-Gaussen, G., Desire, E., Regrain, R., 1998. Particularite des poussières sahariennes distales tombées sur la Picardie et l'Ile de France le 7 mai 1988. Hommes et Terres du Nord 4, 246–251.

d'Almeida, G.A., 1986. A model for Saharan dust transport. Journal of climate and applied meteorology 25 (7), 903–916.

d'Almeida, G.A., 1989. Desert aerosol: characteristics and effects on climate. In: Leinen, M., Sarnthein, M. (Eds.), Palaeoclimatology and Palaeometeorology: Modern and Past Patterns of Global Atmospheric Transport. Kluwer Academic Publishing, Dordrecht, pp. 311–338.

Danin, A., Gerson, R., Carty, J., 1983. Weathering patterns on hard limestone and dolomite by endolithic lichens and cyanobacteria: supporting evidence for eolian contribution to terra rossa soil. Soil Science 136, 213–217.

de Jong, R., Björck, S., Björkman, L., Clemmensen, L.B., 2006. Storminess variation during the last 6500 years as reconstructed from an ombrotrophic peat bog in Halland, southwest Sweden. Journal of Quaternary Science 21 (8), 905–919.

di Sarra, A., Cacciani, M., Chamard, P., Cornwall, C., DeLuisi, J.J., Iorio di, T., Disterhoft, P., Fiocco, G., Fuà, D., Moteleone, F., 2002. Effects of desert dust and ozone on the ultraviolet irradiance at the Mediterranean island of Lampedusa during PAUR II. Journal of Geophysical Research 107 (D18), 8135.

Dobson, M., 1781. An account of the Harmattan, a singular African wind. Philosophical Transactions of the Royal Society of London 71, 46–57.

Draxler, R.R., Rolph, G.D., 2003. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY. NOAA Air Resources Laboratory, Silver Spring, MD 〈http://www.arl.noaa.gov/ready/hysplit4.html〉.

Dubief, J., 1953. Les vents de sable dans le Sahara Francais. Colloques Internationaux de CNRS 35, 45–70.

Durn, G., Ottner, F., Slovenec, D., 1999. Mineralogical and geochemical indicators of the polygenetic nature of terra rossa in Istria. Croatia Geoderma 91 (1–2), 125–150.

Engelstaedter, S., Washington, R., 2007. Atmospheric controls on the annual cycle of North African dust. Journal of Geophysical Research 112, D03103.

Engelstaedter, S., Tegen, I., Washington, R., 2006. North African dust emissions and transport. Earth-Science Reviews 79 (1–2), 73–100.

Evans, R.D., Jefferson, I.F., Kumar, R., O'Hara-Dhand, K., Smalley, I.J., 2004. The nature and early history of airborne dust from North Africa; in particular the Lake Chad basin. Journal of African Earth Sciences 39 (1–2), 81–87.

Fett, W., 1958. Der atmosphärische Staub. Deutsche Verlag der Wissenschaften, Berlin, 309pp.

Franzén, L., 1989. A dustfall episode on the Swedish West Coast, October 1987. Geografiska Annaler Series A, Physical Geography 71 (3–4), 263–267.

Franzén, L., Hjelmroos, M., 1988. A coloured snow episode on the Swedish West Coast, January 1987: a quantitative and qualitative study of air borne particles. Geografiska Annaler Series A, Physical Geography 70 (3), 235–243.

Franzén, L.G., Hjelmroos, M., Kållberg, P., Brorström-Lundén, E., Juntto, S., Savolainen, A.-L., 1994. The 'yellow snow episode' of northern Fennoscandia, March 1991—a case study of long-distance transport of soil, pollen and stable organic compounds. Atmospheric Environment 28 (22), 3587–3604.

Franzén, L.G., Hjelmroos, M., Kallberg, M., Rapp, A., Mattsson, J.O., Brorstrom-Lunden, E., 1995. The Saharan dust episode of south and central Europe, and northern Scandinavia, March 1991. Weather 50, 313–318.

Frechen, M., Oches, E.A., Kohfeld, K.E., 2003. Loess in Europe—mass accumulation rates during the Last Glacial Period. Quaternary Science Reviews 22 (18–19), 1835–1857.

