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Monitoring of Saharan dust fallout on Crete and its contribution to soil formation

By TOMAS NIHLÉN[1]*, JAN O. MATTSSON[1], ANDERS RAPP[1], CHRISOULA GAGAOUDAKI[2], GEORGES KORNAROS[2] and JOHN PAPAGEORGIOU[2], [1]*Department of Physical Geography, University of Lund, Sölvegatan 13, S-223 62 Lund, Sweden*; [2]*Hellenic National Meteorological Service, P. O. Box 73 502 GR 16 603, Athens, Greece*

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ABSTRACT

A series of 6 dust traps was established in 1988 distributed over the island of Crete (Greece). Eolian dust has been collected in the traps each year and in each season during the 4 years of investigation which is still going on. The mean deposition rate for the 6 stations and 4 years was calculated as 21.3 g m^{-2} yr^{-1}. Using the highest and lowest values, the deposition can be extrapolated to 6.6–21.4 mm for 1000 years, which is in agreement with other researchers' findings. The trapped dust shows a homogeneous grain-size distribution. Its mineralogy is similar to what characterizes soil samples from Psiloritis on Crete and source areas in southern Tunisia. In the fine fraction of the soil (particles $< 10\ \mu$m), the contents of the clay mineral kaolinite and of quartz are high. In addition, the oxygen isotope composition of the 3 types of substrate is similar but differs from the weathering products of the limestone bedrock. Statistics of dust episodes covering the period c. 1955–1990 from 10 meteorological stations in Greece revealed that long-distance transport of dust in combination with winds from a southerly sector is common in the Aegean area during spring.

1. Introduction

Warm and dry southerly winds are a common feature of the Mediterranean climate. In Italy and Greece, such wind conditions are well-known as scirocco and livas, respectively. Many authors have studied dust deposition in southern Europe and elsewhere, e.g., in the Pyrenees and France (Bücher, 1989), in the eastern Mediterranean Sea (Chester et al., 1977), in Italy (Prodi and Fea, 1979), in Greece (Angouridakis, 1971; Charantonis et al., 1991; Makrogiannis et al., 1989; Pye, 1992) and in Germany (Littmann, 1991). Except for a few studies on terra rossa soils (MacLeod, 1980 and Rapp, 1984), the rôle of dust deposition in the formation of soil in southern Europe has hardly been considered.

Our project was initiated in 1987 with the aim of studying the rate of dust deposition by using traps in a test area in the Mediterranean.

2. Methods

2.1. *Dust traps and localities*

In 1988, a series of 6 dust traps was established on the island of Crete, Greece. The trap consists of a net-covered plastic funnel, 30 cm in diameter, connected by a plastic tube to a vessel with a volume of 20–50 l (Fig. 1). The funnel opening is 1.8 m above the vessel. Dust is deposited in the trap both by dry and wet deposition. Dry dust is trapped by a plastic net having a mesh-size of 3 × 3 mm and covering the funnel opening and is collected by washing the funnel and net with water. Typical situations with Saharan dust invading southern Europe are southerly winds associated

* Corresponding author.

