Per. Mineral. (2005), *74*, 2, 103-116

http://go.to/permin

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY, ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on *Environment, Archaeometry* and *Cultural Heritage*

Aeolian dust falls in northern Italy in autumn 1996: chemical and mineralogical comparison

PIERRE OZER[1] and GABRIELLA LUCCHETTI[2]

[1] Liege University, Environmental Sciences and Management Department 185, Avenue de Longwy, B-6700 Arlon, Belgium
[2] Università di Genova, Dipartimento per lo Studio del Territorio e delle sue Risorse (DIPTERIS) 26, Corso Europa, I-16132 Genova, Italy

Submitted, June 2004 - Accepted, November 2004

ABSTRACT. — This paper describes two dust fall events in Genoa and Turin (northern Italy) on 12 November 1996 and 7 December 1996 respectively. Meteorological data suggest that the dust-bearing rain that fell on Genoa originated in north-eastern Morocco, where dust mobilisation was reported two days earlier, and had been carried straight to the north-western Italian coast by very strong winds. But the dust fall observed in Turin was not characterised by any specific synoptic situation inducing dust transport from the southern Mediterranean. The analyses include a quantitative and a qualitative study of two dust samples collected in downtown Genoa and Turin. The total amounts of dust that fell give two very high values of 4.05 g m^{-2} for Genoa and 0.54 g m^{-2} for Turin. The median sizes of the dust particles were 14.6 μm and 25.8 μm respectively. Most of the dust material collected in Genoa showed a yellowish-brown to red colour due to surface weathering by ferric hydroxides, and was sometimes coated with clayey particles. This attests to the Saharan origin of the particles. On the contrary, only 15% of the material sampled in Turin was coated with red-like clayey material from the desert. A large part of the sample was covered with a carbon-like substance. In addition, the proportion of organic matter (pollen grains and seeds) and anthropogenic fibrous material was much higher. This suggests that the dust fall observed in Turin very likely originated from local pollution mixed with a low proportion of long-distance Saharan dust.

RIASSUNTO. — In questo lavoro vengono analizzati due eventi di pioggia con polveri verificatisi nel Nord Italia (Genova e Torino) rispettivamente il 12 novembre e il 7 dicembre 1996. In base ai dati metereologici la polvere caduta a Genova avrebbe avuto origine nel Marocco nord orientale, dove è stata riconosciuta una mobilizzazione di polveri avvenuta due giorni prima, mentre per la polvere caduta a Torino non vi sono indicazioni di condizioni che possano aver causato trasporto di polveri dal Mediterraneo meridionale. Le analisi condotte su materiale campionato nelle due città evidenziano una differente dimensione media delle particelle: 14,6 μm and 25,8 μm rispettivamente per la polvere raccolta a Genova e per quella raccolta a Torino. La maggior parte del materiale raccolto a Genova presenta una colorazione da giallo-bruna a rossa, per alterazione superficiale dovuta alla presenza di idrossidi di ferro, ed è talvolta ricoperto da particelle argillose; questo fatto testimonia l'origine sahariana di questa polvere. Al contrario, solo il 15% del materiale raccolto a Torino presenta queste caratteristiche, mentre una gran parte è ricoperta da sostanza carboniosa ed è molto maggiore la proporzione di materia organica (granuli di polline e semi) e di fibre antropogeniche; ne consegue che la polvere caduta a

---

* E-mail: pozer@ulg.ac.be and lucchett@dipteris.unige.it

Torino è probabilmente originata da inquinamento locale con una bassa percentuale di polveri provenienti dal Sahara.

KEY WORDS: *Saharan dust, dust fall, long-range transport, chemistry, mineralogy, northern Italy.*

1. INTRODUCTION

Arid regions in North and West Africa contribute to the aeolian dust input of a large part of the Northern Hemisphere, from the eastern Mediterranean westwards to the Atlantic coast of North America (Goudie and Middleton, 2001; Prospero and Lamb, 2003, Washington *et al.*, 2003).

Atmospheric investigations based on meteorological data and remote sensing analysis have shown that Saharan outbreaks often travel several thousands of kilometres (Deuze *et al.*, 1988; Oliva *et al.*, 1983; Reiff *et al.*, 1986). The chemical and mineralogical dust composition and load of airborne dust over the Atlantic Ocean have been well documented from the Canary and the Cape Verde Islands (Bergametti *et al.*, 1989; Coudé-Gaussen *et al.*, 1987, 1994; Rognon *et al.*, 1996) to as far as Florida, Barbados and the Amazon Basin (Carder *et al.*, 1986; Glaccum and Prospero, 1980; Prospero *et al.*, 1981, 1987; Swap *et al.*, 1992).

Similar work has been done in the Mediterranean on transport northwards through Europe (Chester *et al.*, 1977, 1984; Ganor and Mamane, 1982; Nihlén and Olsson, 1995; Prodi and Fea, 1979; Sala *et al.*, 1996; Tomadin *et al.*, 1984), but Saharan dust can be carried for much longer distances passing over the Alps (De Angelis and Gaudichet, 1991; Wagenbach and Geis, 1989) and the Pyrenees (Dessens and Van Dinh, 1990) to reach Western Europe (Bücher, 1994; Bücher *et al.*, 1983; Coudé-Gaussen, 1991; Coudé-Gaussen *et al.*, 1988; Littmann, 1991) and even Scandinavia (Franzén *et al.*, 1994, 1995, Ansmann *et al.*, 2003).

Air quality deterioration caused by high concentrations of respirable African mineral dust has been reported in various regions as far away from the sources as the Canary Islands (Viana *et al.*, 2002), Spain (Rodriguez *et al.*, 2001, 2003), and the United Kingdom (Ryall *et al.*, 2002). Such particulate matter air pollution is a serious health threat in various regions of the world because it promotes respiratory infection, cardiovascular disease and other ailments (WHO, 2000; Griffin *et al.*, 2001a).

2. THE DUST FALLS OF 12 NOVEMBER 1996 IN GENOA AND 7 DECEMBER 1996 IN TURIN

On 13 November 1996, a brownish-yellow coloured dust was observed on cars in the Province of Genoa after a very low rainfall. The phenomenon, which occurred in two successive phases (late afternoon of Nov. 12 and early morning of Nov. 13), was reported in the regional daily newspapers. A few weeks later, on 7 December 1966, another dust fall event was noticed in the Turin area.