Free, E.E., 1911. The movement of soil material by the wind. US Department of Agriculture Bureau of Soils Bulletin 68, 272pp.

Friedman, G.M., Sanders, J.E., 1978. Principles of Sedimentology. Wiley, New York, 378pp.

Ganor, E., Mamane, Y., 1982. Transport of Saharan dust across the eastern Mediterranean. Atmospheric Environment (1967) 16 (3), 581–587.

Ginoux, P., Prospero, J.M., Torres, O., Chin, M., 2004. Long-term simulation of global dust distribution with the GOCART model: correlation with North Atlantic Oscillation. Environmental Modelling and Software 19, 113–128.

Goudie, A.S., Middleton, N.J., 2001. Saharan dust storms: nature and consequences. Earth-Science Reviews 56 (1–4), 179–204.

Goudie, A.S., Middleton, N.J., 2006. Desert Dust in the Global System. Springer, Berlin, Heidelberg, New York, 287pp.

Grousset, F.E., Ginoux, P., Bory, A., Biscaye, P.E., 2003. Case study of a Chinese dust plume reaching the French Alps. Geophysical Research Letters 30 (6), 1277.

Guerzoni, S., Chester, R., 1996. The Impact of Desert Dust Across the Mediterranean. Kluwer Academic Publisher, Dordrecht, Boston, 389pp.

Guerzoni, S., Quarantotto, G., Cesari, G., Molinaroli, E., Rampazzo, G., Le Bolloch, O., 1996. Trace metal composition and grain size of particulates in aerosols and precipitation collected in NW Mediterranean (39°N, 9°E) a multivariate analysis. In: Guerzoni, S., Chester, R. (Eds.), The Impact of Desert Dust Across the Mediterranean. Kluwer Academic Publishers, Dordrecht, pp. 333–338.

Guerzoni, S., Molinaroli, E., Chester, R., 1997. Saharan dust inputs to the western Mediterranean Sea: depositional patterns, geochemistry and sedimentological implications. Deep-Sea Research Part II: Topical Studies in Oceanography 44 (3–4), 631–654.

Guerzoni, S., Chester, R., Dulac, F., Herut, B., Loye-Pilot, M.-D., Measures, C., Migon, C., Molinaroli, E., Moulin, C., Rossini, P., Saydam, C., Soudine, A., Ziveri, P., 1999. The role of atmospheric deposition in the biogeochemistry of the Mediterranean Sea. Progress in Oceanography 44 (1–3), 147–190.

Haase, D., et al., 2007. Loess in Europe—its spatial distribution based on a European Loess Map, scale 1:2,500,000. Quaternary Science Reviews 26 (9–10), 1301–1312.

Holz, C., Stuut, J.-B.W., Henrich, R., 2004. Terrigenous sedimentation processes along the continental margin off NW-Africa: implications from grain-size analyses of surface sediments. Sedimentology 51 (5), 1145–1154.

Husar, R.B., Prospero, J.M., Stowe, L.L., 1997. Characterization of tropospheric aerosols over the oceans with the NOAA advanced very high resolution radiometer optical thickness operational product. Journal of Geophysical Research 102 (D14), 16,889–816,909.

Husar, R.B., Husar, J.D., Martin, L., 2000. Distribution of continental surface aerosol extinction based on visual range data. Atmospheric Environment 34 (29–30), 5067–5078.

Jackson, M.L., Clayton, R.N., Violante, A., Violante, P., 1982. Eolian influence on terra rossa soils of Italy traced by quartz oxygen isotopic ratio. In: Proceedings of the Seventh International Clay Conference, 1981, Bologna-Pavia, Italy, pp. 293–301.

Kalu, A.E., 1979. The African dust plume: its characteristics and propagation across West Africa in winter. SCOPE 14, 95–118.

Kellogg, C.A., Griffin, D.W., 2006. Aerobiology and the global transport of desert dust. Trends in Ecology and Evolution 21 (11), 638–644.

Koopmann, B., 1979. Saharastaub in den sedimenten des subtropisch-tropischen Nordatlantic während der letzten 20.000 JahreMathematisch-Naturwissenschaftlichen Fakultät. Christian-Albrechts-Universität, Kiel.