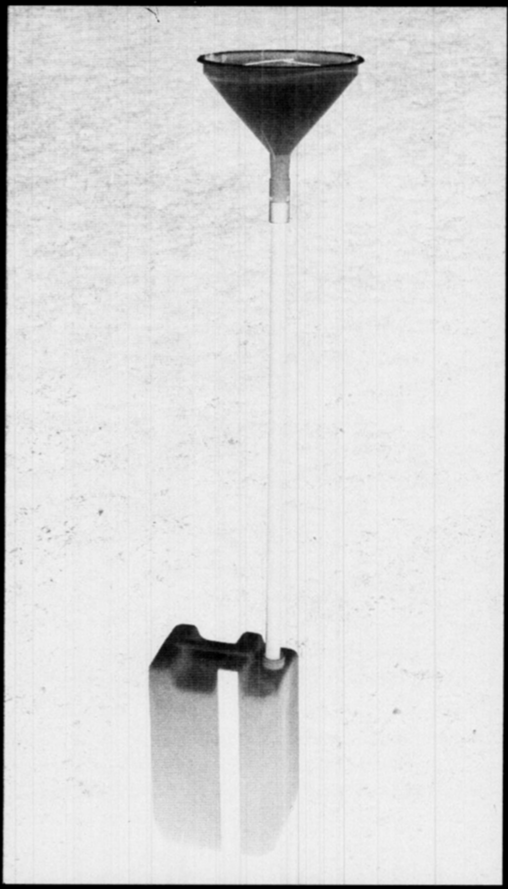

Fig. 1. Dust trap with net-covered plastic funnel, tube and vessel. The black ruler measures 0.5 m. The net has a mesh of 3 × 3 mm.

with a polar low moving eastwards over the Mediterranean (Dubief, 1979). According to the staff at the Hellenic National Meteorological Service in Athens (to which some of the authors belong) an effective mechanism for removing the dust from the air is the frontal rain that follows the warm southerly winds. Hence wet deposition is the principal mechanism of the deposition in dust in southern Europe.

The dust-trap stations are (1) Anogia (c. 700 m a.s.l.), (2) Chania (< 100 m a.s.l.), (3) Heraklion (< 100 m a.s.l.), (4) Ierapetra (< 100 m a.s.l.), (5) Timbaki (< 100 m a.s.l.) and (6) Zaros (c. 400 m a.s.l.), (Fig. 2), all being meteorological stations belonging to the National Meteorological Service, Athens. The localities have been chosen so that contamination by local dust, for example from traffic, building constructions and other activities, is minimized. Each year all traps are emptied and checked at the end of February and June. The reason why we chose these months was that the important deposition of March–June was separated from that of the rest of the year.

In order to compare the aeolian contribution to the soil formation process with the contribution of weathered material, we took samples of the limestone bedrock and of the overlying soil in the Psiloritis massif, central Crete. Contamination of the soil by source material other than weathering bedrock or aeolian dust was eliminated by taking samples on plateaus or ridges at altitudes above 2000 m a.s.l. Samples were also taken from wadi deposits in an area west of the Matmata Mountains in southern Tunisia which is a potential source area for dust blowing in over Europe.

2.2. *Dust data*

In addition to trap data, data on dust episodes were obtained and analysed from a number of long observational series obtained at Greek weather stations (Fig. 3). For most of the ten stations data were available for a period of 35 years (1955–1990). Similar information for a shorter period, 1955–1983, has been published by Nihlén and Mattsson (1989). The code numbers investigated in the codified data are given in Table 1.

It should be noted that the numbers 06–09 in Table 1 denote that no duststorm or sandstorm occurs at the station at the time of observation or, for 09, has occurred during the preceding hour. In the following paragraph *observation of dust* is based on meteorological reports made every three hours. *Day with dust* is a day when one or more observations of dust have been made. *Dust episode* is one dust observation or a period of more (continuous) dust observations, sometimes lasting for several days.

2.3. *Dust analysis*

The dust samples from the traps were analysed in different ways. All samples were dried and weighed, and their colours determined according to Munsell's code system (Munsell Soil Color Charts, 1975). Their content of $CaCO_3$ was measured with HCl in a Passon apparatus. Seven selected samples were also tested for grain size dis-

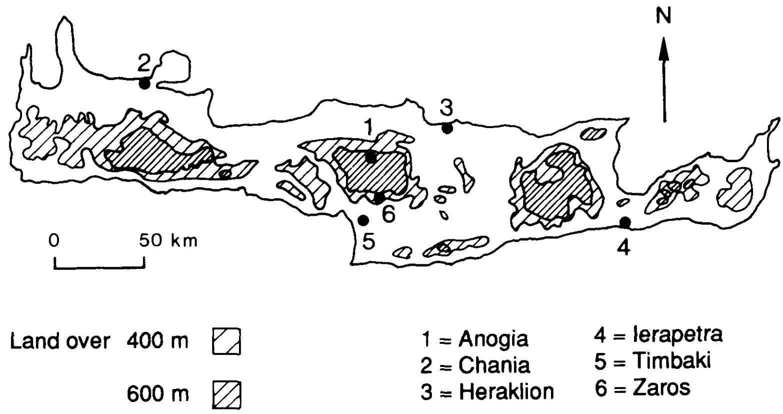

Fig. 2. Meteorological stations where dust traps are placed on Crete. Three of the stations are on the northern slopes or north of the Cretean mountain ranges and three on the southern slopes or south of the ranges.