These muddy rains are not uncommon. They can occur several times a year (Table 1) and have become more frequent since the early 1980s (Bücher, 1994; De Angelis and Gaudichet, 1991; Dessens and Van Dinh, 1990). The reason for presenting this study of the dust samples collected in downtown Genoa on 13 November 1996 and in Turin on December 7 1996 is the very low probability of a dust fall over Europe (less than 8%) from November to February (Dessens and Van Dinh, 1990). This observation has been confirmed by De Angelis and Gaudichet (1991), when analysing ice cores from Mont Blanc (French Alps), who found high dust peaks during the spring that contrasted sharply with extended concentration minima in winter. Moreover, Littmann (1991), studying 92 deposition cases in West Germany, did not present any Saharan dust fall events for the 20 November to 15 December period. Using the daily satellite data from the Total Ozone Mapping Spectrometer (TOMS), Middleton and Goudie (2001) showed that, during 1999, Saharan dust penetrated the troposphere over the

TABLE 1

Occurrence of dust falls over Europe according to various authors.

Area	Events	Time period	Authors
Europe	7.7 y^{-1}	10 years (1980-1989)	Bücher, 1994
Spain (Elche)	2.2 y^{-1}	46 years (1949-1994)	Sala *et al.*, 1996
Spain (Elche)	8.4 y^{-1}	5 years (1990-1994)	Sala *et al.*, 1996
Alps	3.4 y^{-1}	10 years (1967-1977)	Prodi and Fea, 1978
French Pyrenees	9.1 y^{-1}	7 years (1983-1989)	Dessens and Van Dinh, 1990
West Germany	5.7 y^{-1}	19 months (Oct. 1987-Apr. 1989)	Littmann, 1991
British Isles	1 y^{-1}	10 years (1977-1986)	File, 1986
British Isles	1.8 y^{-1}	10 years (1981-1990)	Burt, 1991
British Isles (Dover)	4 y^{-1}	2 years (1991-1992)	Thomas, 1993
British Isles	1.4 y^{-1}	21 years (1981-2000)	Goudie and Middleton, 2001

Mediterranean on more than 60% of days from March to September, with Mediterranean dust outbreaks recorded on 100% of days in June and August. The least active months for the whole Mediterranean were November and December which had less than 15% of days with dusty material over some part of the area.

3. THE METEOROLOGICAL SITUATION

The meteorological situation has been studied for the period 10-13 November 1996 thanks to the European Meteorological Bulletin. During the days preceding the dust fall in Genoa, a low pressure area moved slowly from 60°N, 30°W (10 Nov., 00 GMT) southwards to the Portuguese coast (12 Nov., 00 GMT) while a high pressure area remained relatively stable over Turkey. These synoptic conditions produced some very strong surface winds in north-eastern Morocco as well as in north-western Algeria and, on 11 and 12 November at 12 GMT, dust storms were reported in this area (30-33°N, 0-5°W). The trajectory of this North African dust was almost straight, carried by south-westerly winds and ending in Genoa. The analysis of the synoptic maps at 850mbar shows the perfect concordance between the dust source (Morocco-Algeria) and the transit through the Ligurian Gulf, where the winds converged (Ozer *et al.*, 1998). Low-level clouds generated the two very low rainfalls, which washed the Saharan dust out of the sky above Genoa.

The same type of analysis has been made for the dust fall in Turin. Surprisingly, no specific synoptic situation inducing dust transport from the southern Mediterranean was detected.

4. SAMPLING AND LABORATORY PROCEDURE

Two dust samples were collected from a 50 × 25 cm area of the bodies of two cars parked in downtown Genoa and Turin on the day of the event. We made sure that the cars were clean before the dust-bearing rain fell and that the cars had not been driven since the rain. The dust was carefully collected with a paintbrush. Several measurements were made in the laboratory:

- Estimation of dust fall rate per m^2;
- Grain size;
- Mineral composition;
- Chemical composition.

5. DUST AMOUNTS

The quantity of dust deposited per m^2 was calculated knowing the amount of sediment on the 0.125 m^2 surface. The total amount of dust collected in Genoa on the 13 November 1996 gave a very high value of 4.05 g m^{-2}. This concentration is quite exceptional for a single event and can sometimes represent a high proportion (up to 70%) of the total annual dust deposition (Le Bolloch *et al.*, 1996). In fact, the value measured in Genoa was almost five times greater than the quantity deposited in Bologna in 1977, which was 0.833 g m^{-2}, as measured by Prodi and Fea (1979). But higher dust deposits have been recorded as, for example, in south-western France with 8 g m^{-2} in February 1972 (Bücher and Lucas, 1972) and 6 g m^{-2} in July 1983 (Bücher and Lucas, 1984). On the other hand, the gross quantity of dust brought down in Turin was 0.54 g m^{-2}.

It would be hazardous for us to estimate the yearly dust deposition in the Ligurian area because of the poor data available on this topic for Europe. Indeed, all direct measurements concern relatively short periods (from 2 to 11 years) and have only been carried out in the Mediterranean islands. Moreover, these studies only started when several researchers (e.g. Dessens and Van Dinh, 1990) pointed out the drastic increase in dust outbreaks over Europe to the scientific community. Therefore, the short-term data presented in Table 2 could be overestimated and might be reviewed downwards after longer recordings if this last decade is recognised as an epiphenomenon.

For this reason, the comparison with the values of African dust found in ice cores drilled in the Alps will not be possible. Nevertheless, as shown in Table 2, the highest yearly dust deposition has been measured in the Eastern Mediterranean where the average value is 21 g m^{-2} in Crete (Nihlén and Olsson, 1995), while the different measurements give values ranging from 1 to 12 g m^{-2} in the Western Mediterranean (Le Bolloch and Guerzoni, 1995; Le Bolloch *et al.*, 1996; Guerzoni and Molinaroli, 1997) and between 0.4 to 1 g m^{-2} in the Alps (Wagenbach and Geis, 1989; De Angelis and Gaudichet, 1991).

6. GRAIN SIZE OF THE DUST

The volume size distribution of the dust was carried out using the Coulter Counter Technique with an orifice tubing of 140 µm. A grain size comparison of the two samples is presented (SEM micrographs) in Figure 1.

In Genoa, the two consecutive dust falls were mainly composed of silts with no sand content; the particle size ranged from <1 to 64 µm and presented a median value of 14.6 µm (Fig. 2) which is to be considered as a very high value

TABLE 2

Yearly dust deposition in Europe according to various authors.