Koren, I., Kaufman, Y.J., Washington, R., Todd, M.C., Rudich, Y., Vanderlei Martins, J., Rosenfeld, D., 2006. The Bodélé depression: a single spot in the Sahara that provides most of the mineral dust to the Amazon forest. Environmental Research Letters 1, 5.

Leinen, M., Sarnthein, M., 1989. Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport. NATO Advanced Science Institutes Series, Series C: Mathematical and Physical Sciences, vol. 282. Kluwer Academic Publishers, Dordrecht/Boston/London, 909pp.

Littmann, T., 1991. Dust storm frequency in Asia: climatic control and variability. International Journal of Climatology 11, 292–412.

Littmann, T., Steinrücke, J., 1989. Atmospheric boundary conditions of recent Saharan dust influx into Central Europe. GeoJournal 18 (4), 399–406.

Livingstone, I., Warren, A., 1996. Aeolian Geomorphology: An Introduction. Longman, London, 211pp.

Loÿe-Pilot, M.D., Martin, J.M., Morelli, J., 1986. Influence of Saharan dust on the rain acidity and atmospheric input to the Mediterranean. Nature 321 (6068), 427–428.

Macleod, D.A., 1980. The origin of the red Mediterranean soils in Epirus. Greece European Journal of Soil Science 31 (1), 125–136.

Mahowald, N.M., Baker, A.R., Bergametti, G., Brooks, N., Duce, R.A., Jickells, T.D., Kubilay, N., Prospero, J.M., Tegen, I., 2005. Atmospheric global dust cycle and iron inputs to the ocean. Global Biogeochemical Cycles 19 (GB4025).

Markovic, S.B., Oches, E., Sumegi, P., Jovanovic, M., Gaudenyi, T., 2006. An introduction to the Middle and Upper Pleistocene loess—paleosol sequence at Ruma brickyard, Vojvodina, Serbia. Quaternary International 149 (1), 80–86.

Martin, J.-M., Elbaz-Poulichet, F., Guieu, C., Loye-Pilot, M.-D., Han, G., 1989. River versus atmospheric input of material to the Mediterranean Sea: an overview. Marine Chemistry 28 (1–3), 159–182.

McTainsh, G.H., 1985. Dust processes in Australia and West Africa: a comparison. Search 16 (3–4), 104–106.

McTainsh, G.H., Walker, P.H., 1982. Nature and distribution of Harmattan dust Zeitschrift für. Geomorphologie 26 (4), 417–435.

Menéndez, I., Diaz-Hernandez, J.L., Mangas, J., Alonso, I., Sanchez-Soto, P.J., 2007. Airborne dust accumulation and soil development in the North-East sector of Gran Canaria (Canary Islands, Spain). Journal of Arid Environments 71 (1), 57–81.

Middleton, N.J., 1986. The geography of dust storms. D.Phil. Thesis, University of Oxford, UK.

Middleton, N.J., Goudie, A.S., 2001. Saharan dust: sources and trajectories. Transactions of the Institute of British Geographers 26 (2), 165–181.

Molinaroli, E., 1996. Mineralogical characterisation of Saharan dust with a view to its final destination in Mediterranean sediments. In: Guerzoni, S., Chester, R. (Eds.), The Impact of Desert Dust Across the Mediterranean. Kluwer, Rotterdam, pp. 153–162.

Molinaroli, E., Guerzoni, S., Rampazzo, G., 1993. Contribution of Saharan dust to the Central Mediterranean Basin. Geological Society of America Special Paper 284, 303–312.

Mona, L., Amodeo, A., Pandolfi, M., Pappalardo, G., 2006. Saharan dust intrusions in the Mediterranean area: three years of Raman lidar measurements. Journal of Geophysical Research 111 (D16203), 13.

Morales, C., 1979. Saharan Dust, Mobilization, Transport, deposition-SCOPE, 14. Wiley, Chichester, New York, Brisbane, Toronto, 320pp.

Moreno, T., Querol, X., Castillo, S., Alastuey, A., Cuevas, E., Herrmann, L., Mounkaila, M., Elvira, J., Gibbons, W., 2006. Geochemical variations in aeolian mineral particles from the Sahara–Sahel. Dust Corridor Chemosphere 65 (2), 261–270.