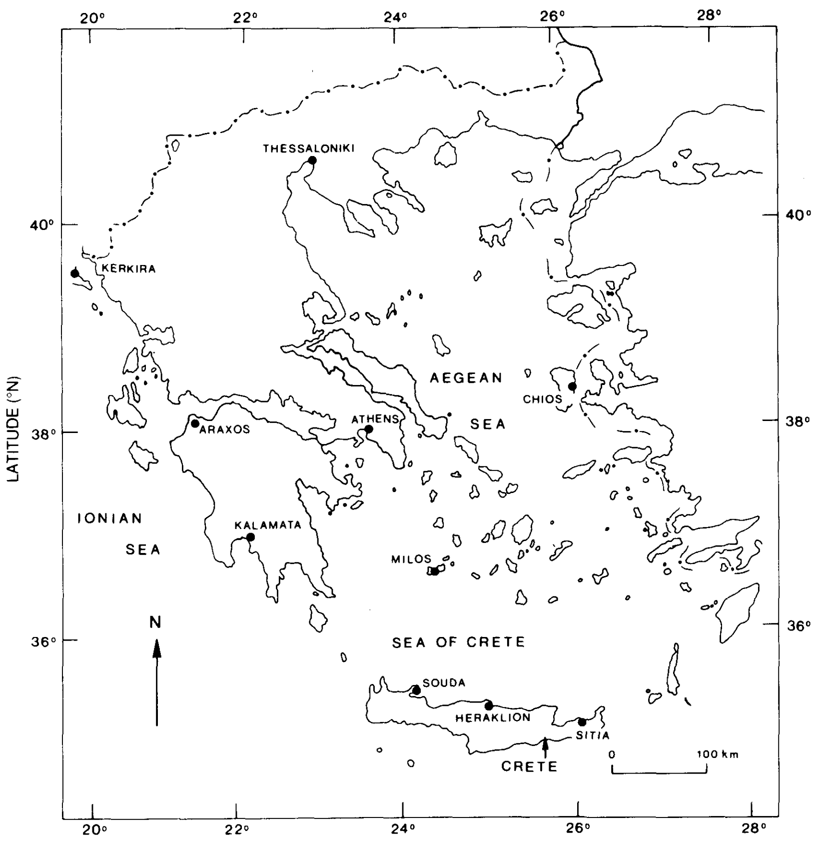

Fig. 3. Greek weather stations for which data on dust episodes were obtained and analysed.

Table 1. *The present weather* (*ww*) *code*

06	Widespread dust in suspension in the air, not raised by wind at or near the station at the time of observation
07	Dust or sand raised by wind at or near the station at the time of observation, but no well-developed dust whirl(s) or sand whirl(s), and no duststorm or sandstorm seen; or, in the case of ships, blowing spray at the station
08	Well-developed dust whirl(s) or sand whirl(s) seen at or near the station during the preceding hour or at the time of observation, but no duststorm or sandstorm
09	Duststorm or sandstorm within sight at the time of observation, or at the station during the preceding hour
30	Slight or moderate duststorm or sandstorm has decreased during the preceding hour
31	Slight or moderate duststorm or sandstorm, no appreciable change during the preceding hour
32	Slight or moderate duststorm or sandstorm has begun or has increased during the preceding hour
33	Severe duststorm or sandstorm has decreased during the preceding hour
34	Severe duststorm or sandstorm, no appreciable change during the preceding hour
35	Severe duststorm or sandstorm has begun or has increased during the preceding hour

tribution (Sedigraph 5000 ET particle analyzer) and content of clay minerals (Philip's diffractometer). (Table 2).

