Saharan dust and the aerosols on the Canary Islands: past and present

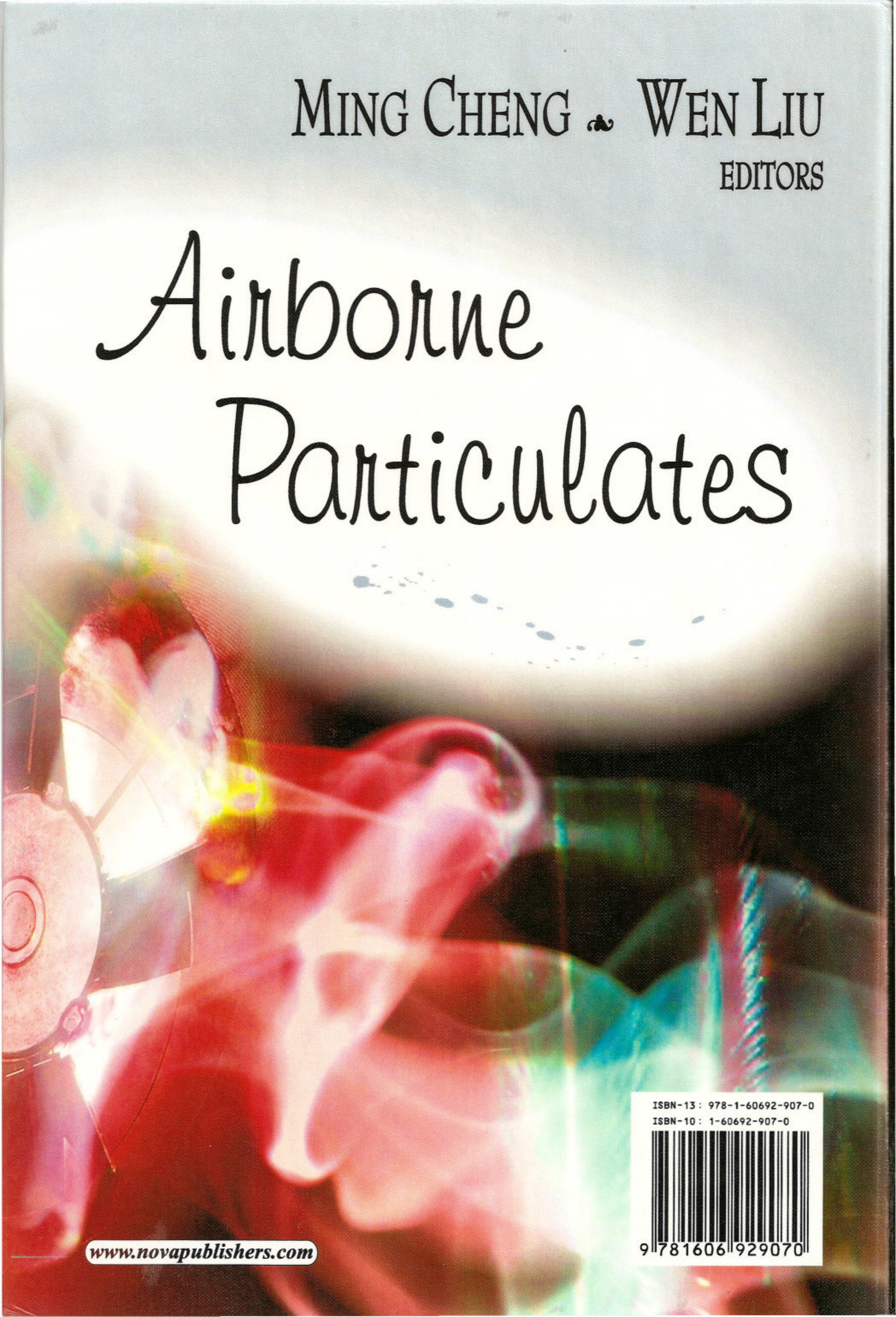
Chapter · January 2009

Inmaculada Menendez
Universidad de Las Palmas de Gran Canaria

Edward Derbyshire
Royal Holloway, University of London

Johann P Engelbrecht
Desert Research Institute

Hans Von Suchodoletz
University of Leipzig



MING CHENG ❧ WEN LIU

EDITORS

Airborne Particulates

ISBN-13: 978-1-60692-907-0
ISBN-10: 1-60692-907-0
9 781606 929070

www.novapublishers.com

In: Airborne Particulates
Editor: Ming Cheng and Wen Liu

ISBN: 978-1-60692-907-0

Chapter 2

SAHARAN DUST AND THE AEROSOLS ON THE CANARY ISLANDS: PAST AND PRESENT

Inmaculada Menendez**[a]**, Edward Derbyshire**[b]**,
Johann Engelbrecht**[c]**, Hans von Suchodoletz**[d]**, Ludwig Zöller**[d]**,
***Pedro Dorta**[e]**, Teresa Carrillo**[f]** and Felipe Rodríguez de Castro**[f]*
[a]Department of Physics, University of Las Palmas de Gran Canaria (Spain)
[b]Royal Holloway, University of London (UK)
[c]Desert Research Institute, Reno (USA)
[d]LS Geomorphologie University of Bayreuth (Germany)
[e]Department of Geography, University of La Laguna, Tenerife (Spain)
[f]Hospital Dr. Negrín, University of Las Palmas de Gran Canaria (Spain)

ABSTRACT

The Canary Islands are located on the western dominant transport path of atmospheric dust plumes generated in the Saharan desert. The Saharan region is widely regarded as the world's greatest source of natural mineral dust, much of which is delivered to the ocean and, from time to time, reaches Southern Europe and the Americas. The fact that the Canary Island archipelago is well placed to receive advected Saharan dust plumes was registered by the State Agency of Meteorology of Spain as long ago as the 1950s. Most studies focus on the observation and monitoring of the dust transport, by analyzing satellite images provided by various agencies (AERONET; MPLNET; EARLINET). Recent research on particulate matter has expanded in recent years to include particle size measurements, aggregation, mineralogy, geochemistry, and particle reactivity, as well as considering the impact on human health and global climate.

This chapter will provide a review of previous research on Saharan dust and other aerosols undertaken on the Canary Islands, research groups and agencies involved and their key findings, as well as the main thrust of current research and prospects for future work. It will consider accumulation of Saharan dust both at present and in the past as well as its textural and mineralogical characteristics in deposits found on the islands. Particular attention will be afforded to the impact on the land surface and human population. It will be shown that for the period 2005-2007 the deposition rates on the island of Gran Canaria were of the order of 20 ± 11 g m^{-2} y^{-1}. A high percentage of aggregate in the deposited dust (> 60%) has been determined using Image Analysis of SEM-EDX. Results from these studies show that particle aggregates have lower bulk densities than individual particles, a characteristic with relevance to some existing dust plume transportation models.

On the basis of geomorphologic mapping, GIS-calculations, luminescence dating and sedimentologic-pedologic analyses of sediments trapped in volcanically-dammed valleys on the Canary Island of Lanzarote, estimates of soil moisture fluctuations in deposited Saharan dust and the hydrologic budget of the island are put forward for the Late Quaternary. These deposits provide information on anthropogenic influence on the dust source area of the nearby Saharan Desert during the Holocene and constitute a basis for quantitative estimates of dust input to this island during a large part of the Quaternary.

1. INTRODUCTION

Advected Saharan air reaches the Canary Islands with relative frequency. Different studies carried out to date indicate that Saharan air masses are present over the islands between 20 and 25% of the days of the year [1, 2, 3]. The influx of these air masses leads a notable transformation in the ambient conditions over the islands, including a pronounced rise in temperature and a marked decrease in the relative humidity especially during the hottest months of the year, a change in the direction of the dominant wind and the presence of a considerable amount of lithogenic particulate material. The analysis of the last item is the principal objective of the work referred to below. However, crustal material is not transported with every incursion of African air; its presence being extremely variable and irregular [4, 5]. On some days there are only small quantities, while on others there are massive intrusions that have a serious impact on various social, economic and environmental aspects of the Canaries.

The Canary Islands are situated on the northern fringe of the Saharan dust plume over the North Atlantic Ocean (Figure 1). Dust export from the Sahara towards the Atlantic has existed since the Lower Cretaceous, increasing in a series of steps during the Neogene and the Quaternary, notably during the desiccation of North Africa in the Upper Miocene (6-5 Ma), with the onset of mid-latitude glaciation (about 2.5 Ma) and between 1.6 and 1.2 Ma [6, 7]. In view of such continuous Saharan influence on the North Atlantic region, it is to be expected that Saharan dust is found in the soils and sedimentary deposits of the Canary Islands that date from the Quaternary.

Airborne dust derived from the Sahara Desert generates a dust plume that seasonally crosses the Canarian Archipelago and thus contributes to the sedimentation cycle on the islands and in the surrounding ocean. Complex processes of gravitational, kinetic, thermal, and aggregation forces are involved in delivering this particulate matter to water and land surfaces.

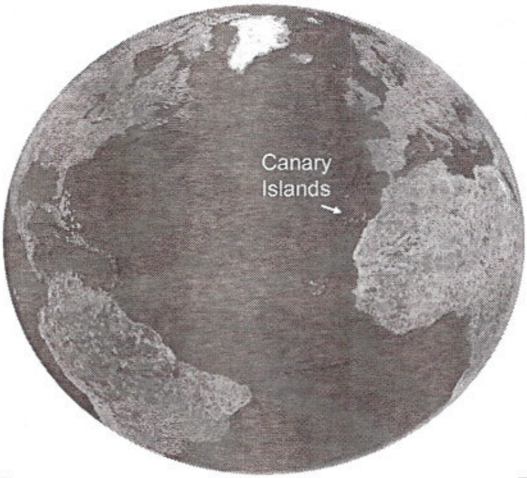


Figure 1. The geographical location of Canary Islands. Modified by Google Earth.

The potential health impact on the population of the Canary Islands of influxes of natural mineral aerosols in Saharan dust storms (local Spanish: calimas) has been recognized for some years [8]. Typically, the densest clouds of dust occur in the winter half-year [1, 9], sometimes considerably reducing daytime visibility (Figure 2) and contributing to hospital admissions in the colder part of the year.

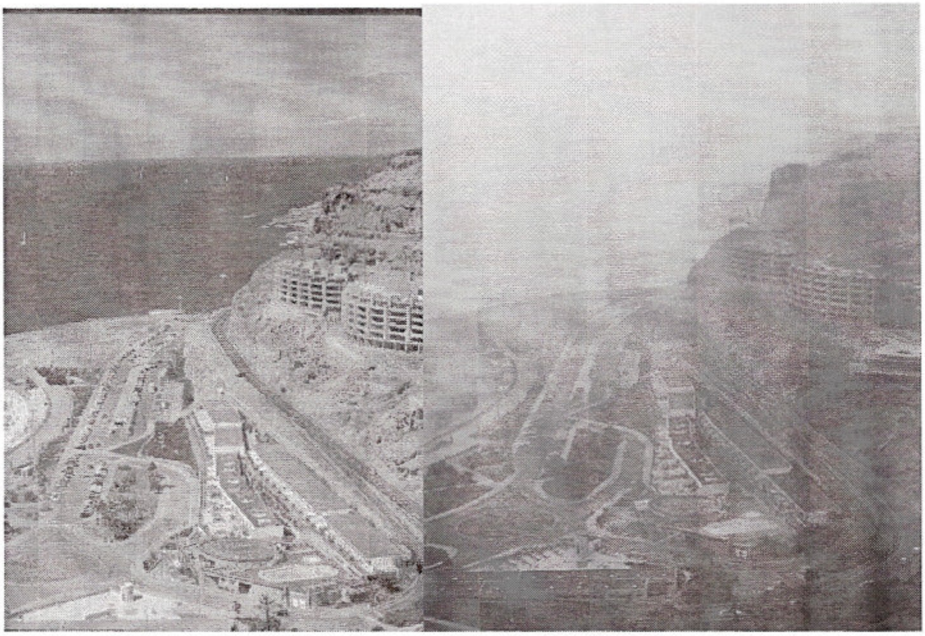


Figure 2. Playa de Amadores, Mogán County, Gran Canaria. before and during a *calima* event in March 2005. Left image – visibility greater than 100km; right image – visibility 1.5 km.

2. ORIGIN AND TRANSPORT OF SAHARAN DUST (TOWARDS CANARY ISLANDS) AND THE ARRIVALS OF SUCH PLUME DUST TO THE ARCHIPELAGO (*PEDRO DORTA)*

2.1. Background

In this sense, these dust plumes are one of the most significant characteristics of the archipelago's climate, as evidenced by its mention in all kinds of texts that have been written throughout history [10]. In addition, academics and scientists from different European countries have documented a few very intense episodes of dust held in suspension above the archipelago observed when they were present on the islands. This is the case of Scott who speaks of one event in February, 1898 [11], and Smith who refers to another such event in February, 1920 [12].

However, sound scientific work focusing specifically on these atmospheric conditions in the Canarian region did not start appearing until the middle of the 20th Century. The first was published in 1950 by the Canarian meteorologist Inocencio Font Tulltot [13], entitled "Invasions of hot African air in the Canarian Archipelago". However, it was not until the end of the 1980s that further work on this topic began emerging [14]. Although incomplete, these early studies inspired researchers at the end of the 1990s [1] to begin examining this situation more thoroughly, culminating in a substantial number of precise and scientifically rigorous works published since 2000 and covering a broad range of aspects related to Saharan aerosols [3, 10, 15, 16, 17, 18,19, 20], to name but a few.). Over the past few years this work has included numerous doctoral theses and around twenty articles published in specialised magazines. This is consistent with investigations on general scale; the number of publications on this subject has increased at a higher percentage rate than work published on climate change; a growth commensurate with the importance of the subject [21].

This ongoing examination of the atmosphere over the Canary Islands region has provided a great deal of insight into a multitude of aspects of which we had almost no information just a decade ago. The meteorological causes of the incursions of Saharan air masses have been analysed along with their approximate frequency; the quantity of material that reaches the islands has been estimated; studies have been carried out on the trajectory of the air masses; correlations with the indices of different climate teleconnections have been examined; the multiple effects of Saharan aerosols on socio-economic and environmental aspects of the Canary Islands have begun to be examined; and, finally, all of this research is making it easier to predict the meteorological conditions that favour the arrival of dust clouds.

2.2. Meteorological Causes

The synoptic situations that cause advection of dust-transporting Saharan air have been analysed in various articles. At first, authors sought to classify different types of weather conditions using somewhat subjective techniques [1, 22], but recently they have started to incorporate more advanced methods and objectives [5, 23]. An analysis of this scientific bibliography demonstrates that the lithogenic material reaches the islands in different ways.