Area	Yearly dust deposition	Time period	Authors
Aegean Area	21 (11.2-36.5) g m^{-2}	5 years (1988-1992)	Nihlén and Olsson, 1995
Western Sardinia	0.7-2 g m^{-2}	2 years (1992-1994)	Le Bolloch and Guerzoni, 1995
Southern Sardinia	6-13 g m^{-2}	5 years (1990-1995)	Le Bolloch *et al.*, 1996
Central Corsica	12 (5-25) g m^{-2}	11 years (1984-1994)	Guerzoni and Molinaroli, 1997
French Alps	1 g m^{-2}	31 years (1955-1985)	De Angelis and Gaudichet, 1991
Swiss Alps	0.4 g m^{-2}	47 years (1936-1982)	Wagenbach and Geis, 1989

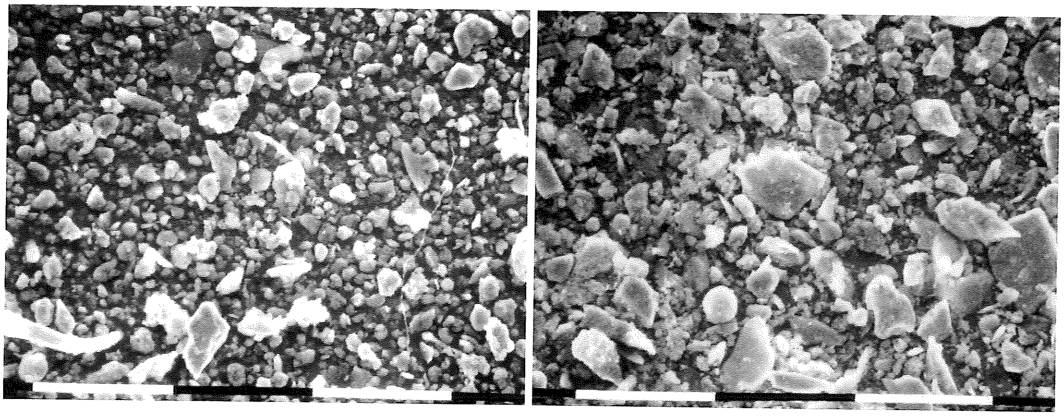

Fig. 1 – SEM micrographs of the dust fall in Genoa (left) and Turin (right), scale = 100 µm.

when compared to other analyses available in the literature (Table 3) which range from 2.2 to 20 µm.

In Turin, the dust collected, mostly composed of silts with very low sand content (particle sizes ranging from <1 to 88 µm), presented a very high median value of 25.8 µm (Fig. 2).

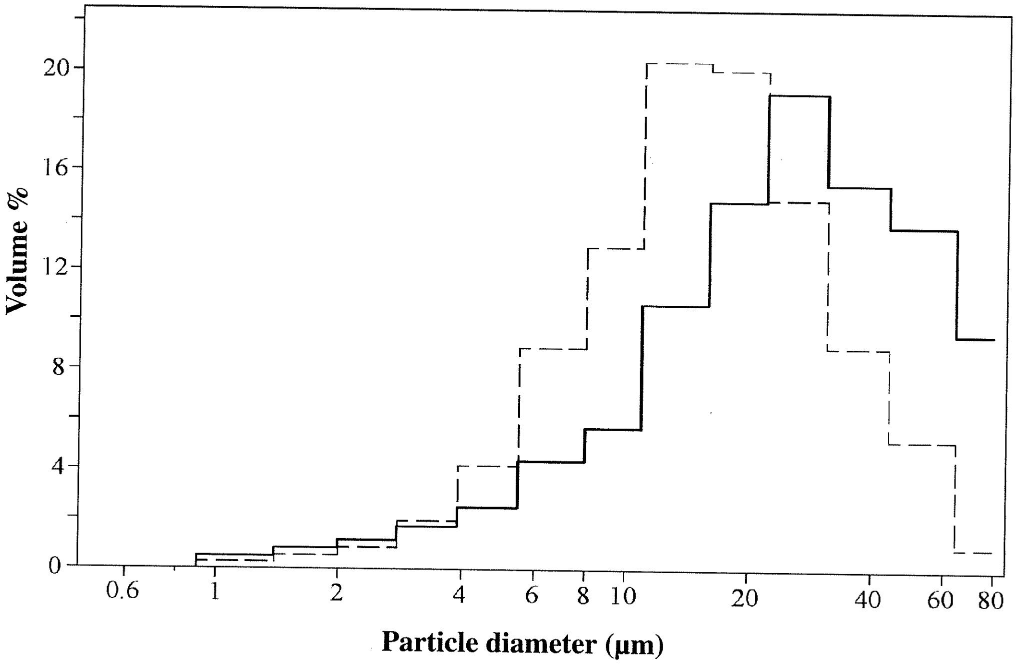

Fig. 2 – Size distribution, as a percentage of volume, of the dust collected in Genoa (broken line) and Turin (solid line).

TABLE 3

Median size of dust fall grains over Europe according to various authors.

Area	Median size	Observations	Authors
Europe	4-12 µm	77 (1980-1989)	Bücher, 1994
France	8-20 µm	4 (1981-1988)	Coudé-Gaussen, 1991
French Pyrenees	8 µm	1 (16 October 1988)	Dessens and Van Dinh, 1990
Aegean Area	8 µm	? (1988-1992)	Nihlén and Olsson, 1995
Swiss Alps	4.5 ± 1.5 µm	? (1936-1982)	Wagenbach and Geis, 1989
British Isles	10 µm	1 (9 November 1986)	File, 1986
Britain	9 µm	1 (July 1968)	Pitty, 1968
West Germany	2.2-16 µm	9 (Oct. 1987-Apr. 1989)	Littmann, 1991
Swedish west coast	2.6 µm	1 (29 October 1987)	Franzén, 1989

7. MINERAL COMPOSITION OF THE DUST

A sampling of about 6000 grains from both dust falls was examined under an optical microscope; the examination was made under polarised light and phase contrast with immersion in water and in a liquid of known refractive index (n = 1.54).

7.1. Genoa

The particles were very inhomogeneous and were grouped as follow:

1 – Grains ranging from 2 to 40 µm, rarely larger, represented more than 90% of the dust material. They generally showed a yellowish-brown to red colour due to surface weathering by ferric hydroxides. They were sometimes coated with clayey particles.

The principal mineral phases were:

1.a – Very rounded and spherical grains, composed of highly-weathered mineral phases or by clayey aggregates; they showed a marked red pigmentation.

1.b – Very rounded quartz grains that were coated (Fig. 3.c); also a few quartz grains poorly pigmented and showing sharp angles.

1.c – Very rounded feldspar grains with low pigmentation (Fig. 3.a).

1.d – Rounded calcite grains of brownish coloration, with a lightly corroded surface and a turbid aspect (Fig. 3.a).

Minor mineral phases components were:

1.e – Amphibole grains (± 1%) of highly variable dimensions: width ranging from 2 to 40 µm and length from 8 to 200 µm. The degree of weathering was very inhomogeneous and most grains showed a corroded surface, sometimes strongly pigmented.

1.f – Pyroxene grains, less common than the amphiboles and with smaller dimensions: width ranging from 2 to 20 µm and length from 3 to 50 µm with a weathering similar to that of the amphiboles.

1.g – Phyllosilicate grains (± 1%) of reddish-brown coloration; the mean flake diameter ranged from 10 to 40 µm. In most cases, these were partially weathered biotite or vermiculite derived from weathered biotite.