In order to make possible comparisons between trapped aeolian dust and soils and bedrocks in the accumulation areas as well as in the source areas, samples were taken for analysis from soils in Crete and from a typical source area in southern Tunisia (see Subsection 4.1).

3. Results

3.1. *Annual and seasonal dust sedimentation*

In Fig. 4, which indicates the annual amounts of trapped dust given in gm^{-2}, it can be seen that the temporal and regional variations in dust deposition are great. The mean for all stations during the four years was calculated as $21.3\ \mathrm{g\,m^{-2}\,yr^{-1}}$ which corresponds to a sedimentation rate of $0.0125\ \mathrm{mm\,yr^{-1}}$. This figure was calculated assuming a bulk density of $1.7\ \mathrm{g\,cm^{-3}}$, which is similar to that of soils with the same grain-size distribution as the dust (about 70% silt and 30% clay).

As can be seen from Table 3, there are great variations in the amount of dust trapped for different seasons of the year (March–June, 4 months; July–February, 8 months). However, with respect to the relative length of the periods the greatest dust deposition rate is found during the spring period.

Table 4 shows deposition figures in relation to the trap localization to the north or to the south of the mountain ranges on Crete. As can be seen the amounts of dust trapped in the northern stations are greater than the amounts from the southern stations (see also Fig. 4).

3.2. *Dust and soil characteristics*

Most of the trapped dust has a high content of $CaCO_3$. The dust ranges from yellowish-brown (10 YR 5/4) over pale brown (10 YR 6/3) to brown (10 YR 5/3). The grain-size distribution of the selected dust samples is uniform. A sand fraction (particles $>63\ \mu m$) is normally absent. The clay content ranges from 20 to 37%. The median particle size varies between 4 and 16 μm. The grain size resemble those of dust that has been transported over long distances. The median grain size of Saharan dust deposited in Bochum, Germany is 2–16 μm (Littmann, 1991) and in the High Pyrenees, France 3–12 μm (Bücher, 1989). Aeolian dust deposits in Japan and Korea have a median of 3–30 μm (Inoue and Naruse, 1991).

The trapped dust was compared with the insoluble residues of the limestone bedrock and overlying soils as well as with Tunisian wadi deposits.

The mineralogy of the fine fraction (particles $<10\ \mu m$) shows great similarities between trapped dust, mountain soils and wadi deposits. The content of the clay mineral kaolinite and of quartz is high (Table 2). In the insoluble residues from the limestone bedrock, on the other hand, no traces of kaolinite and only a low content of quartz are found in this fraction. This is in accordance with other investigations, for example Chester et al. (1984) who showed a high content of kaolinite in Saharan dust samples. Oxygen isotopic composition (carried out by Dr. Chitosi Mizota, University of Kyushu, Japan) of the 1–10 μm fraction of quartz grains from trapped dust, soils and lime-

Table 2. *Semi-quantitative evaluation of the mineralogic composition of the < 10 μm-fraction for selected samples*

Sample	Q + Fp	Sm	Chl	ML	I/M	K
Bedrocks (a) and overlying soils (b):						
Psiloritis, Crete (a)	—	+ + +	+	+	+ + + + M	—
Psiloritis, Crete (b)	+ +	—	+	+ +	+ +	+ +
Psiloritis, Crete (a)	+	+ +	—	+ +	+ + + + M	—
Psiloritis, Crete (b)	+ +	—	+ +	+ +	+ + + M	+ +
Wadi sediments:						
Tunisia	+ + +	—	—	+ +	+ + +	+ +
Tunisia	+ + +	—	—	+ +	+ + +	+ + +
Eolian dust:						
Anogia 88	+ +	—	+	+ +	+ + +	+ + +
Anogia 89	+ + +	—	—	+ + +	+	+ + +
Chania 88	+ +	—	—	+ +	+ + +	+ + +
Chania 89	+ + +	—	—	+ +	+ + +	+ +
Ierapetra 89	+ + +	—	—	+ +	+ +	+ + +
Timbaki 89	+ + +	—	+ +	+	+ + +	+ +
Zaros 89	+ + +	—	—	+ + +	+ +	+ + +