In most cases it is removed from the atmosphere and deposited on the surface through dry deposition, although occasionally wet deposition occurs when raindrops collide with the crustal particles and drag them to the surface [24]. In other words, the majority of the Saharan dust is deposited on the islands when the atmospheric conditions are stable. This also makes clear why even the most recent research on the atmospheric circulation systems that transport dust to the Canaries confirms the prevalence of anticyclones during Saharan intrusions.

The most common synoptic scenario is one in which high pressure located over south-western Europe or north-western Africa originates flows from the second quadrant over the islands along the south-western flank of the anticyclonic centre. This situation is especially frequent during the winter months when the dynamic conditions associated with high Atlantic pressure combine with a certain thermal influence from the European continent to promote anticyclonic conditions. This makes it possible for these conditions to persist over time, giving rise to episodes that last longer than those that occur during the warm months [4]. One example of these conditions took place in February of 2004 (Figure 3).

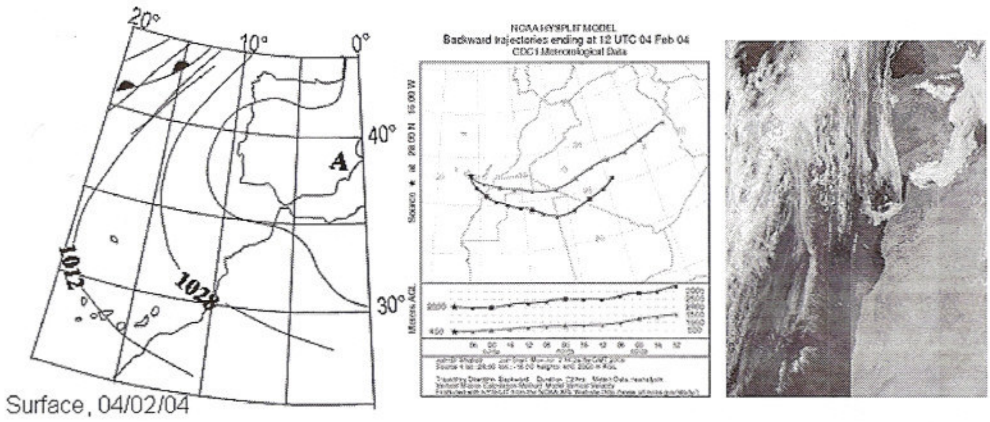


Figure 3. The intrusion of Saharan dust on February of 2004 (synoptic situation, backward trajectories and satellite image). Source: AEMET modified; NOAA: HYSPLIT model; http://oceancolor.gsfc.nasa.gov/

The most typical summer circulation is produced by a depression over the Sahara with a clear thermal influence, as a consequence of the intense desert heat during these months. At the same time, the Atlantic anticyclone extends out as a wedge toward the Mediterranean. When an easterly circulation heading toward the west coast of Africa is created and the Canary Islands are caught between the two pressure centres, intense heat waves are generated that sometimes lead to the transport of crustal material toward the archipelago. As in the earlier case, these are dry deposition episodes. Such an important advection of very hot desert air was recorded on 20 July 2005 with a considerable volume of Saharan dust (Figure 4).

A further synoptic situation is related to the presence of a depression near the archipelago, a situation referred to as "return episodes" [5] by some researchers. It is important to underscore the fact that African dust can remain over the islands for some time after the ocean circulation has been restored. Although the dominant flow has changed, the dust that remains in suspension continues to reach the island for a short period of time because of certain inertia [10, 23].

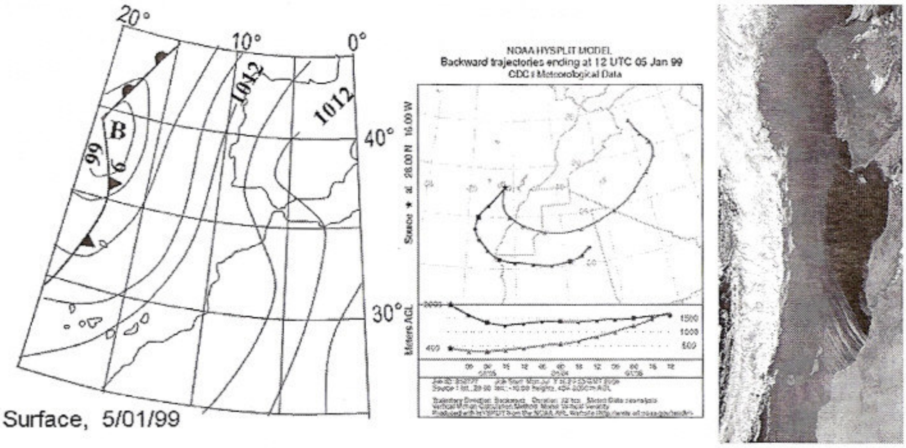


Figure 4. The intrusion of Saharan dust on July of 2005 (synoptic situation, backward trajectories and satellite image). Source: AEMET modified; NOAA: HYSPLIT model; http://oceancolor.gsfc.nasa.gov/

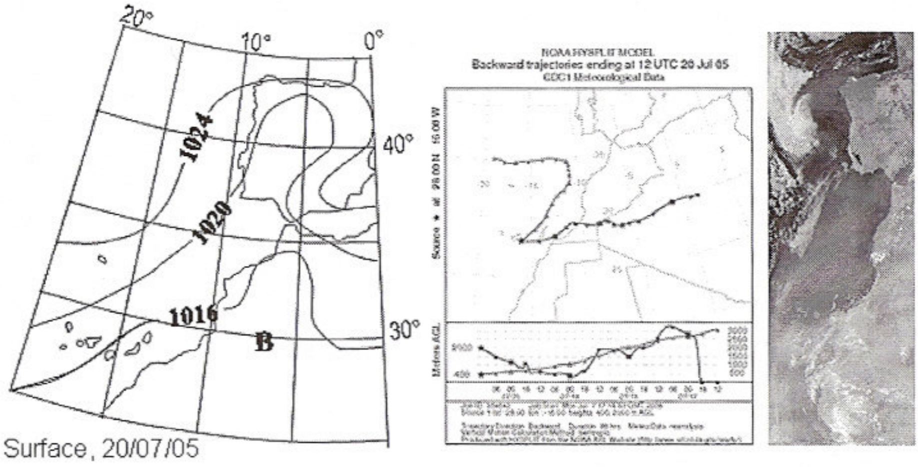


Figure 5. The intrusion of Saharan dust on January of 1999 (synoptic situation, backward trajectories and satellite image). Source: AEMET modified; NOAA: HYSPLIT model; http://oceancolor.gsfc.nasa.gov/

Occasionally, these situations provoke intrusions of Saharan air under conditions of atmospheric instability, which at times can be very intense [25], leading to wet depositional episodes when precipitation drags suspended material down to the surface. Good examples occurred in January 1998 and again in January 1999 (Figure 5). In these atmospheric situations, the low pressure draws in the Saharan air, incorporating it into the cyclonic circulation which creates a situation in which dust reaches the Canaries carried on winds coming from the Atlantic. However, far more material is accumulated on the surface through dry rather than wet deposition to the extent of between 10 and 30 times more [24].

Finally, Saharan aerosols can be dragged to the surface from the middle and upper layers of the troposphere through gravitational deposition. That is to say, material is transported at considerable altitudes during some episodes (which, as we shall see later, frequently occurs during warm months) while a north-easterly oceanic circulation is usually installed in the lower layers. The transfer of material above this first layer sometimes gives rise to a portion of the dust falling due to gravity [23]. This is another case of dry deposition.

2.3. Main Sources of Lithogenic Material

The transport of lithogenic material depends on various factors, the most significant of which are climatic conditions and geomorphological characteristics such as the nature of the wind, the type of substrate and the presence of topographic obstacles [26]. Certain anthropogenic activities such as improper pasturing or changes in land use, among others, can also influence the contribution made by different dust source regions [27]. Similarly, many different terrains across the planet are affected by the presence and transport of crustal material.

Today, the principal sources of lithogenic material contributing to atmospheric transport of aerosols are well known on a planetary scale. The extensive bibliography on this aspect allows us not only to identify different source regions [6, 26, 28, 29, etc.], but also to recognize a global dust belt. This dust source belt includes, in addition to the Sahara, a great proportion of the arid and semi-arid sectors of Asia in which are included the main deserts, such as the Taklamakan, Kyzyl Kum, Karakum, Thar, etc.

It has been estimated that the Sahara is the largest single source of crustal material on the planet, accounting for more than 50% of all the natural aerosols that are deposited on the oceans [27]. The most important sources of lithogenic material in North Africa have also been studied in detail. Today it is known that they are mostly located in the Bodélé Depression, the Sahel Belt and the Western Sahara; especially in an area between Eastern Mauritania, Western Mali and Southern Algeria [27].

Study of the sources of the lithogenic material transported to the Canary Archipelago has only recently begun, it being one of the vanguard lines of research in various research centres in the Canaries. The abundant information on teleconnection (there being various remote sensors that provide information either directly or indirectly about aerosols), the use of different indices to measure the quantities of particulate material in the atmosphere, the vast computational power of statistical tools and, above all, modelling systems have made it possible to analyse precisely the most relevant source regions.

One research technique that has greatly facilitated such studies is the use of backward trajectories created using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model developed by NOAA (National Oceanic and Atmospheric Administration). This modelling system is being implemented because it is efficient, can be applied to many different areas and provides easy access to different sources of information. The first results in the Canaries using this technique are just starting to emerge [3, 18, 19, 23].

Initial findings indicate that the main sources of the lithogenic material that reaches the archipelago are located in parts of the Western Sahara closest to the islands [5]. This region accounts for more of the dust reaching the Canaries than others where global dust production is higher but transport distance is much greater, such as the Sahel Belt or the Bodélé Depression in Chad, the latter being, without a doubt, the region that emits most dust into the atmosphere [29].

Another important conclusion reached by the creation and analysis of backward trajectories is that the air masses which convey the Saharan dust clouds show a marked difference between the boundary layer and the free troposphere. The Canary Archipelago is frequently affected by a strong thermal inversion characteristic of the trade winds which cause two substantially different layers of air to emerge. The first is located beneath the inversion and its height is variable. The second is located above the inversion and has totally different thermohygrometric properties; its first few meters are warmer and, above all, much drier with notably lower relative humidity; its winds also blow in a different direction. These are strikingly different layers of air. Furthermore, this thermal inversion is markedly seasonal, in that its altitude is higher in winter than in summer and stronger during the warm months compared to the colder part of the year [9].

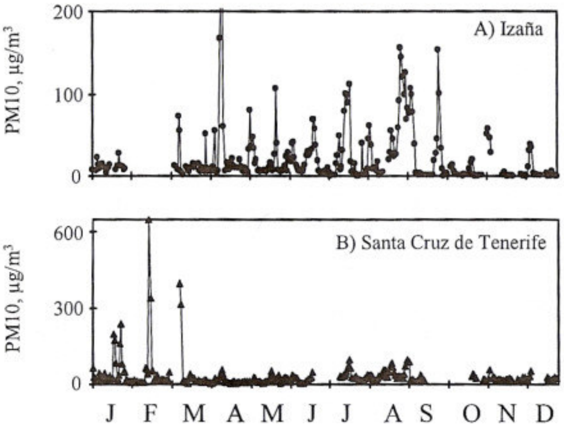


Figure 6. Daily mean concentrations of PM10 during 2005 at two sites in Tenerife Island: A) Izaña Observatory (2367 m a.s.l.; free troposphere) and B) Santa Cruz de Tenerife city Observatory (50 m a.s.l.; boundary layer). Data provided by the Izaña Atmospheric Research Centre. Courtesy of Sergio Rodríguez and E. Cuevas.

In this sense, the transport of crustal material is also clearly seasonal. Along with more frequent intrusions of Saharan air masses, the density of the Saharan aerosol in winter is noticeably higher at low and middle altitudes (mostly below 500 meters above the sea level), located in the boundary layer, where almost the entire population of the island is concentrated; nevertheless, because of its thickness, which may be considerable, the layer of dust sometimes reaches high altitudes, especially during very intense episodes [30]. Meanwhile, during warm months, dust is transported at high altitudes (mostly above 1000 meters above the sea level), above the thermal inversion, as indicated by numerous authors [5, 18]. In other words, during this period it is possible for Atlantic air to predominate in the populated regions, while a flow from the desert, laden with aerosols, is established above. In fact, the Izaña Atmospheric Research Centre, an eminent observatory located on the island at almost 2400 meters above sea level, has been able to confirm this circulation at different altitudes depending on the time of year. In light of this, the island of Tenerife is in a perfect situation to observe these phenomena (Figure 6). This Figure illustrates the different seasonal evolution of Saharan dust transport in the marine boundary layer and in the free troposphere. Observe how high PM10 occur in winter at Santa Cruz de Tenerife and in summer at Izaña

Observatory At Izaña, PM10 concentrations higher than 10μg/m^3 are due to Saharan dust transport. At Santa Cruz de Tenerife, PM10 concentrations higher than 30μg/m^3 are due to Saharan dust transport (S. Rodriguez, personal communication).

2.4. Evolution and Tendencies

As mentioned earlier, intrusions of lithogenic material are caused by the establishment of flows of Saharan air above the islands. Various studies have examined different series of data on these air masses that were recorded by stations on the ground [4] and analysed the tendencies and possible teleconnections. However, the research centred specifically on the load of crustal material is very recent [5, 19] and a large part of its results have not yet been published. Furthermore, the series are not excessively long and it is only possible to provide some estimates.

Findings to date lead to two important conclusions: first, there are significant correlations between the transport of lithogenic material and the ENSO (El niño South Oscillation) and NAO (North Atlantic Oscillation) indices; and second, there is an upward trend in the number of intrusions and the total quantity of particulate material.

Regarding the first conclusion, it can be observed that negative ENSO indices generally imply an increase in the advections of Saharan air masses [2]. It can be assumed that the incursions of crustal material occur similarly. An example of this probable correlation is the observation that there was an intense ENSO in the winter of 1997-1998, while 1998 was one of the years with the greatest amount of Saharan atmospheric dust incursions over the Canaries and a large number of days when Saharan air was prevalent over the islands [2, 15, 24].

There are also studies indicating that there is a link between the NAO and the African intrusions, in that a high positive index implies a greater concentration of dust over the Canaries [24]. Research that employs relatively long series of data obtains moderate but significant correlations, arriving at the conclusion that the pattern of the NAO teleconnection significantly influences the intensity of the winter incursions of Saharan dust [5]. This fact is consistent with what other authors indicate about an increase in the amount of dust being driven out toward the Atlantic during winters with positive NAO indices [31].

Finally, it must be noted that the studies have not found a statistically significant correlation between this phenomenon and another possible teleconnection, the Sahel Rainfall Index (SRI), despite the fact that this region is relatively close to the islands. The author of the main research on this subject points out that this finding demonstrates that the southern edge of the Sahara contributes a negligible proportion of the crustal material that reaches the Canaries, at least in the boundary layer [5].