2 – Anthropogenic fibrous material (like Fig. 3.f):

a – synthetic fibres (about 2%);

b – glassy fibres (about 1%).

Most of these fibres were longer than 100 µm. Glassy fibres, especially, did not show any kind of weathering processes or important surface erosion.

3 – Aggregates of (bituminous?) organic

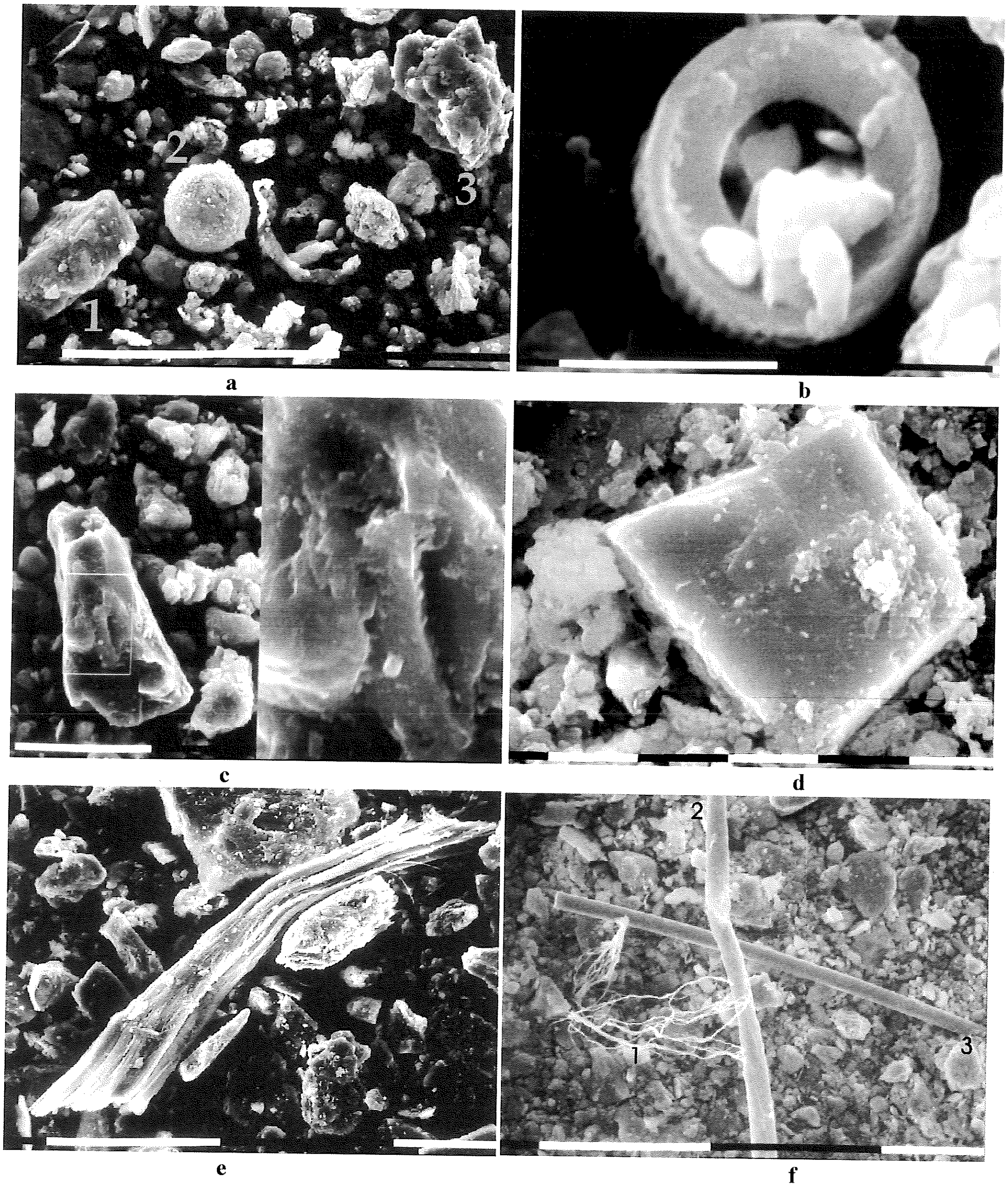

Fig. 3 – SEM micrographs showing some specific compounds of the dust fall in Genoa [GE] and Turin [TU].
(a) Typical rounded desertic material: 1: Calcite, 2: K-feldspar, 3: Quartz, GE, scale = 100 μm; (b) Unknown form of diatom, Si, GE, scale = 10 μm; (c) Highly rounded quartz silt grain, GE, scale = 50 μm, zoom (x 4.3) on the impact features; (d) Angular quartz silt grain, TU, scale = 10 μm; (e) Clinochrysotile, TU, scale = 100 μm; (f) Some fibres: 1: synthetic, 2: organic, 3: glassy, TU, scale = 100 μm.