Q + Fp = quartz + feldspars, Sm = smectite, Chl = chlorite, ML = mixed-layered minerals, I/M = illite/mica (M indicates presence of mica), K = kaolinite. — = not detected, + = ⩽5%, + + = 5–20%, + + + = 21–40%, + + + + = 41–60%, + + + + + = >60%.

stone residues and wadi deposits from our localities on Crete and in Tunisia shows the same pattern. The $\delta^{18}O$ values of trapped dust from Heraklion (+17.7‰), soils from Psiloritis on Crete (+20.4 and +22.2‰) and wadi deposits from Tunisia (+19.3 and +18.3‰) are distinctly lower than those of the limestone bedrock of Psiloritis (+31.4 and +31.9‰) (Mizota et al., 1988).

3.3. *Dust observations over Greece*

The data on dust episodes given by code numbers from ten Greek weather stations show that the commonest code number in the material is 06, followed by 07 (Table 5). In general around 80% of the observations had the code number 06, i.e., dust transported over long distances. The station Souda (the airport of Chania) has the highest frequency of occurrence of this kind of dust, agreeing with the high amounts of dust trapped at this station.

From Table 6, it can be seen that the months of March and April have the greatest number of dust days. This is most marked for the stations Chios, Heraklion, Sitia and Souda, but is not true of Araxos, Athens, Milos and Thessaloniki. The difference in dust observations between Souda and Milos is striking. It can be explained by local topography (downdraught behind the Cretan mountains). Athens (airport) shows a high value for August. Most other stations have low values for July–October.

As seen in Table 7, most dust episodes occur in conjunction with winds from directions within the southerly sector (SE–SSW). This is particularly true of Heraklion and Sitia on Crete. Athens shows a high figure for winds from NW–NNE.

A closer inspection of the data of dust episodes reveals that for most stations the code number ww = 06, indicating long-distance transport, combined with winds from the southerly sector is common during the months of March and April. The code number ww = 06 occurs more than 80% of the time.

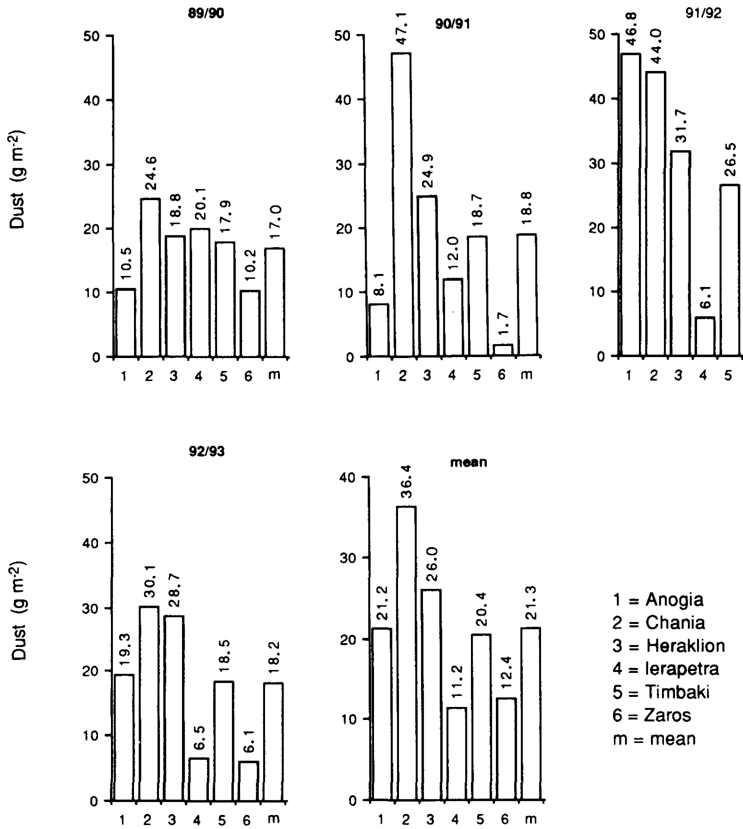

Fig. 4. Amounts of trapped dust in g m^{-2} given for the different years. 89/90, etc., denotes period from March 1989 to February 1990.