Regarding the second conclusion about the upward tendency of the quantity of Saharan aerosols over the Canary Islands, it must be noted that this subject has been studied by researchers with diverse series and data. The most complete statistical study carried out to date shows an upward tendency, although analyses of tendencies is a complex undertaking given that different data sources or different indicators can be employed. Different statistical tests undeniably indicate that there has been a general increase in both the frequency and intensity of the Saharan dust episodes, particularly after the 1970s, and also beneath the thermal inversion, in the boundary layer [5].

Finally, it should be mentioned that the latest research is starting to use indirect methods to detect intrusions of Saharan dust in the Canaries [32, 33]. For instance, the high correlation that seems to exist between the concentration of some radioactive isotopes, like 137Cs and 40K, and the arrival of lithogenic material in the islands allows researchers to trace these dust intrusions by measuring the isotopes, a technique that will make the detection of Saharan dust in the atmosphere even more precise.

3. PAST RECORDS OF SAHARAN DUST ON THE CANARY ISLANDS

(HANS VON SUCHODOLETZ AND LUDWIG ZÖLLER)

3.1. Occurrence of Saharan Dust Deposits on the Canary Islands

Saharan dust is readily recognized in the Canaries by the presence of quartz, which is not authigenically formed by the local basic volcanism [34]. Consequently, the widespread existence of quartz in Canarian soils, or at least in their upper horizons, demonstrates that Saharan dust constitutes a major component of the parent material involved in recent pedogenesis [e.g. 34, 35, 36, 37]. The marginal infiltration of yellowish material containing quartz into lapilli and vesicular basaltic rock fragments that were ejected during volcanic eruptions in the middle of the 18th century on Lanzarote [38] (Figure 7) shows that dust trapping has continued until the present. Furthermore, the occurrence of quartz in palaeosols of different Quaternary ages found in various relief locations in Lanzarote and Fuerteventura shows that all these palaeosols evolved from material containing at least a certain proportion of Saharan dust [36, 39, 40] (Figure 8).

Figure 7. Saharan dust (white arrows) infiltrating a vesicular lava fragment from Lanzarote that was ejected during volcanic eruptions in the middle of the 18th century.

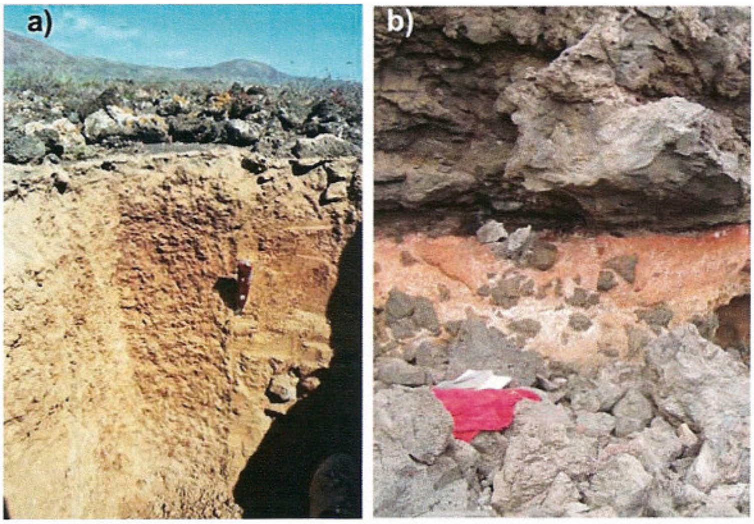


Figure 8. Soils of different ages in the eastern coastal plain of Lanzarote near Costa Teguise, both exhibiting quartz contents during XRD analyses: a) polygenetic soil profile < 170 ka (unpublished data) overlain by a desert pavement, b) palaeosoil fritted by a lava flow ca. 170 ka ago (unpublished data).

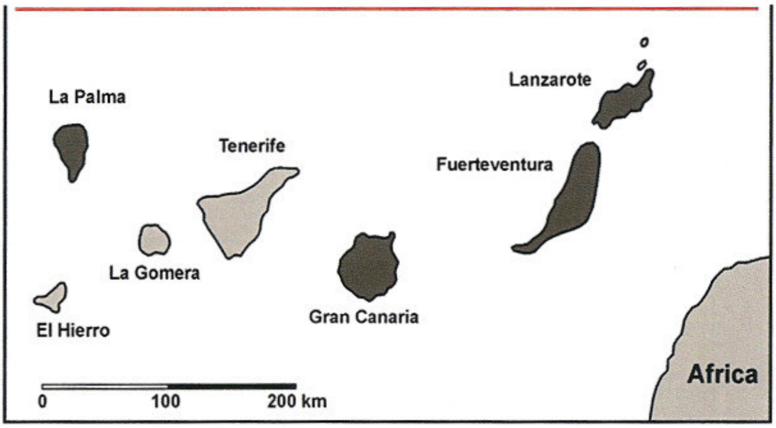


Figure 9. The Canary Islands. Those islands with described or recently discovered stacked Quaternary Saharan dust deposits are dark coloured.

In certain places, Saharan dust deposits form stacked sequences with thicknesses of some meters deposited during some long periods in the Quaternary. Until very recently, such stacked Quaternary sequences were reported only from the oldest and thus most eroded islands of Lanzarote and Fuerteventura on the eastern side of the archipelago [41, 42, 43]; they have not been detected on the younger, western islands, which exhibit a much steeper topography. However, this situation recently changed with the publication by Menéndez et al. [44] of an account of such deposits on Gran Canaria, as well as with the discovery of stacked sediment sequences composed of quartz-bearing material by L. Zöller on La Palma in 2008. Ideally, such deposits develop where old valleys or flat plains were dammed by younger volcanic material of Early Pleistocene to Holocene age, subsequently leading to sediment deposition up to a thickness of a few tens of meters (Figures 9, 10). Similar, but somewhat thinner deposits can be found on flat valley terraces, on the more gentle slopes or on plateau surfaces (e.g., sediments 10 m thick occur on a plateau in northern Lanzarote close to the Mirador del Río; 4 m of sediments are found on a gentle slope in eastern La Palma; Figure 11). However, owing to the high erodibility of the latter deposits hiatuses must be expected here. As is evident from the widespread presence of quartz, the majority of these stacked sediments consist of Saharan dust with only a minority of local volcanic material [44, 45, 46].

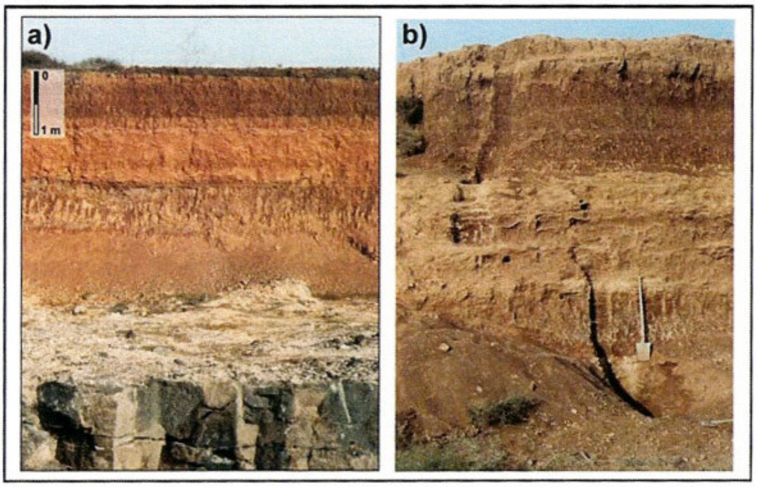


Figure 10. Outcrops of sediments containing Saharan dust mixed with local volcanic material trapped in dammed valleys (*vegas*). Quartz contents were determined by semi quantitative XRD analyses. *a)* Outcrop of 4 m of trapped sediments overlying a Late Quaternary basaltic flow [47] in the *vega* of La Oliva (northern Fuerteventura). The sediments have quartz contents between 7 and 30%. *b)* Outcrop of 6.3 m of trapped sediments in the *vega* of Femés (southern Lanzarote). The sediments contain between 6 and 39% of quartz

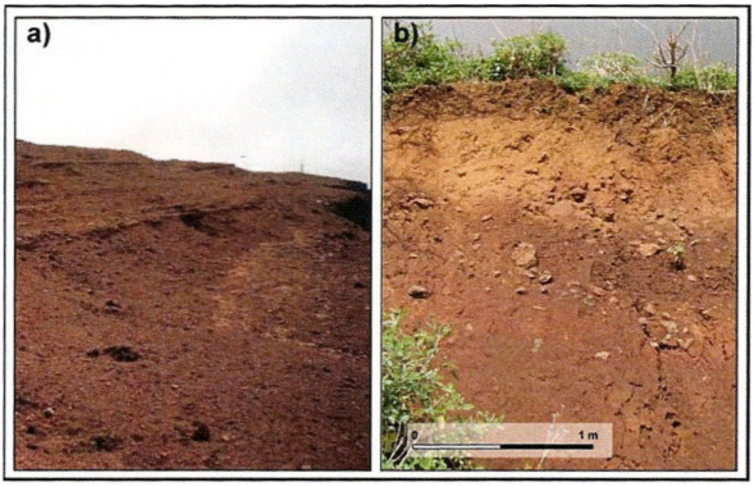


Figure 11. Sediments derived from Saharan dust on plateau positions and slope flattering. The presence of quartz is demonstrated by qualitative XRD analyses. a) 10 m of sediments deposited on a plateau close to Mirador del Río (northern Lanzarote). b) Almost 4 m of sediments deposited on a slope flattening above Santa Cruz (eastern La Palma).

These sediments show marked alternations between reddish-clayey and yellowish-silty layers, and are believed to constitute palaeoenvironmental archives [47] (Figure 10). Below we present results from some investigations of wind-lain dust archives in three lava-dammed valleys in Lanzarote.

3.2. Saharan Dust Deposits from Lanzarote as Palaeoenvironmental Archives

Lanzarote, the northeasternmost of the Canary Islands, has several valleys or flat plains that were dammed by volcanic material during the Quaternary and today are filled with sediment accumulations up to 50 m thick. Locally, these sediment traps are called vegas [48]. The location of vegas in Lanzarote known to the authors is shown in Figure 12.

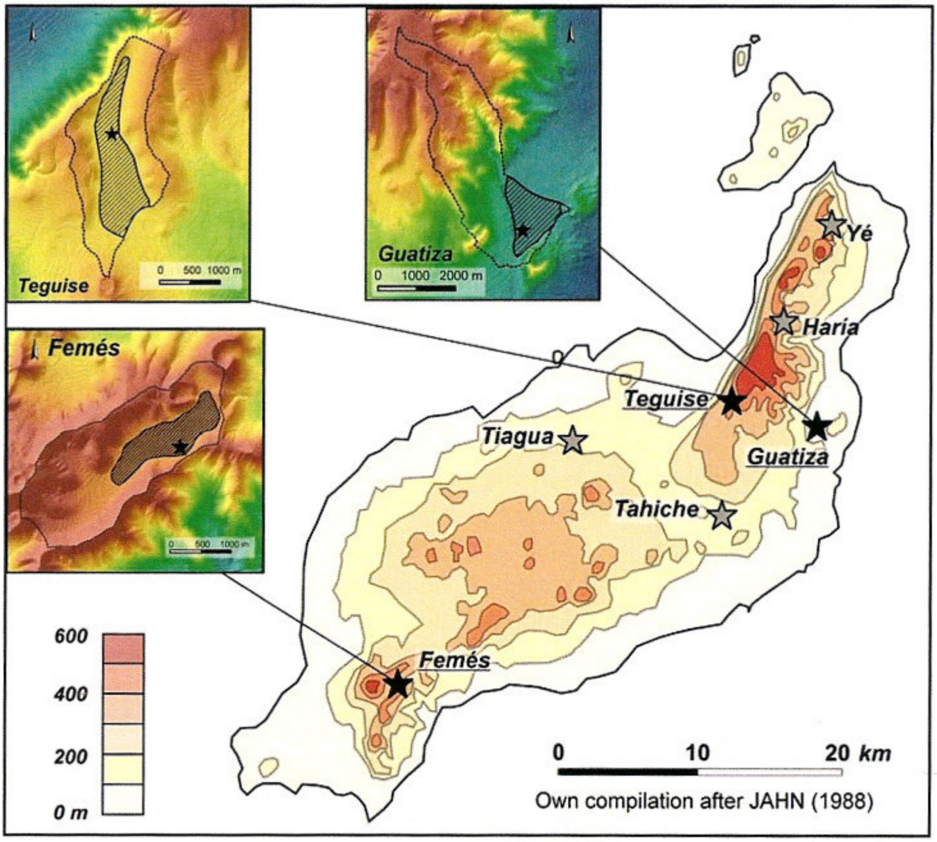


Figure 12. Location of outcropped *vegas* on Lanzarote known to the authors. Further investigated sites are shown in black and their name is underlined, whereas not investigated sites are indicated in grey and their name is not underlined. The insets show GIS-models of further investigated *vegas*, where dashed lines indicate the catchment areas and hatched surfaces highlight the valley bottoms. The location of investigated outcrops in the *vegas* is shown with black stars.

3.2.1. Dust Deposits as Archives of Palaeo-Soil Moisture

Loamy *vega* sediments were outcropped by the local population in order to gain material for agricultural purposes, and clearly show various distinct layers of reddish and yellowish material. This intercalation of different layers is believed to reflect archives of past palaeoenvironmental conditions. Thus, during a research project carried out by a research group from the University of Bayreuth (Germany), three *vegas* in Lanzarote with a well developed stratification (Guatiza, Teguise, Femés) were investigated with a view to revealing the palaeoenvironmental history of Lanzarote (Figure 12). The investigations were based on a multi-method approach that comprised geomorphological mapping, GIS-analyses, environmental magnetic measurements and sedimentologic-pedologic analyses. Chronostratigraphies of the *vegas* sediment accumulations were built up using luminescence dating, further supported by interprofile correlations and correlations with proxies from nearby marine cores [46].

The results show that outcropped sediments in the valley bottoms were almost continuously deposited between the Middle Pleistocene and the Holocene (Figure 13). Owing to the fact that the sediment archives are situated on the local erosional base level in the valleys or *vegas*, however, trapped sediments contain *in situ* eolian material (Saharan dust and volcanic fallout) as well as material that was originally deposited as eolian fallout on the slopes, but was later reworked and transported to the floors of the *vegas* by colluvial processes. Sedimentation rate and the proportion of *in situ* and reworked material in the archives directly depend on the valley bottom: catchment area ratio, which was determined by GIS-analyses (Figure 12, insets). Consequently, the outcrop in the Guatiza *vega* (Guatiza III) with a valley bottom: catchment area ratio of 1:6.2, has the highest proportion of reworked material and thus the highest sedimentation rate, followed by the Femés *vega* with a ratio of 1:5.4 and the Teguise *vega* with a ratio of 1:2.9 [49].