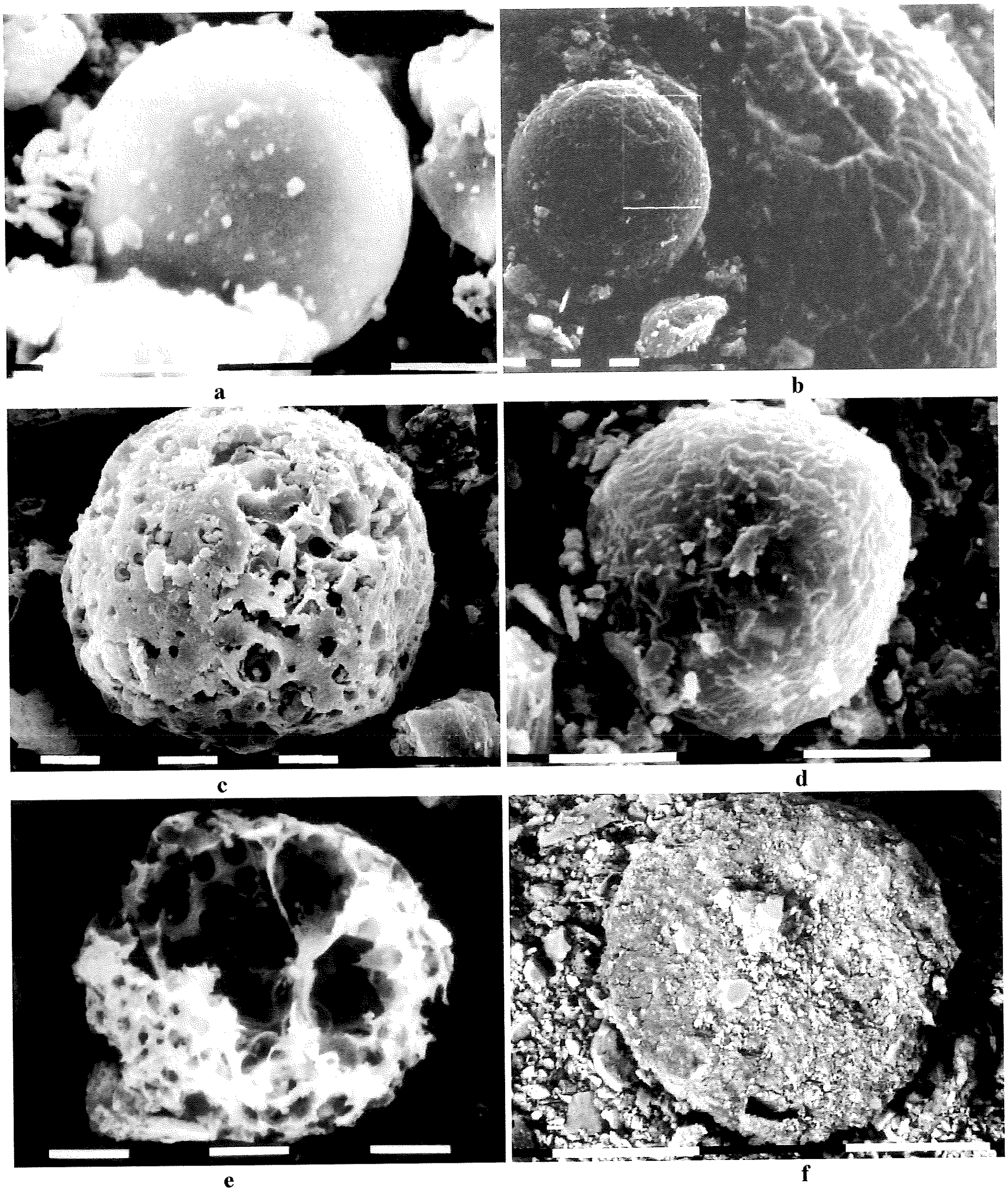

Fig. 4 – SEM micrographs showing some unknown or anthropogenic compounds of the dust fall in Turin.
(a) Perfectly spherical and smooth particle common to all samples with unknown origin (fly-ash ? according to Coudé-Gaussen, 1991, p. 93), [Si,Al,Ca,Fe,K,Ti], scale = 10 µm; (b) Spherical particle of titanium probably industrial emission, scale = 5 µm, zoom (x 3.8) on the relatively rough surface; (c) Soot particle, scale = 10 µm; (d) Type of spherule, probably industrial emission, [Si,S,Fe,Ca,K,Al,Mg], scale = 10 µm; (e) fly-ash, [Si,Fe,Ca,Cl,Al,Ti], scale = 10 µm; (f) Very large flat spherical «framboide», [Si,Mg,Fe], scale = 100 µm.

compounds, often mixed with mineral granules, especially calcite.

4 – Grains which reached a size of 100 µm or more (± 2%) but without evidence of pedogenic weathering. They were mainly composed of:

a – Quartz with very little roundness and the absence of redness processes;

b – Calcite, often in relatively large polycrystalline grains.

5 – Opaque organic grains with a size larger than 100 µm (± 3%), which were probably pitch.

6 – A few whole diatoms, always of the same dimension: 10 µm (Fig. 3.b).

7 – Finally, of particular interest was the presence of some perfectly spherical grains with an extremely smooth surface without traces of weathering: limpid, transparent, light yellow, isotropic and with a diameter ranging from 20 to 40 µm (like Fig. 4.a). The optical isotropy and low refractive index (< 1,54) suggested a glassy nature.

7.2. Turin

The mineral composition of the dust collected in Turin was:

- Quartz, slightly predominant;
- Feldspar;
- Biotite, fresh;
- Pyroxene, poorly elaborated;
- Amphibole (up to 2 mm long);
- Epidote, very scarce;
- Clinochrysotile fibres, very scarce.

Most of the particles were larger than those that fell on Genoa, ranging from 10 to 200 µm, and coarser (e.g. Quartz, Fig. 3.d). The proportion of asbestos fibres (amphibole + chrysotile, Fig. 3.e) reached 2‰. Only 15% of the particles were coated with red clayey material. A large part of the sample was covered with a carbon-like substance that impeded the analysis of the particle surface. The proportion of organic matter (pollen grains and seeds) and anthropogenic fibrous material was also much higher. We also have to underline the frequent presence of spongy and highly porous particles (> 1%), with dimensions up to 100 µm which might be soot (Fig. 4.c and e), glassy spherules (± 2‰) with diameters up to 50 µm (Fig. 4.a), others types of spherules which probably came from industrial emissions (Fig. 4.b and d), and very large flat to spherical «framboide» aggregates.

8. CHEMICAL COMPOSITION OF THE DUST

DUST. The dust particles, gold-coated, were analysed with a scanning electron microscope (SEM). A semi-quantitative chemical analysis was obtained on four windows for each dust fall, on a specifically prepared sample presenting a high grain concentration as in Figure 1. The result of this analysis, which shows the percentage of the major elements contained in the muddy rains compared with literature data, is presented in Table 4.

The first observation of Table 4 leads to an obvious conclusion: the relative concentration of crustal elements, considered as characteristic of continental erosion (Al, Si, Na, K, Ca, Fe), is very different in the two samples. Indeed, the proportion of Fe_2O_3 and MgO is remarkably higher in Turin whereas CaO and Al_2O_3 are clearly less represented than in the sample collected in Genoa. This indicates that the dust sources are different.

SPHERULES. The chemical composition of the spherules found in the two samples was determined with a SEM, also measuring the dimension, because of the very poor literature relative to these spherical particles (Del Monte *et al.*, 1984).

The three spherules investigated in the dust collected in Genoa, which dimensions are 20, 30, and 40 µm, present a similar chemical composition. A representative composition is: SiO_2 57.30, Al_2O_3 28.80, Fe_2O_{3TOT} 5.96, Cr_2O_3 0.00, TiO_2 1.44, MgO 1.25, CaO 0.75, MnO 0.00, K_2O 5.20, Na_2O 0.40.

A deeper study was carried out on the sixty spherules collected in Turin. On the whole, five types can be distinguished and some representative compositions are presented in Table 5.

TABLE 4

Chemical composition: major elements of both dust falls in Genoa and Turin. Comparison with Coudé-Gaussen (1982) a dust falls over Italy and France from 1813 to 1926 (13 samples) and b dust falls over Europe (7 samples), c Bücher et al. (1983) on a dust outbreak in the Pyrenees in 1980 and d Nihlén and Olsson (1995) on four stations on Crete.