Table 3. *Amounts of trapped dust in g m^{-2} given for different seasons of the year (March–June, 4 months, denoted 1, and July–February, 8 months, denoted 2; the last mentioned amounts, reduced to 50%, are given within brackets to allow comparisons)*

	1988	1989		1990		1991		1992		1993	Mean	
	1	1	2	1	2	1	2	1	2	1	1	2
Anogia	12.7	3.2	7.2 (3.6)	3.5	4.5 (2.3)	31.8	15.0 (7.5)	10.5	8.8 (4.4)	2.8	10.8	8.9 (4.5)
Chania	12.7	8.3	16.3 (8.2)	15.8	31.3 (15.7)	21.8	22.2 (11.1)	9.0	21.1 (10.6)	2.1	11.6	22.7 (11.4)
Heraklion	9.9	4.9	13.9 (7.0)	10.9	14.0 (7.0)	19.8	11.9 (6.0)	8.9	19.8 (9.9)	1.0	9.2	14.9 (7.5)
Ierapetra	7.2	6.1	14.0 (7.0)	6.2	5.8 (2.9)	3.2	2.8 (1.4)	1.4	5.1 (2.6)	2.0	4.4	6.9 (3.5)
Timbaki	1.1	10.3	7.6 (3.8)	4.4	14.3 (7.2)	12.3	14.2 (7.1)	8.6	9.9 (5.0)	1.8	6.4	11.5 (5.8)
Zaros	2.8	8.2	2.0 (1.0)	0.6	1.1 (0.6)	26.5	5.1 (2.6)	4.5	1.6 (0.8)	2.0	7.4	2.4 (1.2)
mean	7.7	6.8	10.2 (5.1)	6.9	11.8 (5.9)	19.2	11.9 (6.0)	7.2	11.0 (5.5)	2.0	8.3	11.2 (5.6)

Table 4. *Yearly amounts of trapped dust* ($g\ m^{-2}$) *for 3 stations localized to the north of the mountains* (*N*) *and 3 stations to the south of the mountains* (*S*)

		89/90	90/91	91/92	92/93	Mean
N	Anogia	10.5	8.1	46.8	19.3	21.2
	Chania	24.6	47.1	44.0	30.1	36.4
	Heraklion	18.8	24.9	31.7	28.7	26.0
	mean	18.0	26.7	40.8	26.0	27.9
S	Ierapetra	20.1	12.0	6.1	6.5	11.2
	Timbaki	17.9	18.7	26.5	18.5	20.4
	Zaros	10.2	1.7	31.6	6.1	12.4
	mean	16.1	10.8	21.4	10.4	14.7

When ww = 06 is reported, visibility can vary over a great range of distances. It was therefore considered to be of interest to study the distribution of ww = 06 for different values of visibility (Table 8); most 06-observations were made when visibility was between 4 and 10 km.

4. Discussion

4.1. Source areas

The data presented show that most of the dust passing Greece is carried from northern Africa by southeasterly to southwesterly winds. Mountains and associated wadis are common features of the landscape of northern Africa. We have chosen southern Tunisia as a key source area for dust transport to southern Europe, since it has this type of landscape that promotes dust formation. Great amounts of fine-grained material (silt and clay) are washed down from mountains in southern Tunisia during rainstorms, and are deposited by the wadis on the plains. From there it is carried by the winds to southern Europe. In the Sahara duststorms are largely confined to the spring (Abdel Salam and Sowelin, 1967; Ruiz-Pino et al., 1990; Yaalon and Ganor, 1973), the season when southerly winds and dust episodes are most common in the Greek area. In particular, on the slopes of the Matmata Mountains (bedrock: limestones of Mesozoic age) with an accompanying systems of wadis extending east and west, enormous amounts of fine material are washed down on to the plains where strong winds will carry the dust up into the atmosphere and transport it from the region in Tunisia.