The crucial question raised by these archives is whether the colluvial transport from the slopes occurred in "low frequency/high magnitude" fashion or if it was a "high frequency/low magnitude" process. In the former, rare events would have deposited large quantities of sediment, strongly disturbing the chronological sequence of the sediments. In the latter case, however, frequent erosional events would have mobilised small amounts of material, causing only small disturbances of the chronological sequence. In the latter case, therefore, a palaeoenvironmental interpretation would be possible, albeit with a somewhat reduced temporal resolution compared to sediments exclusively deposited as eolian fallout. In order to address this problem, it is useful to recall a classic study of landscape stability related to annual precipitation. Langbein et al. [50] demonstrated that the highest erosion rates generally occur in a precipitation regime with annual precipitation rates of between 100 and 550 mm, conditions that prevail on the island of Lanzarote today (100 - 250 mm/a, [36]) and that are assumed to apply also to former moister palaeoclimatic (ca. 560 mm/a, see below; [51]). Furthermore, marine studies off NW-Africa show that the climate of the region during the last glacial cycle was strongly influenced by high-frequency millennial climate fluctuations, such as Heinrich-events and Dansgaard-Oeschger cycles [52, 53] that probably impeded continuous stabilisation of slopes by vegetation growth. Thus, the colluvial sedimentation most probably occurred as a "high frequency/low magnitude" process, with frequencies at a scale of hundreds to a maximum of some thousands of years.

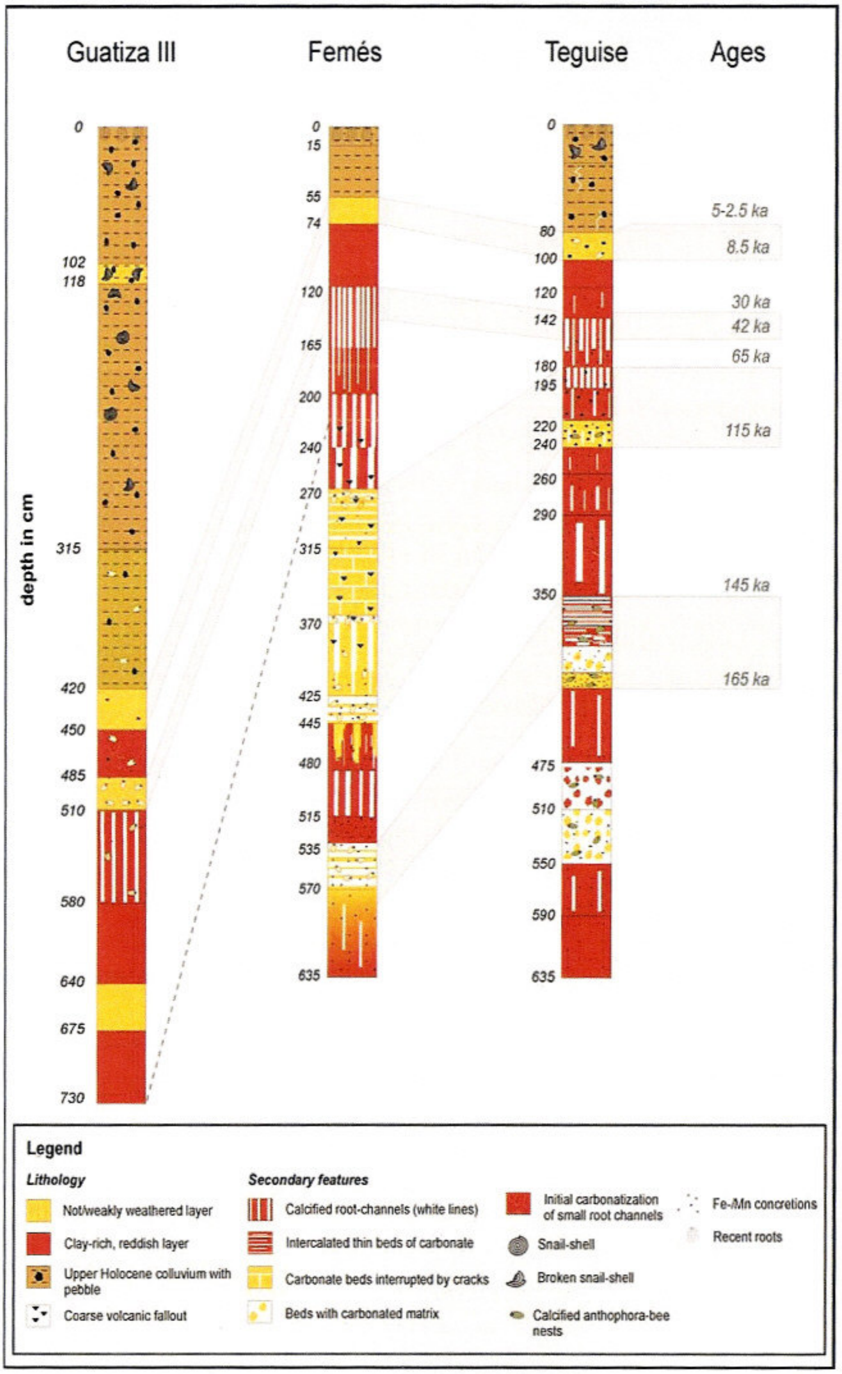


Figure 13. Investigated profiles in Guatiza III, Femés and Teguise with chronological frame. The upper horizons contain anthropogenically triggered colluvia of various thicknesses (from 55 to 420 cm) that can not be used for palaeoenvironmental inferences.

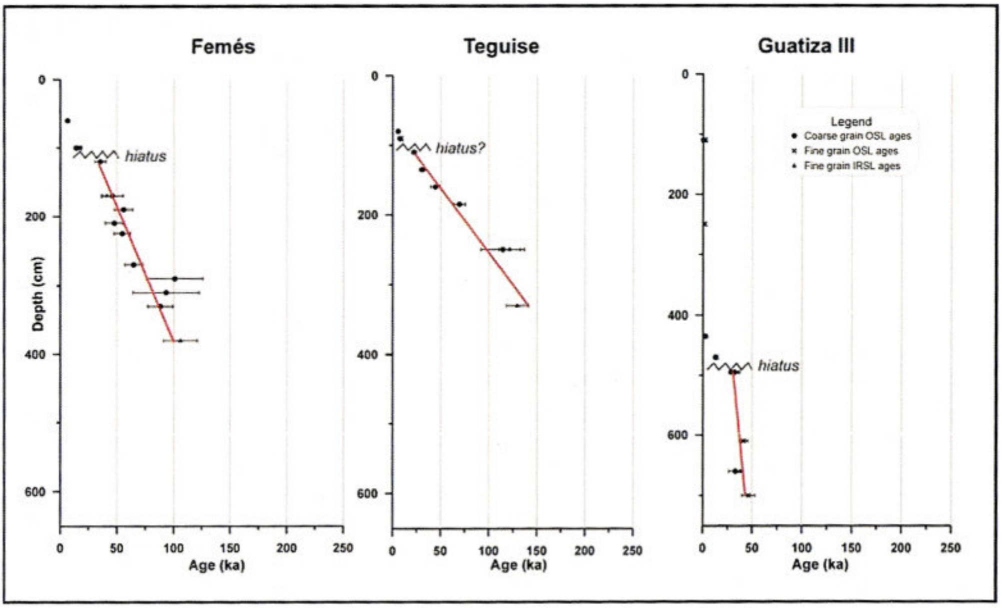


Figure 14. Luminescence dating results from the *vegas* of Lanzarote. Mean sedimentation rates are drawn as a red line in every *vega*. No large disruptions of this rate within error bars are detected arguing for a more or less continuous sedimentation into the valley bottoms.

This hypothesis is supported by our luminescence dating results, which indicate a largely continuous sedimentation rate in the valleys without notable disruptions (one exception being a conspicuous hiatus between ca. 15 and 25-30 ka in all *vegas*; Figure 14). This demonstrates that the *vega* deposits can be used as palaeoclimatic archives, even given that temporal resolution is unlikely ever to be better than some hundreds or thousands of years.

In order to investigate past palaeoenvironmental conditions, proxies sensitive to changes in palaeoenvironmental parameters have to be identified. In the case of the sediments from Lanzarote, the change from reddish-clayey to yellowish-silty layers is believed to have been caused by different intensities of pedogenesis, a process directly dependent on palaeo-soil moisture. However, because of the high proportion of colluvial material in the valley floor sediments, it is clear that reddish/clayey layers are mostly soil sediments derived from pedogenesis that occurred on the slopes, rather than as *in situ* palaeosols. Furthermore, a crucial question is whether the observed alternation of sediment properties was acquired *in situ* during pedogenesis on the island, or if these properties were inherited from a change in Saharan dust source(s). To investigate this problem, clay contents were measured in silty and clayey horizons, exhibiting values between 23 and 80% [51]. However, dust recently collected close to the Canary Islands shows clay contents of <15% [25, 54, 55], and a marine study 300 km north of the Canary islands revealed maximal clay contents of only 25% derived from Saharan dust during the last 250 ka [56]. This indicates that clay contents of up to 80% in the *vega* sediments are not directly inherited from Saharan dust, but were instead formed by pedogenesis in Lanzarote. It follows that the clay content can serve as a proxy of pedogenesis on Lanzarote during the Late Quaternary. The proportion of ultra-fine superparamagnetic particles in sediments can be identified by measuring frequency dependent magnetic susceptibility (κ_{fd}). These small particles are produced during pedogenesis and are often used as a proxy of pedogenesis in palaeopedological studies [57, 58]. This parameter is found to be strongly enhanced in reddish/clayey layers in the *vegas* of Lanzarote, with its depth dependent function running almost parallel to that of the clay content (Figure 15). This confirms the pedogenetic origin of superparamagnetic particles on the island, adding strength to the view that frequency dependent magnetic susceptibility can also be taken as a proxy of pedogenesis and thus of palaeo-soil moisture. When looking at the depth dependent distribution of these proxies, it emerges that parts of Marine Isotope Stages (MIS) 2, 3, 4 and 6 experienced a higher soil moisture than today, whereas most parts of MIS 1 and 5 were apparently as dry or even drier than the present (Figure 15). This pattern shows that global cold periods were generally characterized by moister, and globally warm periods by drier conditions on Lanzarote. Furthermore, we compared pedogenetic features from the *vegas* of Lanzarote with those of a catena developed on Holocene volcanic material on Tenerife [59], supported by a comparison of the occurrence pattern of ground-nesting anthophora-bees in the *vega* profiles with their ecological spectrum [39, 60] (Figure 13). These comparisons lead us to the conclusion that maximal soil humidity on Lanzarote during periods of strong pedogenesis was equivalent to that in a region of Tenerife with a recent precipitation amount of about 560 mm/a [51]. Due to the dependence of soil moisture on precipitation, temperature and insolation (cloudiness) this value is not directly transformable into palaeoprecipitation values. However, it does provide a broad indication of past humidity conditions on Lanzarote during generally cold phases of the Late Quaternary.

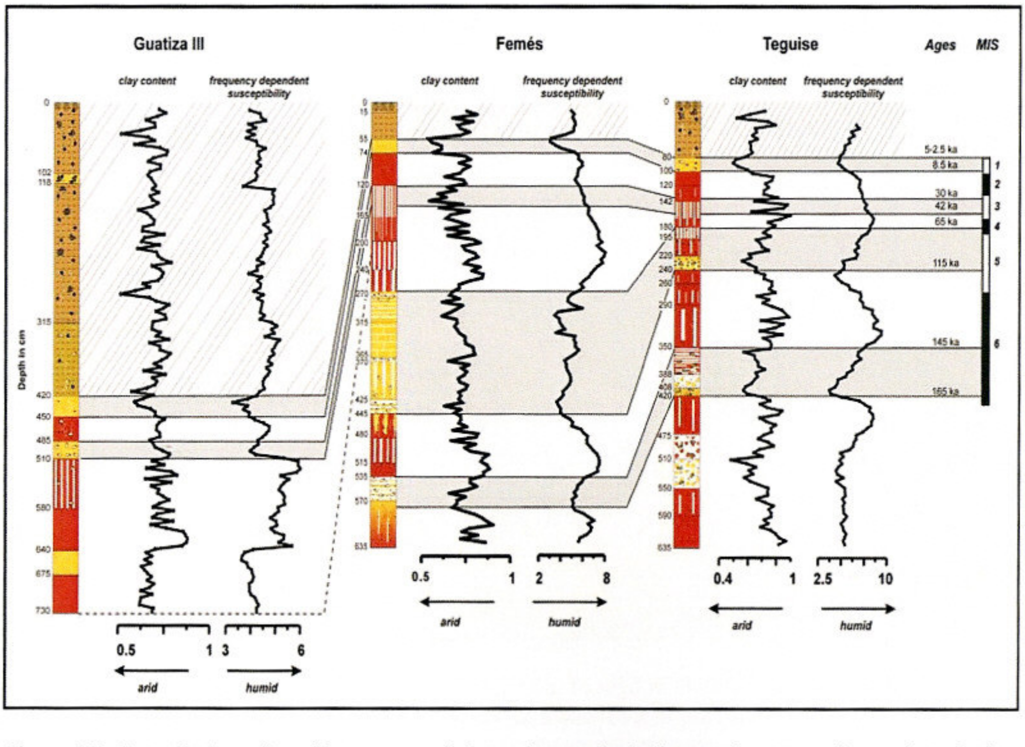


Figure 15. Compilation of profiles, ages and the pedogenetic (palaeoenvironmental) proxies relative clay content (arbitrary scale) and frequency dependent magnetic susceptibility (%). Shaded sections indicate more arid periods, hatched areas anthropogenically triggered colluvial. Ages and Marine Isotope Stages (MIS) are indicated on the right side.

3.2.2. Saharan Dust Deposits as Archives Of Palaeo-Dust Input

Using geomorphological mapping and GIS-analyses in combination with our chronostratigraphy, as well as with K/Ar-datings of volcanites from the same volcanic group that makes up the lava flows that dam the vegas [61, 62], it was possible to calculate a chronological sediment mass balance for the completely dammed vega of Femés [49] so as to provide a base for conclusions about changes of Saharan dust input on the island. In order to construct this mass balance, the floor of the Femés vega was divided into 10 different segments for which sediment volumes were calculated separately. Sediment thicknesses for every valley segment needed for this calculation were determined by extrapolating the slope forms into the valley bottom using GIS software (Figure 16). Results of geomorphological mapping were used to estimate surface and thickness of alluvial fan deposits as well as the remaining sediment thickness on eroded slopes.