Sample	SiO_2	CaO	Al_2O_3	Fe_2O_3	K_2O	MgO	TiO_2	Na_2O	MnO	Total
Genoa	46.4	16.5	12.5	10.6	4.0	2.3	1.1	0.6	0.3	94.2
Turin	49.3	6.6	9	19.3	2.7	4.5	1.1	0.8	0.2	93.5
ITandFRa	45	13	10.4	5.7	1.9	2.5	1.9	0.9	0.7	82
EUROPE[b]	58	8.6	11	6	1.8	2.7	1.2	1.6	1.6	92.5
PYREN[c]	54.7	12.1	17.7	7.1	2.4	3.6	1	0.4	?	99
CRETE[d]	51.6	21.5	12.6	6.6	1.9	4.1	0.8	0.6	0.1	99.8

TABLE 5

Major element composition of some analysed spherules found in the Turin dust sample.

	Type I					Type III	Type V	
	Si,Al,Fe	Si,Al,K	Si,Al,Ti	Si,Ca,Al	Si,Al,K	Iron	Copper	Titanium
Na_2O	0.15	0.38	-	0.09	-	0.14	-	-
MgO	1.08	1.73	0.90	6.72	1.24	0.28	-	-
Al_2O_3	33.50	35.57	24.85	17.38	28.99	0.40	-	3.63
SiO_2	55.68	55.68	46.49	34.91	55.74	1.59	0.52	1.10
S	0.41	-	-	-	-	-	-	-
Cl	0.33	-	-	-	-	-	-	-
K_2O	2.71	3.85	2.87	5.34	6.10	0.08	0.08	-
CaO	0.69	0.59	5.73	22.51	0.73	0.34	0.24	0.28
TiO_2	1.12	0.30	12.11	1.93	1.40	0.17	0.15	94.39
Cr_2O_3	-	-	-	0.30	-	0.16	0.09	0.05
MnO	-	-	-	0.94	-	0.21	0.05	-
Fe_2O_{3TOT}	3.64	1.90	7.05	9.89	5.79	96.63	0.59	0.53
CuO	-	-	-	-	-	-	98.28	0.02

– Type I (30% of the spherules): these have a glassy nature with Si, Fe and Al as the main constituents and Ca, S, K, Ti, Mn or Mg in variable amounts (Table 5); they are perfectly smooth. Their diameter ranges from 4 to 40 µm, the median size is 14 µm.

– Type II (25% of the spherules): these are glassy and similar in composition to those found in Genoa: [Si, Al, Fe, Ca, Mg, K Na, Ti]; they are perfectly smooth with a diameter ranging from 2 to 50 µm, the median size is 10 µm (Fig. 4.a).

– Type III (25% of the spherules): their main component is iron (Fe_2O_{3TOT}>95%) and they are perfectly smooth. Their diameter ranges from 2 to 30 μm, the median size is 10 μm (Table 5).

– Type IV (10% of the spherules): these have a complex and variable composition with Si, S, Fe, Ca, K, Al, Mg as major constituents; they show a relatively rough surface. Their diameter ranges from 20 to 30 μm and their median size is 23 μm (Fig. 4.d).

– Type V (10% of the spherules): these have a chemical composition characterized by one (Ti, Fig. 4.b, or Cu) (Table 5) or a few (Ti, Ca; Cl, Fe; Fe, Ca; Si, S) elements as major constituents. Their surface is slightly rough. Their diameter ranges from 8 to 25 μm, the median size is 18 μm.

Ba traces were observed in Types I, IV, V.

9. DISCUSSION

Coudé-Gaussen (1982) underlines the evident affinity between the mean chemical compositions of the Saharan dust collected over Europe, which, indeed, fits well with the data found by Bücher *et al.* (1983) in the Pyrenees, while the analyses made by Nihlén and Olsson (1995) in Crete are quite different, probably because of the different dust sources (essentially southern Tunisia) affecting the Eastern Mediterranean. The comparison of the Western European measurements with the Genoa and Turin samples shows an important difference in the proportion of Fe_2O_3, which is two to three times higher in Genoa and Turin respectively. The iron oxides encrusting the grains surface and the analytical method likely account for the relatively large Fe_2O_3 over-estimation. The ratio of K_2O in Genoa is also more than two times greater than the European mean, whereas the proportion of MnO remains very low in both samples.

Some of the mineral grains show a yellowish-brown to red colour due to ferric hydroxides on the weathered surfaces, and are sometimes corroded or coated with clayey particles. The weathering well accords with long-lasting, sub-aerial exposure to warm, arid conditions, and a Saharan origin. In Genoa these grains represented more than 90%, in Turin only 15%.

In Genoa, the grain size distribution is unimodal, which proves, according to Littmann (1991), that the dust came from a single source. Moreover, a significant number of particles considered of Saharan origin had a size larger than 30 μm (Fig. 4c). If the presence of large-sized grains is not uncommon (Coudé-Gaussen, 1991), such dimensions are incompatible with classical physico-mathematical models. In fact, Tomadin *et al.* (1984) estimated that, under normal conditions, significant quantities of particles > 16 μm are usually deposited during the first thousand kilometres of transport. As a consequence, the median size of the samples analysed attests to very turbulent wind conditions able to maintain quite large particles in suspension in the air over more than 2000 kilometres. In Turin, the large size of most particles leads us to doubt the Saharan origin of the material.

Diatoms (group 6) were probably freshwater diatoms, as often found in Saharan dust falls over Europe as far away as Paris or Germany (Coudé-Gaussen, 1991; Littmann, 1991). They are very common over the West African coast where their concentration can exceed 25 million whole diatoms per gram of airborne dust collected in the atmosphere (Melia, 1984).

Amphiboles and, subordinately, pyroxenes showing weathered, sometimes corroded, surfaces were well represented and are considered of Saharan provenance. They generally lack fibrous habit. Amphibole (mostly sodic) and chrysotile fibbers occurred in the Turin dust; they lacked weathered surfaces and likely represent a local provenance.

Quartz and calcite grains (group 4 of Genoa sample) lacking evidence of weathering could represent a local dust contribution.

Synthetic and glassy fibbers probably attest to local industrial pollution.

Organic compound (groups 3 and 5 of

Genoa) can be linked to local pollution but are also associated with the long-distance transport of stable organic compounds (Franzén *et al.*, 1994; Griffin *et al.*, 2001b).

The spherules represented a small percentage of the dust but their origin is noteworthy. The origin of glassy spherules is commonly associated with industrial emissions (Coudé-Gaussen, 1991). Other hypotheses include volcanic dust produced by explosive eruptions or cosmic dust formed by disintegration of meteorites entering the Earth's atmosphere. In the dust from Turin, glassy spherules of type I (Table 5) and metallic spherules (types III and V in Table 5) as well as the framboidal aggregates, likely originated from anthropogenic emissions.

Glassy spherules from Genoa and type II spherules from Turin yield a semi-quantitative composition comparable with glass drops from industrial wool rock. However, the glass drops commonly show cuspate surfaces, in contrast with the spherical form of the dust spherules. Therefore, an origin in volcanic dust cannot be excluded.