One support for the North African origin of the trapped dust is the great similarity in mineral composition, grain-size distribution and colour between the Greek dust and the wadi material sampled from southern Tunisia. The oxygen isotope composition is also similar for the two kinds of material. The composition of deep-sea sediments, particularly the high content of kaolinite, from the sea surrounding Crete also confirms the presence of aeolian material (Venkatarathnam and Ryan, 1971 and Chester et al., 1977).

4.2. Dust and precipitation

The relationship between the amount of trapped dust and the amount of precipitation is not simple. A glance at Tables 3 and 9 shows that the correlation between these two quantities is weak, both when the amounts for the different stations are

Table 5. *Total number of observations of dust given in code figures*

Stations	code figures 06	07	08	09	30	31	32	33	34	35	Measuring period	Total no. of used observations
Araxos	3	5	1	4	—	1	—	—	—	—	1955–90	105 120
Athens (airport)	76	13	2	—	1	1	—	—	—	—	1955–90	105 120
Chios	62	1	1	1	—	1	—	1	—	—	1955–90	105 120
Heraklion	70	18	2	1	2	—	2	—	—	3	1955–90	105 120
Kalamata	24	6	2	1	—	—	—	—	1	—	1956–90	102 200
Kerkira	28	1	—	—	2	1	—	—	—	—	1955–90	105 120
Milos	1	5	1	2	1	1	—	—	—	—	1955–90	105 120
Sitia	19	8	—	—	—	1	1	—	—	—	1960–90	90 520
Souda	118	9	4	2	2	3	2	—	1	1	1958–90	96 360
Thessaloniki	6	4	—	—	2	2	—	—	1	—	1959–90	93 440
total	407	70	13	11	10	11	5	1	3	4		

Table 6. *Total number of days with dust in the air*

Stations	J	F	M	A	M	J	J	A	S	O	N	D	Sum	(March + April)/year
Araxos	2	4	1	0	1	1	1	0	0	3	1	0	14	0.07
Athens (airport)	2	5	5	9	1	9	7	17	2	1	1	1	60	0.23
Chios	1	2	14	4	5	2	0	0	0	0	0	1	29	0.62
Heraklion	9	2	15	8	4	5	0	0	0	1	2	1	47	0.49
Kalamata	5	1	2	4	1	2	1	0	3	0	1	1	21	0.29
Kerkira	2	2	4	3	3	0	0	0	1	0	4	1	20	0.35
Milos	1	1	1	1	0	0	2	1	0	1	0	2	10	0.20
Sitia	2	2	6	5	0	3	0	0	0	1	1	1	21	0.52
Souda	6	7	21	9	11	5	2	1	0	1	2	7	72	0.42
Thessaloniki	1	0	1	2	1	0	1	4	0	2	2	0	14	0.21
total	31	26	70	45	27	27	14	23	6	10	14	15	308	0.37

Table 7. *Wind direction at the beginning of the dust episodes (one dust observation or period of more (continuous) dust observations, sometimes lasting for several days)*

Stations	NW–NNE	NE–ESE	SE–SSW	SW–WNW	calm	SE–SSW / total
Araxos	4	1	2	3	4	0.14
Athens (airport)	28	7	12	4	2	0.23
Chios	5	3	11	6	2	0.41
Heraklion	6	0	31	0	4	0.76
Kalamata	3	2	9	1	3	0.50
Kerkira	1	5	10	2	0	0.56
Milos	1	2	2	4	0	0.22
Sitia	2	0	14	2	3	0.67
Souda	5	5	22	14	11	0.39
Thessaloniki	10	0	2	1	1	0.14
total	65	25	115	37	30	0.42

Table 8. *The distribution (number of observations) of the code figure (ww) 06 for different values of visibility*