The results of this investigation demonstrate that dust input steadily increased from about 1.0 Ma until the present, as already stated in former studies of the eastern Atlantic [6, 7] (Figure 17). Despite some smaller uncertainties in luminescence dating and in measurements of recent dust falls over the Canary Islands, it is apparent that the highest dust input of the period of the Quaternary studied here, occurred during the Holocene, whereas extremely high values exceeding all past magnitudes are found today [37, 55]. This would appear to indicate that the elevated values of dust input recorded during the Holocene and especially during the recent period have not only a climatic cause but must, in addition, have been triggered by factors other than aridity, e.g. human impact in the Saharan dust source areas.

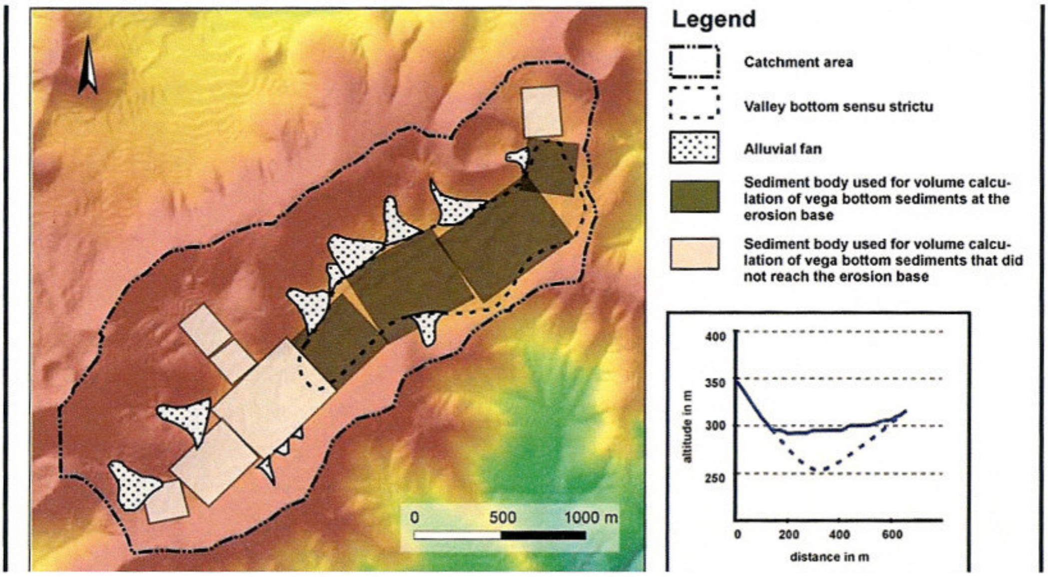


Figure 16. Calculation of the sediment budget of the *vega* of Femés: The *vega* bottom was divided into different sediment bodies whereof some are located at the erosion base (in the valley bottom *sensu strictu*) and others at somewhat higher elevations where the material must be regarded as temporarily stored. In order to calculate the depth of every sediment body, cuts were made through the valley and the sediment depth in the sediment bodies was finally determined by extrapolation of the slopes (see dashed line in the example of the inset). The limits of the valley bottom *sensu strictu* and of alluvial fans were determined by geomorphologic mapping.

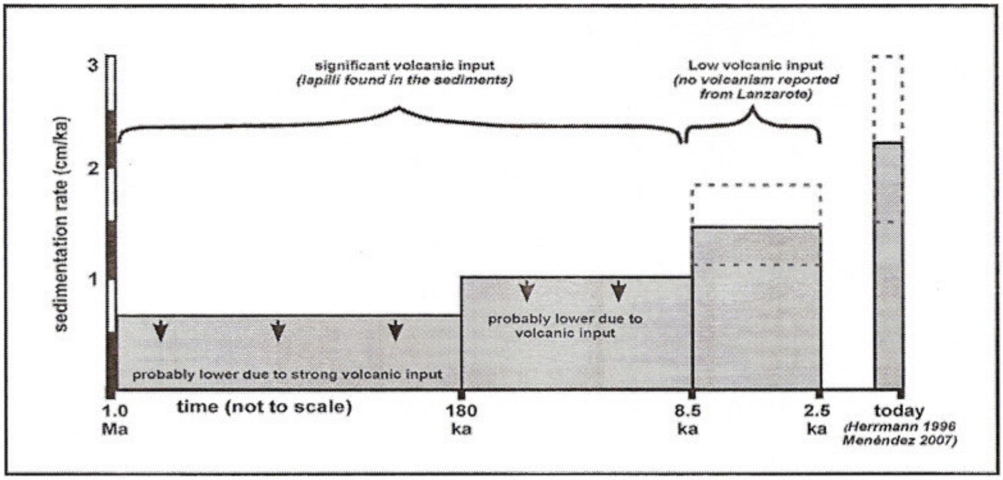


Figure 17. Evolution of dust input on Lanzarote based on the sediment mass balance of the *vega* of Femés. Dashed lines indicate the uncertainty of calculations during the Holocene (own data) and for the recent period [37, 55]. Between 180 and 8.5 ka as well as between 1.0 Ma and 180 ka dust input was probably lower than derived from the sediment mass balance due to volcanic input recognizable in the profiles. In the latter case this reduction was probably more important, since a layer of 30 cm almost exclusively composed of lapilli and tephra was found in a drilling below the recent surface of the outcrop [43].

4. DEPOSITION RATES, GRAIN-SIZE DISTRIBUTION AND MINERALOGY OF SAHARAN DUST ON THE CANARY ISLANDS

(INMACULADA MENENDEZ AND JOHANN ENGELBERCHT)

4.1. Deposition Rates of Saharan Dust on the Canary Islands

4.1.1. Dust in the Air

Dust concentrations in air over the Canary Islands and their surrounding oceanic areas were measured over a decade ago in Fuerteventura [14] and in Tenerife (Izaña Observatory, 16°29'58'' W, 28°18'32'' N [63, 64, 65]), revealing equivalent mineral dust concentrations ranging from 0.14 to 285.7 μg m^{-3} (deduced from the average concentration of Al in crustal materials: 6-8%; [65, 66]). Direct measurements were made also during a specific Saharan event (July 2002: 396-345 μg m^{-3}; [67]), with a Saharan dust episode threshold in Tenerife later deduced, at a concentration up to 28.5 μg m^{-3} [23]. Since the 1990s, airborne dust measurements have been extended to Gran Canaria [15, 24, 68, 69] with a mean value of 47 μg m^{-3} and Saharan dust pulses exceeding 1000 μg m^{-3} (Figure 18).

One of the most interesting characteristics of this airborne particulate matter is its impact on the air quality. The Saharan dust influence is now analyzed in the two most populated islands of the Archipelago (Gran Canaria and Tenerife; [23, 70], with atmospheric particulate matter (PM10 and PM2.5) being monitored by the air quality network of the Canarian Government, following EU Air Quality Directive EC/30/1999.

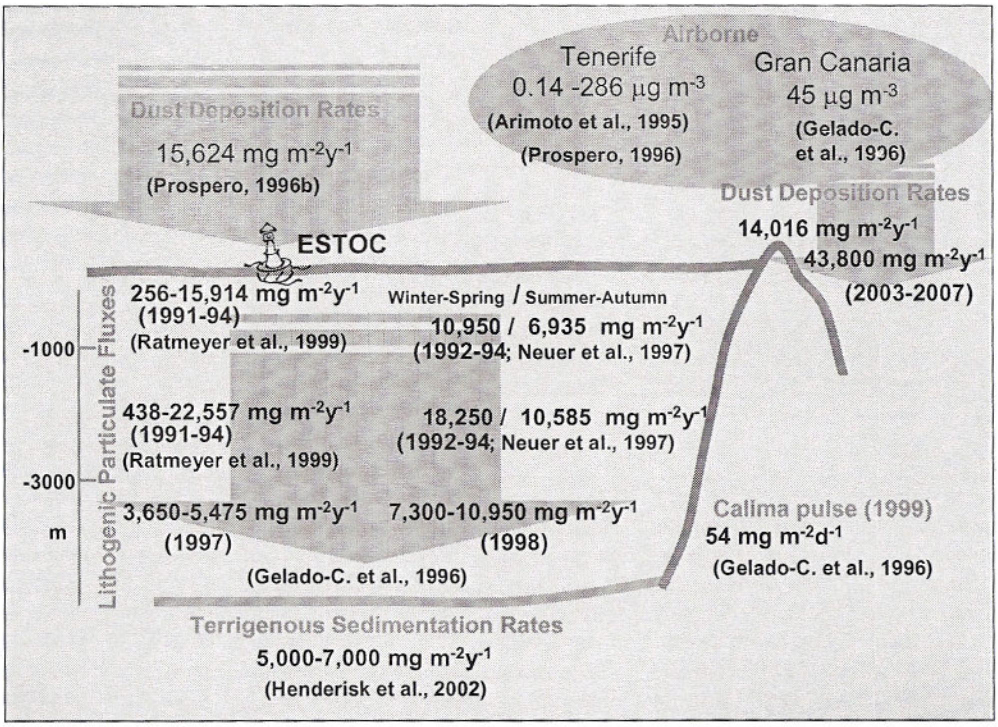


Figure 18. Process of Saharan dust distribution in the region of Canary Islands, from the air to the land surface and to the ocean surface, towards the water column and last sedimentation in the basin.

4.1.2. Dust Deposition Rates on The Islands

Deposition rates for the Canary Islands were estimated by Prospero ([64], in Table 2.a pp. 142, in a grid box of 20°-30°N/20°-10°W), following the GESMAP empirical model, with a value of 15624 mg m^{-2} y^{-1}. In contrast, current manually measured dust inputs on Gran Canaria (from 2003 to 2007) at different altitudes and geographical locations indicates deposition rates of between 14016 and 43800 mg m^{-2} y^{-1} . The highest rates were registered at the lowest altitudes [55] and in the areas with greater exposure to the trade winds (N-NE-E; Figure 19). The recycled product, occurring as local dust, of this deposited Saharan particulate matter in the more arid and populated coastal areas may account for the higher values obtained by manual measurements compared to previous estimates.

4.1.3. Lithogenic Particulate Fluxes in the Ocean

When airborne dust is deposited in the ocean it is called lithogenic particulate. Such Saharan-derived particulate fluxes add to the phytoplankton development [24, 68, 71]. The input of such airborne dust plumes to the oceanic fluxes probably favours physical aggregation and rate of settlement of oceanic particles [72, 73].

A number of lithogenic particle fluxes have been monitored in the proximity of the Canary Islands (European Station for Time-Series in the Ocean, Canary Islands, ESTOC Station 29°15'N-27°11'W; [69, 71. 74] (Figure 18). Deposition rates of airborne dust at the ocean surface defined for the Canary Islands region (15624 mg m^{-2} y^{-1}; [64]) falls in the maximal range obtained for lithogenic fluxes at 0-1000 m depth by Ratmeyer et al. ([74];

256-15914 mg m^{-2} y^{-1}). A marked seasonality was found in the study period carry out by Neuer et al. ([71]; sampling period from 1992 to 1994), clearly showing higher lithogenic fluxes in late winter-spring than in the summer-autumn period. This result matches the periodicity of the highest calima pulses in the Canarian region; here, also, the dust input peaks more frequently in winter-spring than in summer-autumn [1, 9].

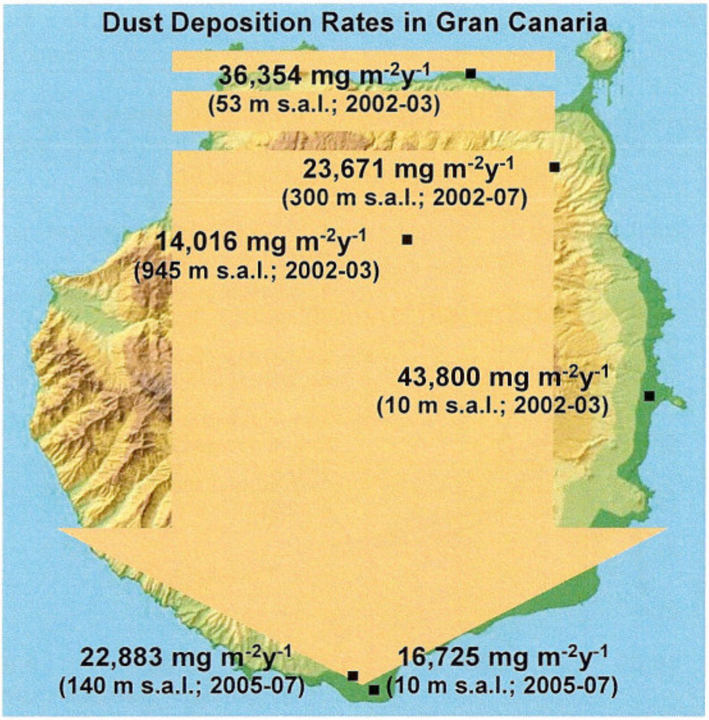


Figure 19. Dust deposition rates, in mg m^{-2} y^{-1}, on the Gran Canaria Island, at different altitudes and exposures.

4.1.4. Deposition Rates on the Seafloor

Airborne input to the ocean water column is integrated in the gross particulate production of the ocean (including mainly organic matter, carbonates and siliceous skeletons). Henderiks et al. [74] have defined a sedimentation rate for the Holocene in the Canary Basin of 1-2 g $cm^{-2}ka^{-1}$ (10000-20000 mg m^{-2} y^{-1}). Lithogenic particles (the terrigenous fraction, most of which is assumed to be aeolian in provenance) total 0.5-0.7 g $cm^{-2}ka^{-1}$ (5000-7000 mg m^{-2} y^{-1}). These rates are lower than measured at land sites, a result arising from the different densities and viscosities of the media, being higher in the ocean water column than in the air.

4.2. Grain-Size Distribution of Saharan Dust on Canary Islands

4.2.1. Particle Size of Airborne Dust

Measurements of airborne dust made in Gran Canaria (1980 m s.a.l.) in the period 1997-1998 reveal unimodal curves centred on the 4.9 or 2.7 μm range with a fine fraction 'tail'

(Figure 20; [24]). Apart from this characteristic, there does not appear to be a great difference in Saharan dust fall from one day to another. Grain size distribution in Tenerife, measured in July and August 2005, also produced a unimodal curve centred on 1.5 μm [76] (Figure 20). This same mode was also detected by Maring et al. [77] and a secondary mode, for aerosols, was found at around 0.2 μm, which increases with distance from the source (comparing Tenerife with, for example, Puerto Rico in Gran Canaria) because of the preferential removal of the coarser grain sizes during atmospheric transport.