Moss, A.J., Green, P., 1975. Sand and silt grains: Predetermination of their formation and properties by microfractures in quartz Australian Journal of Earth Sciences 22 (4), 485–495.

Moulin, C., Guillard, F., Dulac, F., Lambert, C.E., 1997. Long-term daily monitoring of Saharan dust load over ocean using Meteosat ISCCP-B2 data 1. Methodology and preliminary results for 1983–1994 in the Mediterranean. Journal of Geophysical Research 102 (D14), 16,947–916,958.

Nihlén, T., Mattsson, J.O., 1989. Studies on eolian dust in Greece. Geografiska Annaler 71A (3–4), 269–274.

Passerini, N., 1902. Sopra ‘‘pioggia di sangue’’ dei 10 marzo 1901 (On the ‘‘rain of blood’’ of 10 March 1901). Bollettino Della Società Meteorologica Italiana 22 (2), 73–74.

Pérez-Marrero, J., Llinás, O., Maroto, L., Rueda, M.J., Cianca, A., 2002. Saharan dust storms over the Canary Islands during winter 1998 as depicted from the advanced very high-resolution radiometer. Deep-Sea Research Part II: Topical Studies in Oceanography 49 (17), 3465–3479.

Péwé, T.L., 1984. Desert Dust: Origin, Characteristics, and Effect on Man, Special Paper, 186. The Geological Society of America, Boulder, 303pp.

Pitty, A.F., 1968. Particle size of the Saharan dust which fell in Britain in July 1968. Nature 220, 364–365.

Prodi, F., Fea, G., 1979. A case of transport and deposition of Saharan dust over the Italian peninsula and southern. Europe Journal of Geophysical Research 84 (C11), 6951–6960.

Prospero, J.M., Bonatti, E., Schubert, C., Carlson, T.N., 1970. Dust in the Caribbean atmosphere traced to an African dust storm. Earth and Planetary Science Letters 9 (3), 287–293.

Prospero, J.M., Ginoux, P., Torres, O., Nicholson, S.E., Gill, T.E., 2002. Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 total ozone mapping spectrometer (TOMS) absorbing aerosol product. Reviews of Geophysics 40 (1), 1–31.

Pye, K., 1992. Aeolian dust transport and deposition over Crete and adjacent parts of the Mediterranean Sea. Earth Surface Processes and Landforms 17, 271–288.

Rapp, A., 1984. Are terra rossa soils in Europe eolian deposits from Africa? Geol. Foren. i Stockholm Forhanl. 105, 161–168.

Rapp, A., Nihlén, T., 1991. Desert dust-storms and Loess deposits in North Africa and South Europe. Catena 20 (Suppl.), 43–55.

Reiff, J., Forbes, G.S., Spieksma, F.T.M., Reynders, J.J., 1986. African dust reaching Northwestern Europe: a case study to verify trajectory calculations. Journal of Applied Meteorology 25 (11), 1543–1567.

Ricq de Bouard, M., Thomas, A., 1972. La Météorologie (Paris) 24, 65–83.

Rodá, F., Bellot, J., Avila, A., Escarré, A., Piñol, J., Terradas, J., 1993. Saharan dust and the atmospheric inputs of elements and alkalinity to Mediterranean ecosystems. Water, Air, & Soil Pollution 66 (3), 277–288.

Rodriguez, S., Querol, X., Alastuey, A., Kallos, G., Kakaliagou, O., 2001. Saharan dust contributions to PM10 and TSP levels in Southern and Eastern Spain. Atmospheric Environment 35 (14), 2433–2447.

Rognon, P., Coude-Gaussen, G., Revel, M., Grousset, F.E., Pedemay, P., 1996. Holocene Saharan dust deposition on the Cape Verde Islands: sedimentological and Nd–Sr isotopic evidence. Sedimentology 43 (2), 359–366.

Rogora, M., Mosello, R., Marchetto, A., 2004. Long-term trends in the chemistry of atmospheric deposition in Northwestern Italy: the role of increasing Saharan dust deposition. Tellus B 56 (5), 426–434.