Station	Visibility, km 0.5	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	⩾20
Araxos							1		1												1
Athens (airport)				2	5	5	5	5	9	2	26		9	3		3			1		1
Chios				1	3	26	2	2	12		15					1					
Heraklion			2	3	10	12	10	10	14	7	1										1
Kalamata	1	2	1	1	5	5	6	2			1										
Kerkira		1		2	2		3	9	9		1								1		
Milos						1															
Sitia	2	1		1	2	4	3		2		1		2								1
Souda		1	4	2	6	7	18	15	33	27	5										
Thessaloniki							1	1	4												
total	3	5	7	12	33	60	49	44	84	36	50		11	3		4			2		4

Table 9. *Amounts of precipitation in mm at the dust stations in Crete*

	1988	1989		1990	Mean	
	1	1	2	1	1	2
Anogia	138.9	172.3	607.3	58.7	223.3	878.2 (1975–90)
Chania	121.8	195.1	377.4	19.7	128.3	507.0 (1961–90)
Heraklion	74.1	133.4	278.5	10.4	103.8	386.8 (1955–90)
Ierapetra	78.6	50.5	222.9	11.0	84.6	425.1 (1956–90)
Timbaki	116.8	61.1	242.2	31.0	81.5	413.9 (1959–90)
Zaros	195.0	96.0	265.7	72.5	129.1	649.9 (1976–90)

1: March–June; 2: July–February. Data were available only until 1990.

compared during a single season and when the amounts of the different seasons are compared for a single station, the reasons being that part of the deposition is dry fallout, and that the first fallout raindrops contribute the major part of the deposition. The frequency of rain may therefore play a greater part than the total amount of rain for determining the amount of dust deposited. Table 9 shows (1) that the total precipitation during the spring season was much less (up to 1/3) than during the autumn to winter season and (2) that despite this considerable amounts of dust were deposited during the spring season, on an average about 46% of the total annual amount. Dust inflow from the south followed by frontal rain is frequent during spring.

4.3. *Dust and topography*

Three of the trap stations, Anogia, Chania and Heraklion, are on the northern side or north of the Cretan mountain ranges, and three stations, Ierapetra, Timbaki and Zaros, on the southern side or south of the ranges (Fig. 2). As seen from Table 3 the amounts of trapped dust are generally greater at the northern than at the southern stations, the average amount for the whole investigation period being 27.9 g m^{-2} for the northern stations and 14.7 g m^{-2} for the southern ones. This difference can be explained by the fact that Anogia and Chania receive more precipitation than Ierapetra and Timbaki. Another factor may be the sheltering effect of the mountain ranges increasing the concentration of dust in atmosphere in the lee of the mountains due to the downwards-directed movement of the wind.

Anogia on the northern slopes of Psiloritis at c. 700 m a.s.l. receives an average of 21.2 g m^{-2} dust, and Zaros at c. 400 m a.s.l. on the southern slopes receives 12.4 g m^{-2} which illustrate the difference between the two sides of the range.

5. Conclusion

Aeolian dust was collected in our traps each year and each measuring season during the duration of the investigation. This dust shows a homogeneous grain-size distribution, and the mineralogy is similar to that of soil samples from Psiloritis on Crete and assumed source areas in southern Tunisia. Dust data reveal that dust episodes in southern Greece are concentrated to the spring and are connected with winds from southerly directions. All these facts taken together indicate that the dust originated from North Africa.

Assuming that the deposition rate has remained unaltered for the last 1000 years the thickness of the dust layer deposited during this millennium can be taken to be 12.5 mm. Taking the highest and lowest values (for Chania and Ierapetra respectively, see Table 4) deposition may have ranged between 6.6 mm and 21.4 mm for 1000 years. All these values agree roughly with the values calculated for Corsica by Loye-Pilot et al. (1986), 10 mm/1000 years, for Israel by Yaalon and Dan (1974), 20–80 mm/1000 years and for the Pyrenees by Bücher and Lucas (1975), 18–23 mm/1000 years.

If we extend our deposition period to 10,000 years and keep the deposition rate as above this would give us a soil layer of between 7 and 22 cm unevenly distributed over the island with thick deposition pockets in the valleys. Such a rate of deposition if unchanged during the Holocene, may have been of importance in the formation of terra rossa soils in the Aegean area, even if weathering of limestone contributes to the formation of these soils.

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