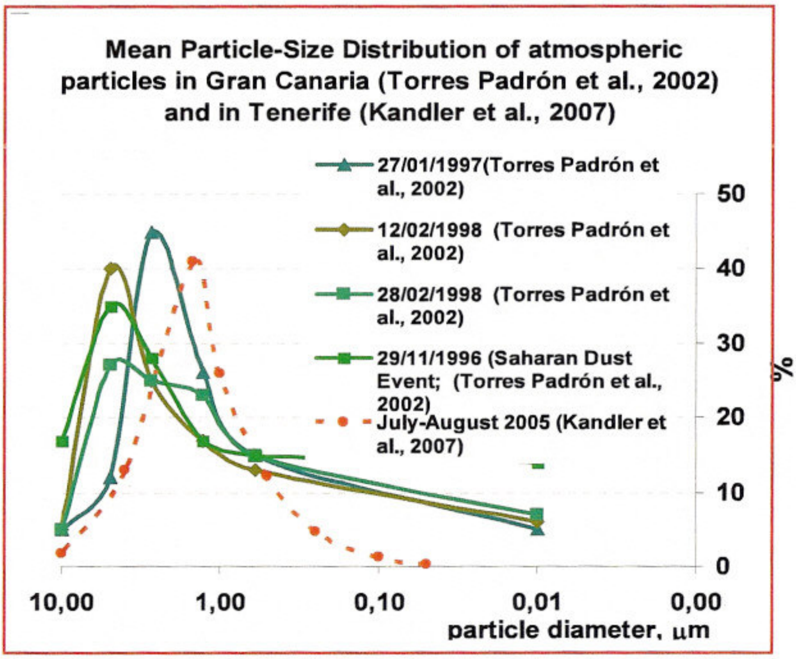


Figure 20. The particle-size distribution of the Saharan airborne dust at Gran Canaria and Tenerife Islands. It is remarkable the unimodal tendency.

Airborne plumes from Saharan sources are not composed of individual particles only, but include aggregates of particles [67]. The occurrence of these aggregates in airborne dust may well be a factor in the overestimation of the Stokes gravitational settling rates of large particles during atmospheric transport from North Africa across the tropical North Atlantic and the Caribbean, detected by Maring et al. [77].

The presence of Saharan dust in urban/industrial areas may enhance the secondary particles formation due to heterogeneous reactions. For example, the formation of sulphate and nitrate onto Saharan dust particles has been documented on Santa Cruz de Tenerife [67]. This implies that Saharan dust impairs the air quality by increasing PM10 and PM2.5 concentrations by two ways: 1) by increasing the concentrations of mineral compounds, and 2) by enhancing the SO_2 (gas) → sulphate (PM) and NOx/HNO_3 → NO_3^- (PM) conversion. The latter process alters the surface of the dust particles and consequently its impact on the environment (S. Rodríguez, *personal communication*).

4.2.2. Dust Grain-Size on the Islands

The granulometry of samples of deposited dust collected from sites on Gran Canaria Island during 2003-2004 also display a bimodal curve with a principal mode around the medium silt size (0.016 mm), with another, secondary peak in the very fine silt size (0.004 mm), and a coarser fraction 'tail' (Figure 21). Comparison of the granulometry of airborne dust and that deposited on the land surface poses no problem because each has a distinctive size range (airborne >10 µm - <0.01µm compared to >250 µm - <2 µm for land-deposited dust). Both types share a common size range (>10 µm - <2 µm) as shown by the two measured points in deposited dust (8 µm and 2 µm). Comparison of this size range in both sample types clearly shows a tendency for airborne dust to peak towards the finer fraction and the converse to be true of dust deposited on the land surface. This is consistent with the gravitational settling effect in which the coarser particles tend to settle before the finer fractions, as well as the greater abundance of coarse fractions in deposited dust.

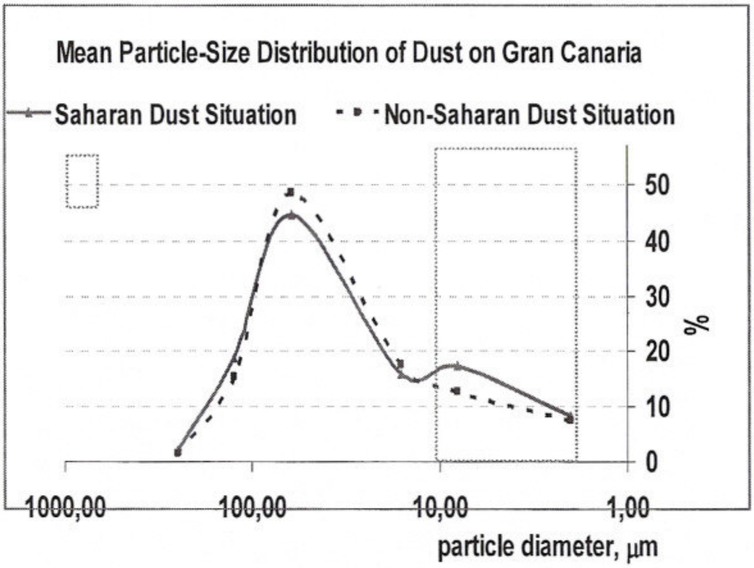


Figure 21. The particle -size distribution of the deposited dust on Gran Canaria Island, differentiating the Saharan dust presence and absence in the atmosphere of the island. The dotted area is the particle range comparable with the particle distribution of the airborne dust of the islands.

As with airborne dust samples, numerous aggregates (Figures 22-24) made up of mixed size particles are present in land-lain samples that form aggregations in which the medium-coarse silt fraction is dominant. The aggregates quantified using SEM-EDX images are frequently more numerous than individual particles, estimated at around 60%. Such a high percentage is important because the particular physical characteristics of the aggregates gives them a lower bulk density and slower fall velocity when compared with single mineral particles of the same dimensions.

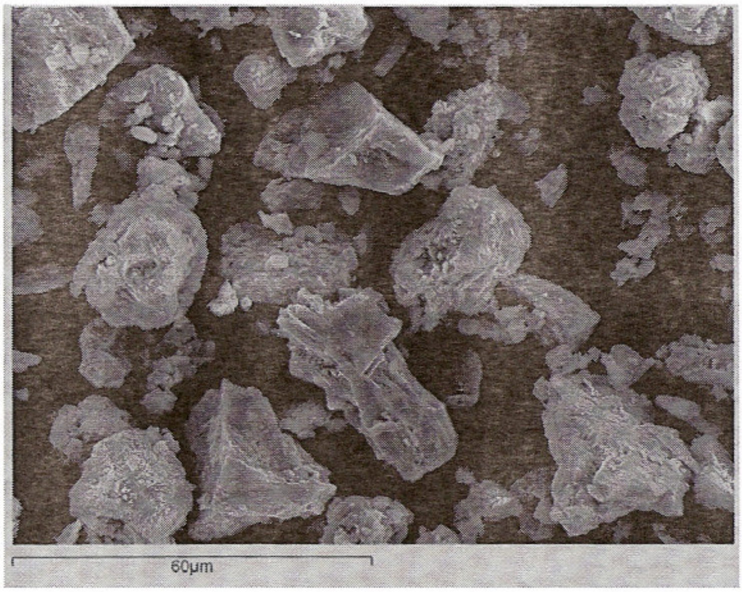


Figure 22. SEM-EDX image of the deposited dust on the Gran Canaria Island, showing mineral particles and aggregates.

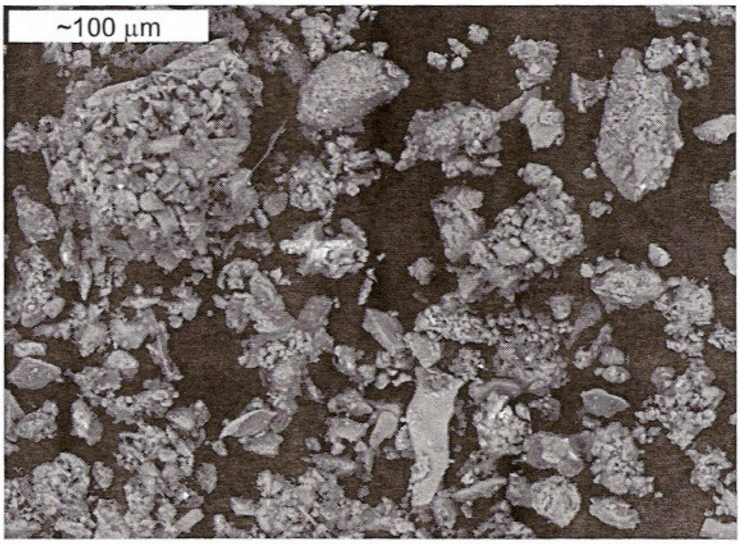


Figure 23. Other example of the EDX image from the deposited dust on the Gran Canaria Island, showing mineral particles and aggregates.

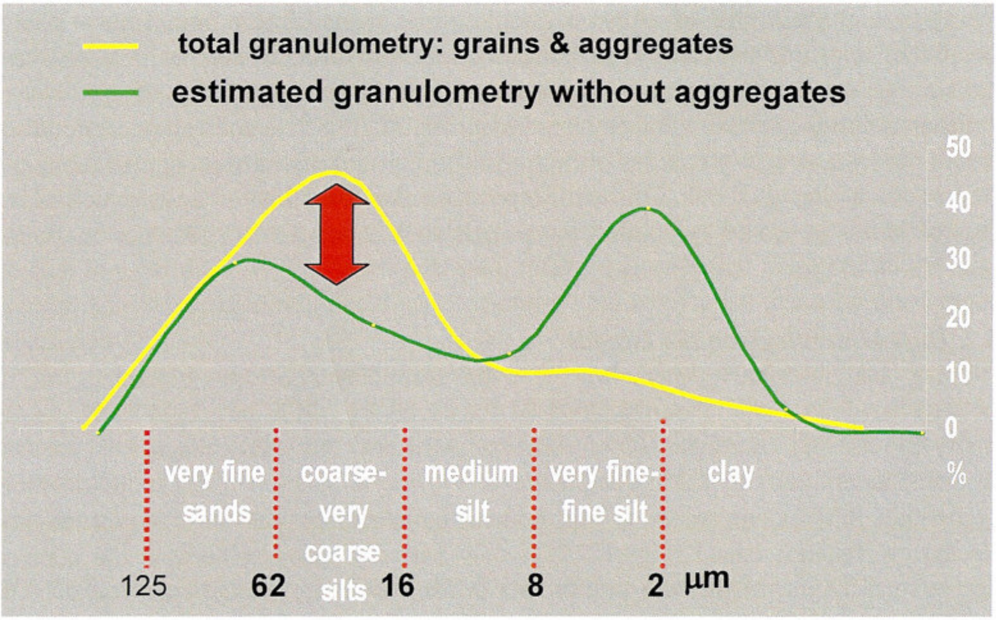


Figure 24. The polymodal curve of particle size distribution in deposited dust samples on Gran Canaria, considering the total particles (grains and aggregates) and the estimated curve of the disaggregated sample, with a consequent increment of the finer fractions.

4.2.3. Lithogenic Grain-Size Within the Ocean and on the Seafloor

Using a variety of instrumental methods including Sedigraph, FRITSCH laser and CIS-GALAI particle analyzer, Ratmeyer et al. [74] found that particle size of dust samples varied greatly according to the instrument used. For example, the < 6 µm particle fraction in a Gran Canaria site was 68, 43, and 7% according to the Sedigraph, FRITSCH laser and CIS-GALAI particle analyzer, respectively. The < 2 µm showed even greater variability (49, 18 and 0% for Sedigraph, FRITSCH laser, CIS-GALAI particle analyzer, respectively). Not surprisingly, these authors rejected the < 6 µm particles size for the purpose of comparison with airborne dust, but they considered that the > 10 µm grades were sufficiently reliable for valid comparisons. Our work inclines us to agree with this decision because grains > 10 µm in diameter represent 80 % of the sizes in a sample [55].

Other authors [78] (in their study of the Namibian Slope) also give more weight to the coarse-grained component of their two cores as reflecting the airborne dust input to the ocean.

4.3. Mineralogy of Saharan Dust on the Canary Islands

4.3.1. Mineralogy of Airborne Dust

African dust collected on Tenerife and analyzed using XRD (X-ray diffraction) and SEM-EDAX (scanning electron microscope-electron dispersion and X-ray; [67]) was found to be made up of clay minerals and quartz (47% and 23%, respectively). The majority of the particles appear to be coated with sulphates, with an average thickness of 60 nm; aggregation of these particles was observed clearly by SEM-EDX (Figure 5 of [67]). Examination of the mineralogy and grain size of airborne samples finer than 0.5 μm from Izaña (Tenerife) showed that sulphates and carbonaceous material dominate aerosol composition. Above this grain size, the dominant composition is dominated by the silicates [76].

Saharan dust may act as cloud condensation nuclei (CCN). It is not well understood at the moment the hydroscopic properties of dust and if this is able for absorb significant amounts of water for acting as CCN. This will depend on the solubility of dust, which may be enhanced if this is coated by soluble compounds such as sulphate (S. Rodríguez, *personal communication*) [76].

4.3.2. Dust Mineralogy on the Islands

Using semiquantitative methods, the main components of the mineralogy of dust deposited on Gran Canaria during 2003-04, analyzed by XRD and SEM-EDX, includes quartz (42% ± 22%), carbonates (40% ± 13%), feldspars (11% ± 8%), magnetite (7% ± 8%) and small quantities of halite, sulphates and clay minerals (illite, kaolinite-chlorite, palygorskite; [55]). Comparison of this mineral composition with the composition in air collected on Tenerife Island (Figure 25) is only partially possible, because the grain size range is so different, so that the proportions differ. However, the minerals found in both fractions are similar (excepting magnetite) while, with respect to the mineral proportions, there is an increase in quartz and carbonates and a decrease in clay minerals in deposited dust compared to airborne particulates. The reason for this difference may arise from the smaller bulk particle size of the airborne dust samples in which the clays are concentrated. Magnetite is a heavy mineral (5200 kg m-3), its high density explaining why it is not detected in the airborne dust collected in Tenerife.

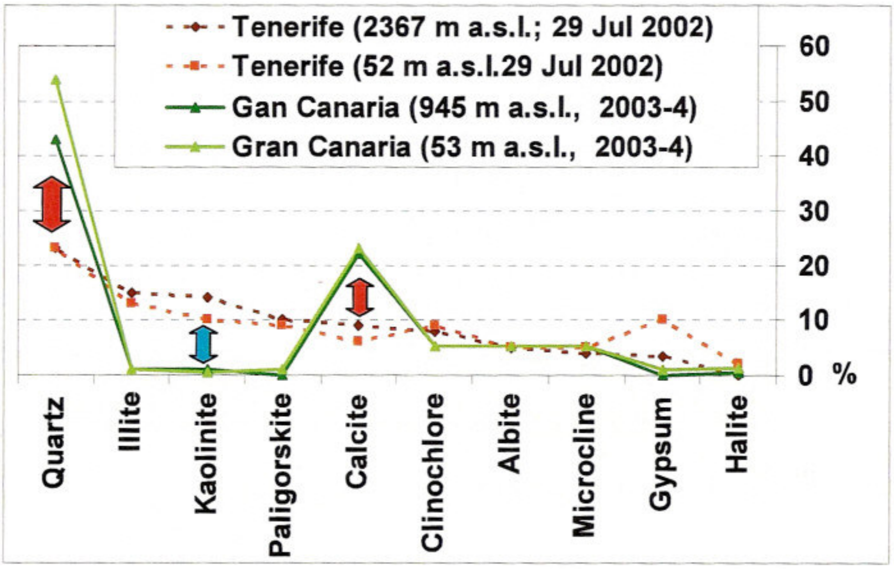


Figure 25. The mineral composition and abundance on the airborne dust samples collected in Tenerife and deposited dust on Gran Canaria Islands, at different altitudes.