The dust fall over Turin was, on the whole, characterised by a high proportion of local natural input and anthropogenic pollution with a low proportion of material of Saharan provenance. Such a situation, that is a Saharan dust contribution to aerosols, has been observed elsewhere in southern Europe (Putaud *et al.*, 2004) as some of the fine dust fraction can remain in the atmosphere over several days before being precipitated by rainfalls.

10. Conclusion

The two dust fall events in northern Italy in autumn 1996 are only two of many well-documented events in Europe during the last decades. However, the characteristics of these events deserve special attention for the following reasons:

a) the low probability of a dust fall over Europe from November to February;

b) the extremely high amount of dust that fell on Genoa on 13 November 1996 (4.05 g m^{-2}) which is quite a rare concentration for a single event. The dust fall on Turin (on 7 December 1996) was not so abundant as that in Genoa with 0.54 g m^{-2}.

c) the high median sizes of the dust particles (14.6 μm and 25.8 μm respectively in Genoa and Turin).

The dust material was collected downtown in urban areas and was therefore locally contaminated. The local-particle input in Genoa is estimated at 8%, which reduces the Saharan contribution to the still-high value of 3.73 g m^{-2}. On the other hand, local dusts appear to have made the greatest contribution to the fall in Turin. With only 15% of the material having a desert origin, only about 0.08 g m^{-2} coming from the Sahara.

Acknowledgments

The authors are grateful to L. Fanfani for his constructive comments.

REFERENCES

Ansmann A., Bösenberg J., Chaikovsky A., Comeron A., Eckhardt S., Eixmann R., Freudenthaler V., Ginoux P., Komguem L., Linné H., Marquez M.Á.L., Matthias V., 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. and Wiegner M. (2003) — *Long-range transport of Saharan dust to northern Europe: The 11-16 October 2001 outbreak observed with EARLINET.* J. Geophys. Res., **108**, No. D24, 4783, doi: 10.1029/2003JD003757.

Bergametti G., Gomes L., Coudé-Gaussen G., Rognon P. and Le Coustumer M.N. (1989) — *African dust observed over Canary Islands: Source-regions identification and transport pattern for some summer situations.* J. Geophys. Res., **94**, 14855-14864.

Bücher A. (1994) — *Etude en Europe des retombées de poussières d'origine saharienne.* R.G.D., **43**, 23-25.

Bücher A. and Lucas C. (1972) — *Le nuage de poussière rouge du 7 février 1972.* Bull. Soc. Hist. nat. Toulouse, **108**, 437-445.

Bücher A. and Lucas C. (1984) — *Sédimentation* *éolienne intercontinentale, poussières sahariennes et géologie.* Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine, **8**, 151-165.

Bücher A., Dubief J. and Lucas C. (1983) — *Retombées estivales de poussières sahariennes sur l'Europe.* Rev. Géol. Dyn. Géogr. Phys., **24**, 153-165.

Burt S. (1991) — *Falls of dust rain within the British Isles.* Weather, **46**, 347-353.

Carder K.L., Steward R.G., Betzer P.R. and Prospero J.M. (1986) — *Dynamics and composition of particles from aeolian input event to the Sargasso sea.* J. Geophys. Res., **91**, 1055-1066.

Chester R., Baxter G.G., Behairy A.K.A., Connor K., Cross D., Elderfield H. and Padgham R.C. (1977) — *Soil-sized dusts from the lower troposphere of the Eastern Mediterranean Sea.* Mar. Geol., **24**, 201-217.

Chester R., Sharples E.J., Sanders G.S. and Saydam A.C. (1984) — *Saharan incursion incursion over the Tyrrhenian Sea.* Atmos. Environ., **18**, 929-935.

Coudé-Gaussen G. (1982) — *Les poussières éoliennes sahariennes: mise au point.* Rev. Géomorph. Dyn., **31**, 2: 49-70.

Coudé-Gaussen G. (1991) — *Les poussières sahariennes. Cycle sédimentaire et place dans les environnements et paléoenvironnements désertiques.* John Libbey Eurotext, Paris, 485 pp.

Coudé-Gaussen G., Désiré E. and Regrain R. (1988) — *Particularité 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.

Coudé-Gaussen G., Rognon P. and Le Coustumier M. (1994) — *Incorporation progressive de poussières sahariennes aux limons des îles orientales du Cap Vert.* C. R. Acad. Sci. Paris, **319**, série II, 1343-1349.

Coudé-Gaussen G., Rognon P., Bergametti G., Gomes L., Strauss B., Gros J.M. and Le Coustumer M.N. (1987) — *Saharan dust on Fuerteventure Island: chemical and mineralogical characteristics, air mass trajectories and probable sources.* J. Geophys. Res., **92**, 9753-9771.

De Angelis M. and Gaudichet A. (1991) — *Saharan dust deposition over Mont Blanc (French Alps) during the last 30 years.* Tellus, **43**, 61-75.

Del Monte M., Landuzzi V., Lenaz R., Sabbioni C. and Tomadin L. (1984) — *Characterization of individual airborne particles: an open problem.* Mem. Soc. Geol. It., **27**, 303-309.

Dessens J. and Van Dinh P. (1990) — *Frequent Saharan dust outbreaks north of the Pyrenees: a sign of a climatic change?* Weather, **45**, 9: 327-333.

Deuze J.L., Devaux C., Herman M., Santer R. and Tanre D. (1988) — *Saharan Aerosols over the South of France: Characterization Derived from Satellite Data and Ground Based Measurements.* J. Appl. Meteor., **27**, 680-686.

File R.F. (1986) — *Dust deposits in England on 9 November 1986.* Weather, **41**, 6: 191-195.

Franzén L. (1989) — *A dustfall episode ob the Swedish west coast, October 1987.* Geografiska Annaler, **71**, 263-267.

Franzén L.G., Hjelmroos M., Kallberg P., Brorström-Lundén E., Juntto S. and 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.* Atmos. Environ., **28**, 3587-3604.

Franzén L.G., Hjelmroos M., Kallberg P., Rapp A., Mattsson J.O. and Brorström-Lundén E. (1995) — *The Saharan dust episode of south and central Europe, and northern Scandinavia, March 1991.* Weather, **50**, 313-318.

Ganor E. and Mamane Y. (1982) — *Transport of Saharan dust across the eastern Mediterranean.* Atmos. Environ., **16**, 581-587.

Glaccum R.A. and Prospero J.M. (1980) — *Saharan aerosols over the tropical North Atlantic.* Mineralogy. Mar. Geol., **37**, 295-321.

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

Griffin D.W., Kellogg C.A. and Shinn E.A. (2001a) — *Dust in the wind: Long range transport of dust in the atmosphere and its implications for global public and ecosystem health.* Global Change and Human Health, **2**, 20-33.