Rousseau, D.-D., Derbyshire, E., Antoine, P., Hatté, C., 2007. Loess Records: Europe. In: Elias, S. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Amsterdam, pp. 1440–1456.

Smalley, I.J., 1966. The properties of glacial loess and the formation of loess deposits. Journal of Sedimentary Petrology 36, 669–676.

Smalley, I.J., 1970. Cohesion of soil particles and the intrinsic resistance of simple soil systems to wind erosion. European Journal of Soil Science 21 (1), 154–161.

Smalley, I.J., Vita-Finzi, C., 1968. The formation of fine particles in sandy deserts and the nature of 'desert' loess. Journal of Sedimentary Petrology 38, 766–774.

Smalley, I.J., Kumar, R., O'Hara-Dhand, K., Jefferson, I.F., Evans, R.D., 2005. The formation of silt material for terrestrial sediments; particularly loess and dust. Sedimentary Geology 179, 321–328.

Stevenson, C.M., 1969. The dust fall and severe storms of July 1, 1968. Weather 24, 126–132.

Stuut, J.-B.W., Zabel, M., Ratmeyer, V., Helmke, P., Schefuß, E., Lavik, G., Schneider, R.R., 2005. Provenance of present-day eolian dust collected off NW Africa. Journal of Geophysical Research 110 (D04202), 14.

Stuntz, S.C., Free, E.E., 1911. Bibliography of Eolian Geology. Appended to US Department of Agriculture Bureau of Soils Bulletin 68. Republished as The First Great Loess Bibliography: Stuntz & Free Republished 1911–1991. Leicester Univ. Geogr. Dept. Occ. Paper 19.

Swap, R., Ulanski, S., Cobbett, M., Garstrang, M., 1996. Temporal and spatial characteristics of Saharan dust outbreaks. Journal of Geophysical Research 101 (D2), 4205–4220.

Tomadin, L., Lenaz, R., 1989. Eolian dust over the Mediterranean and their contribution to the present sedimentation. In: Leinen, M., Sarnthein, M. (Eds.), Palaeoclimatology and Palaeometeorology: Modern and Past Patterns of Global Atmospheric Transport (NATO ASI Series. Series C, vol. 282). Kluwer Academic Publishers, Dordrecht, pp. 267–282.

Tomadin, L., Cesari, G., Fuzzi, S., Landuzzi, V., Lenaz, R., Lobietti, A., Mandrioli, P., Mariotti, M., Mazzucotelli, A., Vannucci, R., 1989. Eolian dust collected in springtime (1979 and 1984 years) at the seawater–air interface of the Northern Red Sea. In: Leinen, M., Sarnthein, M. (Eds.), Palaeoclimatology and Palaeometeorology: Modern and Past Patterns of Global Atmospheric Transport. Kluwer Academic Publishers, Dordrecht, pp. 283–310.

Torres-Padrón, M.E., Gelado-Caballero, M.D., Collado-Sánchez, C., Siruela-Matos, V.F., Cardona-Castellano, P.J., Hernández-Brito, J.J., 2002. Variability of dust inputs to the CANIGO zone. Deep-Sea Research Part II: Topical Studies in Oceanography 49 (17), 3455–3464.

Tullet, M.T., 1978. A dust-fall on 6 March 1977. Weather 33, 48–52.

Weltje, G.J., Prins, M.A., 2003. Muddled or mixed? Inferring palaeoclimate from size distributions of deep-sea clastics. Sedimentary Geology 162 (1), 39–62.

Westphal, D.L., Toon, O.B., Carlson, T.N., 1988. A case study of mobilization and transport of Saharan dust. Journal of the Atmospheric Sciences 45 (15), 2145–2175.

Wheeler, D.A., 1986. The meteorological background to the fall of Saharan dust, November 1984. Meteorological Magazine 115 (1362), 1–9.

Wright, J.S., 2001. 'Desert' loess versus 'glacial' loess; quartz silt formation, source areas and sediment pathways in the formation of loess deposits. Geomorphology 36 (3–4), 231–256.

Yaalon, D.H., Ganor, E., 1973. The influence of dust on soils during the Quaternary. Soil Science 116 (3), 146–155.