The silica-subsaturated nature of potential protoliths in the Canary Islands [79], characteristic of an oceanic island volcanic setting, precludes source of the widespread quartz presence by paragenesis of the underlying rocks. The origin of the quartz is clearly allochthonous since the volcanic rocks in this archipelago rarely contain this primary mineral. Yet the overwhelmingly external origin of the airborne dust minerals does not prevent some recycling circulation in the islands. This can be affirmed from the fact that the concentration of quartz in airborne dust sampled on days with a Saharan dust pall is very similar to dust collected in clear days with no such dust pall, quartz concentration being only 10% higher under Saharan dust pall conditions, thus confirming both an external and a recycled input of Saharan dust [55].

There are eight major minerals in most mineral dusts and soils of arid areas: i.e. quartz, feldspar, calcite, gypsum, illite, kaolinite, smectite and hematite, for both the clay and silt fractions. On a global scale, there seems to be a reasonable relationship between the dust and soil mineralogies [80]. However, this is not always the case for soils from the Canary Islands where there is no local source for quartz.

4.3.3. Lithogenic Mineralogy Within the Ocean and on the Seafloor

Lithogenic accounts of particle fluxes in the ocean usually detail its terrigenous fraction [56, 81]. It mainly consists of quartz and clay particles reflecting the mineral composition and climatic conditions of the source. The highest frequency of airborne input in Canary Islands seems to correspond to glacial-interglacial transitions [56].

5. POTENTIAL IMPACT ON HUMAN HEALTH OF SAHARAN DUST PALLS OVER THE CANARY ISLANDS

(EDWARD DERBYSHIRE, TERESA CARRILLO AND FELIPE RODRÍGUEZ-DE CASTRO)

5.1. Potential Pathology

Pathological effects associated with prolonged or chronic inhalation of mineral dust are subject to many factors. Particle size and composition are of particular importance. Inhaled mineral particles larger than 10µm (PM10) tend to lodge in the upper respiratory tract and are rejected by expectoration. However, the potential impact of coarser particulates may have been underestimated in the face of increasing legislative attention being concentrated upon the PM2.5 fraction; we need to know to what extent different mineral species are toxic wherever they may lodge in the respiratory system. The component of airborne dust finer than 10µm (the *respirable fraction*) may remain suspended in the atmosphere for weeks. These finer fractions and especially those finer than 4 µm (including the conventional PM2.5) are able to penetrate deeply into the narrower lung passages. In many parts of the world, case studies strongly suggest that rates of chronic respiratory disease increase with denser ambient dust loads and longer (decadal) periods of exposure [82].

Prolonged inhalation of the <4 µm mineral dust fraction eventually leads to deposition and accumulation in the pulmonary alveoli (where oxygen exchange takes place) in which chronic lung disease is initiated. Although the precise nature of the pulmonary response to mineral dust particles is complex, a number of factors are known to influence potential toxicity. These include the presence of specific minerals within the respirable fraction, the shape of particles (which influences clearance from the lungs), the presence or absence of mineral coatings, and particle surface characteristics including surface area and surface chemistry.

The numerous agents found within natural mineral dust palls have the potential to cause cell damage if absorbed by animal and human tissue. Important naturally occurring groups present as particles, encased within larger particles or as particle coatings, include the silicate minerals (notably quartz), asbestiform minerals, and metals and metalloids such as arsenic, cadmium, iron, led and mercury. The toxicity of minerals varies with their valences and species [83]. Examples include divalent iron (Fe^{2+}) as particle surface coatings and the quartz species cristobalite in volcanic situations (*e.g.* [84]). Some metals are known to cause lung cell damage because of a potential for oxidative stress (imbalance involving increased oxidants compared to antioxidants) and the generation of free radicals (groups of atoms with one unpaired electron - hence unstable and highly reactive), which interfere with cell function and cause DNA mutation [85], leading to pathology.

Taking a regional view, quartz (SiO_2: 'free silica') is the dominant mineral in natural dust derived from the extensive North Africa-Middle East drylands. The measured quartz content in major dust storms emanating from parts of North Africa (60.95%) is closely similar to the average quartz content of Earth's crustal rocks (58.98%), although the percentage varies with distance from source and dust pathway, as shown by the reported range of quartz content in dust palls over the Canary islands (>60% to <25%).

Free silica is a highly fibrogenic agent in the lungs; prolonged exposure to it can lead to the progressive and seriously disabling disease known as silicosis. Most of what is known about silicosis (including the sequence inflammation-low level fibrosis-massive fibrosis) has been drawn from *occupational* situations, however; non-occupational silicosis has received relatively little attention even in locations where large communities are exposed to high concentrations of ambient dust [82]. At the same time, some contaminants in quartz may reduce its toxicity, notably aluminium salts with which it commonly occurs. Association of silicosis with tuberculosis has been recognized for many years, notably in inhabitants of some dryland regions.

Some forms of biogenic silica (mainly occurring as diatoms, phytoliths and testate amoeba with diameters <10μm), many associated with palaeo-lake basins (Figure 26, modified of a world map of potential lake areas by Tegen [86]), are quite commonly seen in deposited mineral aerosols including Saharan dust over the Canaries (Figure 27). Typically, they contain a number of impurities, including alkali metals, alkaline earth oxides and Fe ions. Little research has been undertaken on this group but, because they lack surface radicals, their impact on lung tissue is considered to be benign [87], although a view exists that biogenic silica forms found in soils and aerosols may be a potential health hazard, albeit an unproven one (*e.g.* [88]).

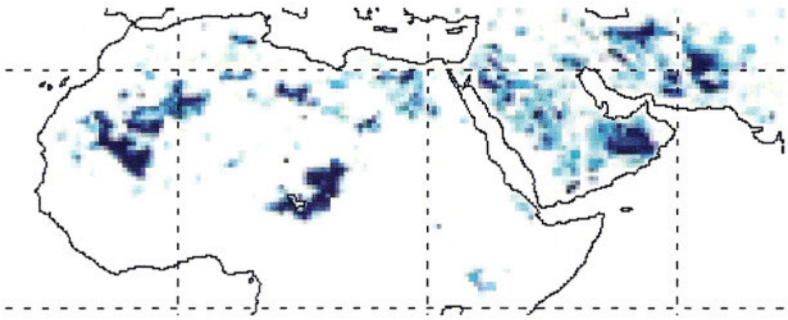


Figure 26. Areal coverage of preferential dust sources in the Greater Saharan Desert calculated from the extent of potential lake areas, excluding actual lakes but including palaeo-lake basins. (Fragment of a world map of potential lake areas by Tegen [86]).

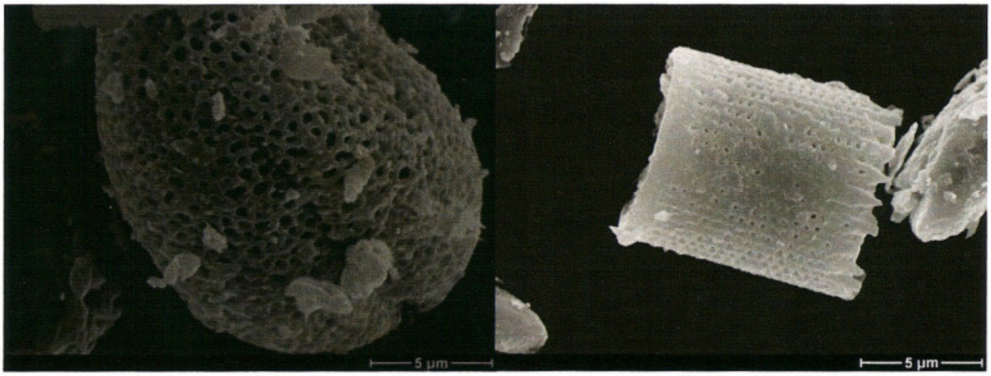


Figure 27. Diatoms typical of those deflated from desiccated Saharan-Sahelian lakes, *e.g. Aulacoseira granulata*, deposited on Gran Canaria in dense *calima* conditions on 4 March 2004.

The impact of airborne mineral dust on lung tissue may be further exacerbated by the presence within fine dust particles of bacteria, fungi, viruses and other micro-organisms (*e.g.* [89]). The long-distance transport of such organisms has the potential to damage plants and animals, including human subjects (*e.g.* [90, 91, 92]). While most micro-organisms are destroyed by exposure to ultra-violet radiation, a proportion will survive if lodged in cavities and cracks within suspended mineral dust particles. A comprehensive assessment of micro-organisms in dust storms and their health implications has recently been published by Griffin [93].

5.2. Saharan Dust over the Canaries: Recent Progress and Future Potential

The perceived importance of natural dust influxes such as those experienced in the Canary Islands and the Mediterranean Basin has led the European Commission to pass air quality legislation (Directive 1999/30/EC) that sets the standard for controlling emissions of particulates finer than 10 µm (PM10). This directive has been recently replaced by a new directive which establishes limit values for PM10 and PM2.5.(Directive 2008/50/EC). For this reason, PM10 and PM2.5 concentrations are already been monitored by the government of the Canary Islands (there as 3 stations at the moment, and about 4 new stations will be installed in the next year; S. Rodriguez, personal communication).

Al these actions has stimulated scientific work designed to measure the transportation and deposition of all types of atmospheric particles [89, 91, 93, 94, 95, 96, 97, 98, 99]. As already indicated, the vast majority of PM10 particles found in the Canaries are of Saharan origin. Their quantitative study and analysis is thus a priority in Canarian sampling and measurement stations such as the Center for Atmospheric Research Izaña from which initial results are now available [23]. An important outcome of the Directive concerns the measurement of the impact upon populations in many of the regions surrounding the Sahara, such as the Mediterranean Basin, where frequent incursions of mineral aerosols are of Saharan origin. Ways and means of measuring and quantifying the crustal material that reaches the archipelago are now emerging, in order to distinguish natural input from those arising from anthropogenic activities [100]. High quality meteorological data for the detection of imminent dust incursions is also a priority, there being several general prediction models such as SKIRON (http://forecast.uoa.gr/dustindx.html) of the University of Athens, MEIDEX (http://luna.tau.ac.il/~peter/MEIDEX/english.htm) of the University of Tel Aviv and DREAM (http://www.bsc.es/plantillaH.php?cat_id=519; Dust Regional Atmospheric Model) based in the Division of Earth Sciences in the supercomputing center in Barcelona. All provide real-time information and are available online.

When the respirable dust percentage is high during dust storm events in the Canaries, some 35% - 40% by volume may be finer than 10μm with about 20% being finer than 5μm ([101]; Figure 28). This may give rise to increased hospital admissions for cases of breathing disorders, including asthma, from early winter to early summer. Dust samples collected regularly during Saharan dust falls at several sites on the island of Gran Canaria, including a summit site (1930 m), contain measurable amounts of several elements implicated in lung function disorders and disease. Silicon is dominant in all cases (quartz > 60% [102]; Gelado et al. unpublished; Table 1).

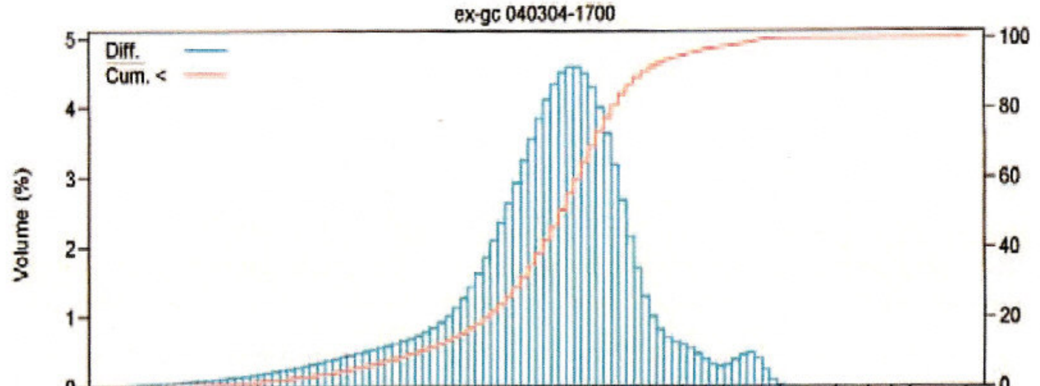


Figure 28. Modal and cumulative percentage volume curves for natural Saharan dust deposited on the island of Gran Canaria in the first week of March 2004. The PM10 fraction makes up almost 40%, and the PM2.5 almost 20% of the total volume. [101] (original analysis courtesy of Kenneth Pye).

Table 1. Gran Canarian Dust - Trace Aerosol Composition (at Taliarte site – near sea level). Potential links between selected elements in Saharan dust over Gran Canaria and some known lung function conditions and diseases. Key to colours. Red = cancer. Purple = cancer suspected. Brown = cancer and asthma. Turquoise = emphysema. Yellow = asthma. Other agents such as As (cancer) and V (asthma): no data for Gran Canaria. Geochemical data kindly provided by Dr. Maria Dolores Gelado, Universidad de Las Palmas de Gran Canaria.

	N	Minimum	Max	Median	Dep. typical
Mn (ng/m3)	63	2.12	1096.02	50.14	141.69
Fe (µg/m3)	101	0.9	57.00	1.98	5.85
Co (ng/m3)	101	0.16	23.00	1.13	2.46
Pb (ng/m3)	101	1.51	44.78	9.90	7.83
Cu (ng/m3)	101	1.76	63.93	11.64	12.90
Cd (ng/m3)	101	0.01	2.75	0.24	0.40
Mg (µ/m3)	100	0.03	429.39	17.56	59.94
Al (µ/m3)	100	0.30	148.60	4.40	15.06
Ca (µ/m3)	78	0.23	786.10	23.82	119.56
Na (µ/m3)	100	0.27	802.48	70.84	103.81
Cr (ng/m3) [but species critical]	41	1.20	154.38	18.72	29.62
Zn (µ/m3)	79	0.01	11.92	0.50	1.36
Ni (ng/m3)	38	0.32	31.72	3.38	5.71
Ti (µ/m3)	38	0.05	0.46	0.15	0.09

In general, the impact of natural wind-borne dust on human health in the form of chronic pathology reflects long-term exposure of subjects, commonly measured in decades. However, certain short-term high-density dust palls may give rise to a number of responses, especially in vulnerable subjects such as the young, the old and the infirm. Some results from the Canary Islands illustrate such short-term responses. For example, a recent unpublished analysis of emergency cases admitted to the Dr. Negrín Hospital in Gran Canaria provides a comparison between ailments recorded both outside of and within Saharan dust (calima) situations for the period 2005 to 2008. It appears that the admissions for tonsillitis, asthma, breathlessness, nasopharyngitis and pneumonia do not appear to correlate with the incidence of calima conditions, but that cases of bronchitis, sore throat and other non-specific respiratory problems do show a correlation (Table 2). In a study of admissions on the island of Tenerife, the control group was ten times larger and the total number of patient cases much greater than in the Gran Canaria case, such that the Tenerife results may eventually prove to be more indicative. However, further research will be necessary to explain these preliminary results.