Griffin D.W., Garrison V.H., Herman J.R. and Shinn E.A. (2001b) — *African desert dust in the Caribbean atmosphere: Microbiology and public health.* Aerobiologia, **17**, 203-213.

Guerzoni S. and Molinaroli E. (1997) — *Le polveri sahariane.* Le Scienze, **341**, 68-75.

Le Bolloch O. and Guerzoni S. (1995) — *Acid and alkaline deposition in precipitation on the western coast of Sardinia, Central Mediterranean (40°N,8°E).* Water, Air and Soil Pollution. **85**, 2155-2160.

Le Bolloch O., Guerzoni S. and Molinaroli E. (1996) — *Atmosphere-ocean mass fluxes at two coastal sites in Sardinia (39-41°N,8-10°E).* In: «The impact of desert dust across the Mediterranean» (eds. Guerzoni S. and Chester R.), Kluwer Academic Publ., 217-222.

Littmann T. (1991) — *Recent African dust deposition in West Germany - Sediment characteristics and climatological aspects.* Catena suppl., **20**, 57-73.

MELIA M.B. (1984) — *The distribution and relationship between palynomorphs in aerosols and deep-sea sediments off the coast of northwest Africa.* Mar. Geol., **58**, 345-371.

MIDDLETON N.J. and GOUDIE A.S. (2001) — *Saharan dust: sources and trajectories.* Trans. Inst. British Geographers, **26**, 165-181.

NIHLÉN T. and OLSSON S. (1995) — *Influence of eolian dust on soil formation in the Aegean area.* Z. Geomorph. N.F., **39**, 341-361.

OLIVA P., COUDÉ-GAUSSEN G., DELANNOY H., DORIZE L., ROGNON P. and TABEAUD M. (1983) — *Etude de la dynamique de quelques lithométéores sahariens par la télédétection spatiale.* Meditérranée, **3**, 21-52.

OZER P., ERPICUM M., CORTEMIGLIA G.C. and LUCCHETTI G. (1998) — *A dustfall event in November 1996 in Genoa, Italy.* Weather, **53**, 140-145.

PITTY A. (1968) — *Particle size of the Saharan dust which fell in Britain in July 1968.* Nature, **220**, 364-365.

PRODI F. and FEA G. (1978) — *Transport and deposition of saharan dust over the Alps.* Proc. 15 Int. Tagung Meteorol., **1**, 179-182.

PRODI F. and FEA G. (1979) — *A case of transport and deposition of saharan dust over the Italian peninsula and Southern Europe.* J. Geophys. Res., **84**, 6951-6960.

PROSPERO J.M. and LAMB P.J. (2003) — *African droughts and dust transport to the Carribean: Climate change implications.* Science, **302**, 1024-1027.

PROSPERO J.M., GLACCUM R.A. and NEES R.T. (1981) — *Atmospheric transport of soil dust from Africa to South America.* Nature, **289**, 570-572.

PROSPERO J.M., NEES R.T. and UEMATSU M. (1987) — *Deposition rate of particulate and dissolved aluminum derived from Saharan dust in precipitation at Miami, Florida.* J. Geophys. Res., **92**, 14723-14731.

PUTAUD J.P., RAES F., VAN DINGENEN R., BRÜGGEMANN E., FACCHINI M.C., DECESARI S., FUZZI S., GEHRIG R., HÜGLIN C., LAJ P., LORBEER G., MAENHAUT W., MIHALOPOULOS N., MÜLLER K., QUEROL X., RODRIGUEZ S., SCHNEIDER J., SPINDLER G., TEN BRINK H., TØRSETH K. and WIEDENSOHLER A. (2004) — *A European aerosol phenomenology–2: chemical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe.* Atmos. Environ., **38**, 2579-2595.

REIFF J., FORBES G.S., SPIEKSMA F.T.M. and REYNDERS J.J. (1986) — *African dust reaching northwestern Europe: A case study to verify trajectory calculations.* J. Climate Appl. Meteor., **25**, 1543-1567.

RODRIGUEZ S., QUEROL X., ALASTUEY A., KALLOS G. and KAKALIAGOU O. (2001) — *Saharan dust contributions to PM10 and TSP levels in Southern and Eastern Spain.* Atmos. Environ., **35**, 2433-2447.

RODRIGUEZ S., QUEROL X., ALASTUEY A., VIANA M. and MANTILLA E. (2003) — *Events affecting levels and seasonal evolution of airborne particulate matter concentrations in the Western Mediterranean.* Environmental Science and Technology, **37**, 216-222.

ROGNON P., COUDÉ-GAUSSEN G., REVEL M., GROUSSET F.E. and PEDEMAY P. (1996) — *Holocene Saharan dust deposition on the Cape Verde Islands: sedimentological and Nd-Sr isotopic evidence.* Sedimentology, **43**, 359-366.

RYALL D.B., DERWENT R.G., MANNING A.J., REDINGTON A.L., CORDEN J., MILLINGTON W., SIMMONDS P.G., O'DOHERTY S., CARSLAW N. and FULLER G.W. (2002) — *The origin of high particulate concentrations over the United Kingdom, March 2000.* Atmos. Environ., **36**, 1363-1378.

SALA J.Q., CANTOS J.O. and CHIVA E.M. (1996) — *Red dust rain within the Spanish Mediterranean area.* Clim. Change, **32**, 215-228.

SWAP R., GARSTANG M., GRECO S., TALBOT R. and KALLBERG P. (1992) — *Saharan dust in the Amazon Basin.* Tellus, **44B**, 133-149.

THOMAS F.G. (1993) — *Dust rain.* Weather, **48**, 193.

TOMADIN L., LENAZ R., LANDUZZI V., MAZZUCOTELLI A. and VANNUCCI R. (1984) — *Wind-blown dusts over the Central Mediterranean.* Oceanologica Acta, **7**, 13-23.

VIANA M., QUEROL X., ALASTUEY A., CUEVAS E. and RODRIGUEZ S. (2002) — *Influence of African dust on the levels of atmospheric particulates in the Canary Islands air quality network.* Atmos. Environ., **36**, 5861-5875.

WAGENBACH D. and GEIS K. (1989) — *The mineral dust record in a high alpine glacier (Colle Gnifetti, Swiss Alps).* In: «Paleoclimatology and paleometeorology: modern and past patterns of global atmospheric transport» (eds. Leinen M. and Sarnthein M.). Kluwer Academic Publ., NATO ASI Series, Serie C282, 543-564.

WASHINGTON R., TODD M., MIDDLETON N.J. and GOUDIE A.S. (2003) — *Dust-storm source areas determined by the Total Ozone Monitoring Spectrometer (TOMS) and surface observations.* Annals of the Association of American Geographers, **93**, 299-315.

WORLD HEALTH ORGANIZATION (WHO) (2000) — *Guidelines for air quality.* WHO, Geneva.