Table 2. Incidence of hospital cases of selected clinical conditions in Gran Canaria in relation to *calima* events from January 2005 to March 2008 inclusive.

	Number of clinical cases in hospital emergency			
	Mean	sd	sum	n
	1	0	5	5
AMIGDALITIS ACUTE	1	0	6	5
	2	1	115	62
ASTHMA	2	1	77	42
	6	3	448	76
ACUTE BRONCHITIS	4	3	268	60
DISNEA ALTERATIONS IN	5	3	425	80
RESPIRATORY SYSTEM	5	4	316	61
	2	1	21	13
FARINGITIS ACUTE	1	0	8	7
NASOFARINGITIS ACUTE	1	1	15	11
(COMMON COLD)	1	0	8	7
PNEUMONIA, AGENT NOT	3	2	183	71
SPECIFY	3	2	164	55
OTHER RESPIRATORY and	4	2	281	74
Chronic obstructions	3	2	199	61

🟨 calima situation

The potential for major advances in the study of this branch of the multi-disciplinary science of medical geology is substantial. Given their location in relation to the greatest single source of geogenic dust on Earth, the Canary Islands are well placed to contribute to this rapidly emerging and societally relevant field.

There is much to be discovered using the aggregated skills and expertise of Earth, atmospheric, medical and social scientists. Notwithstanding the half century record and limited number of field and clinical case studies of silica-related diseases, for example, together with more recent laboratory experiments, understanding of the nature of the reactive mechanisms of environmental particulate silica at the molecular level remains incomplete. So far, none of the physicochemical features of silica used to explain its evident pathogenicity appear to be compatible with the available toxicity data [87]. Lung cell response to silica toxicity varies with dust sources, mineral species and even different surfaces of the same mineral specimen [103], suggesting an important degree of variability in 'the quartz hazard' [104].

6. CONCLUSION

The Canary Islands constitute a privileged observatory for investigation of aerosols. Its geographic situation on the western edge of the Sahara, its topography, with measuring stations sited at different altitudes and their scientific infrastructure, with three important research centers including two universities and the Izaña Atmospheric Research Centre, facilitates contributions leading to substantial advances in this scientific topic. This is so, especially in studies about the transport of lithogenic material, the effects on the population, and the properties and role of these aerosols in the energy balance of the planet and, therefore, in climatic change.

The work carried out to date gives rise to the following important conclusions: The Canary Islands lie along the northern edge of the habitual Saharan dust plume, so that the archipelago is only occasionally invaded by intrusions of lithogenic material, although massive arrivals are not unknown. Irregularity is one of the main characteristics of these intrusions. Most of these events take place in winter at low levels with summer events generally being higher. In both cases the most common synoptic situation is essentially anticyclonic. The main source of lithogenic material that reaches the islands is one sector of the Western Sahara nearest to the archipelago. Finally, it must be noted that a relation exists between a greater dust concentration on the Canary Islands and an intense ENSO in the Pacific, as well as high positive NAO indices.

Deposits derived from Saharan dust are ubiquitously found on the Canary archipelago, being more widespread on the eastern than on the western islands due to the old, smooth topography of the eastern islands. In some places, this dust forms stacked sequences which, in cases where the valley floor sediments have been securely dammed by volcanic action, the sediments can be used as valuable palaeoenvironmental archives indicative of local humidity conditions as well as for tracing the input of Saharan dust to the archipelago. Although numerous studies exist based on marine cores along the African coast that reveal different aspects of the palaeoclimatic (e.g. [105, 106, 107, 108]), long continuous terrestrial archives indicating changing humidity conditions are generally lacking in the NW African region. Thus, Saharan dust deposits on the Canary Islands are the only quasi-continuous palaeoenvironmental archives in a broad region stretching from southern Spain (pollen sequence of Padul; [109]) to tropical West Africa (lake Bosumtwi; [110]), partially filling a conspicuous gap in palaeoenvironmental knowledge. In contrast to monsoonal West Africa where warm periods were characterized by higher humidity and cold periods by arid conditions [111, 112], humidity on Lanzarote was generally enhanced during cold and lowered during warm periods. Our soil moisture record also contrasts with the palaeoclimatic record in the Mediterranean region. Whereas the Early and Mid-Holocene are described as humid in the Mediterranean [113], vega sediments from Lanzarote show continuous aridity during that time. However, the observed soil moisture pattern of Lanzarote clearly shows that it is dominantly controlled by northern high latitude processes controlled by glacial/interglacial cycles, rather than by a low latitude monsoonal influence triggered by the precessional cycle [114].

The buildup of a sediment mass balance in the completely closed Femés vega provides insights into the evolution of Saharan dust input to the Canary Islands region located, as it is, on the northern margin of the Saharan dust plume. Unlike regions crossed by the central and southern dust plume [6, 7], long-term quantitative changes of dust input have not previously been investigated in this northern area. Our investigations in the Canarian region confirm the general trend of increasing dust input as found in the central East Atlantic during the last 1.0 Ma [6, 7]. However, it appears that strong dust mobilization, probably triggered by human activity in the Sahara, had already begun by the Early Holocene, whereas an increase in dust mobilisation as shown by marine cores taken from off the Southern Sahara and the Sahel is recorded only during the Middle Holocene [112].

These results demonstrate that Saharan dust deposits on the Canary Islands constitute a valuable palaeoenvironmental archive that cast light upon several palaeoenvironmental problems yet to be thoroughly investigated in the NW African region.

Under current arid conditions prevailing for this interglacial epoch, with the contributions from human activity in the last centuries, over the recent decades, deposition rate of Saharan dust on the islands increased substantially to more than a dozen grams per square meter per year (14016 to 43800 mg m-2 y-1 [55]. For social and environmental reasons airborne dust on the Canary Islands is being investigated by several groups [15, 23, 24, 67, 68, 69], The mean value of 47 □ m-3, with 1000 micrograms per cubic meter during Saharan dust events was measured by the EU Air Quality Directive EC/30/1999. This obligated the Canary Island government agencies to set up a well regulated air quality network for the Canary Islands.

Other subsequent studies are the influence of Saharan dust on biogeochemical fluxes in the ocean surrounding the Canary Islands, and the increased marine fertilization with lithogenic fluxes during Saharan dust events [69, 71, 74].

Particle-size distribution of airborne dust in Canary Islands remained consistent, showing a unimodal distribution about the limit of silt-clay size (2 □m; [24, 76, 77]). However, the particle-size distribution of dust deposits on the Canary Islands display a bimodal distribution about the mean particle size of silt. Gravitational settling processes can explain such an increase of particle size and distribution of deposited Saharan dust. Alternatively, this can be explained by a process of aggregation, commonly seen in the dust deposits and aerosols [67].

Quartz is a diagnostic tracer mineral for Saharan dust, due to its absence in the mineral paragenesis of these volcanic islands. Quartz in local dust predominates due to it being recycled.

There must also be taken into account that Saharan dust may acts as a "carrier" providing surface where microorganims (pathogens: bacteria, fungi, etc.) may be transported from North Africa to distant regions. Some examples the studies performed by Griffin et al. [91, 94, 95] and Kellogg et al. [89, 98] in the Caribbean As it is shown in these articles, there is an open debate on if the impact of Saharan dust on human health is caused by "minerals" or by the "micro organism" transported by dust (S. Rodríguez personal communication).

Respecting to potential impact on human health of Saharan dust palls over the Canary Islands, the limited number of examples mentioned in this chapter, neither epidemiological nor clinical studies are widely available on many aspects of this important societally-centred subject. Understandably, such gaps in knowledge still give rise to some scepticism about whether or not chronic exposure to natural dusts generally leads to disease. To overcome this situation, an unprecedented level of collaboration among a range of conventional scientific disciplines will be necessary. The Canary Islands are well placed to share in this process.

ACKNOWLEDGMENTS

We wish to express our gratitude to Silvia Alonso-Pérez who contributed to the section "Origin and Transport of Saharan Dust (Towards Canary Islands) and the Arrivals of Such Plume Dust to the Archipelago" with her doctoral thesis.

We thank to the Dr. Sergio Rodriguez (srodriguez@inm.es; Izaña Atmospheric Observatory, and University of Huelva, Spain), and Dr. Jan-Berend Stuut (jbstuut@ marum.de; University of Bremen) for their scientific review and contributions, that improved the quality of the manuscript.

REFERENCES

[1] Dorta, P. Las invasiones de aire sahariano en Canarias. Consejería de Agricultura, Pesca y Alimentación del Gobierno de Canarias y Caja Rural de Tenerife Publ.: *Santa Cruz de Tenerife*, 1999, pp. 1-287.

[2] Dorta, P.; Gelado, M.D.; Hernández, J.; Cardona, P.; Collado, C.; Mendoza, S.; Rodríguez, M.J. Siruela, V.; Torres, ME. Frecuencia, estacionalidad y tendencias de las advecciones de aire sahariano en Canarias M. *Investigaciones Geográficas* 2005a, 38, 23-45.

[3] Viana, M.M. Niveles, composición y origen del material particulado atmosférico en los sectores Norte y Este de la Península Ibérica y Canarias. Ph.D. *Thesis. Universitat de Barcelona*, 2003.

[4] Dorta, P.; Gelado, M.D.; Criado, C.; Cardona, P.; Collado, C.; Hernández-Brito, J.J.; Mendoza, S.; Torres, M.E.; Rodríguez, M.J.; Siruela, V.F. Sahara air incursions and dust deposition over the Canary Islands and its impact on the terrestrial and oceanic environment. In Proceedings of the VIII Seminario *Internacional Forum Unesco*. El Patrimonio Mundial Natural: Los Espacios Naturales, Desarrollo, Sostenibilidad y Ética, 2005b, pp. 276-282.

[5] Alonso-Pérez, S. Caracterización de las intrusiones de polvo africano en Canarias. Ph.D. *Thesis. Universidad de La Laguna*, 2007.

[6] Goudie, A.S.; Middleton, N.J. Saharan dust storms: nature and consequences. *Earth-Sci Rev* 2001, 56, 179-204.

[7] Pflaumann, U.; Sarnthein, N.; Ficken, K.; Grothmann, A.; Winkler, A. Variations in eolian and carbonate sedimentation, sea-surface temperature, and productivity over the last 3 Ma at site 958 off Northwest Africa. In Proceedings of the Ocean Drilling Program, *Scientific Results; Firth*, J.V. Ed.: 1998, 159T, pp. 3-16.

[8] García, J.; Hernández, A.; Blasco, A.; Rodríguez, C.; Rancaño, E.; Núñez, S. Invasión de viento sahariano y su impacto en la asistencia sanitaria urgente. *Emergencias* 2001, 13, 372-376.

[9] Dorta, P. Las inversiones térmicas en Canarias. *Investigaciones Geográficas* 1996, 15, 109-124.

[10] Dorta, P.; Cardona, P.; Collado, C.; Criado, C.; Gelado, Mª.D.; Hernández, J.J.; Mendoza, S.; Siruela, V.; Torres, M.E. Algunas consideraciones sobre la importancia del polvo de origen sahariano en el clima del archipiélago canario y su aporte a las

aguas superficiales oceánicas: el episodio de abril de 2002. *In Proceedings of the III Congreso de la Asociación Española de Climatología: El agua y el clima; Asociación Española de Climatología: Palma de Mallorca, Spain,* 2002, pp.13-24.

[11] Scott, R.H. Note of a remarkable dust haze experienced at Tenerife, Canary Islands, february 1898. *Royal Meteorological Office* 1900, 33-36.

[12] Smith, W.C. Note on a fall of dust, "Blood rain" at Gran Canaria, 8th to 11th February 1920. In The Canary Island, their History, *Natural History and Scenery Appendix A at the Bannerman;* David, A. Ed.; London, 1922.

[13] [13] Font Tullot, I. Las invasiones de aire caliente africano en el Archipiélago Canario. *Revista de Geofísica* 1980, IX (36), 334-349.

[14] Bergametti, G.; Gomes, L.; Coude-Gaussen, G.; Rognon, P.; Le Coustumer, M.-N. African dust observed over Canary Islands: Source-regions identification and transport pattern for some summer situations. *J Geophys Res* 1989, 94 (D12), 14855-14864.

[15] Pérez-Marrero J.; Llinas O.; Maroto L.; Rueda M.J.; Cianca A. Saharan dust storms over the Canary Islands during winter 1998 as depicted from the advanced very high-resolution radiometer. *Deep-Sea Res Pt II* 2002, 49 (17), 3465-3479.

[16] Gelado, M.D.; Brito De Acevedo, E.M.; Hernández, J.J.; Dorta, P.; Díaz, J.P.; Somoza, MJ.; Collado, C.; Cardona, P.; Siruela, V.; Bergasa, O. Caracterización de los eventos de polvo africano en Gran Canaria (Islas Canarias). In Proceedings of the 4° Simpósio de Meteorologia e Geofísica da APMG/6° *Encontro luso-espanhol de Meteorologia, Lisboa*, 2005a, pp. 195-199.

[17] Gelado, M.D.; Rodríguez, M.J.; Hernández, J.J.; Brito De Acevedo, E.M.; Llinás, O.; Collado, C.; Cardona, P.; López, P. Dust deposition fluxes to north-eastern subtropical Atlantic (Canary Islands). *Geophys Res Abstr* 2005b, 7, 08399.

[18] Díaz, A.M.; García, O.E.; González, J.; Guirado, C.; Expósito, F.J.; Díaz, J.P.; Guerra, J.C. Estructura vertical de las invasiones de polvo mineral sobre las Islas Canarias durante 2004. *Revista de Teledetección* 2005, 24, 89-94.

[19] Díaz, A.M. Caracterización de los aerosoles atmosféricos y su influencia en los niveles de radiación UV en la región de Canarias. Ph.D. Thesis. Universidad de La Laguna, 2006.

[20] Díaz, A.M.; Díaz, J.P.; Expósito, F.J.; Hernández-Leal, P.A.; Savoie, D.; Querol, X. Air masses and aerosols chemical components in the free troposphere at the subtropical Northeast Atlantic region". *J Atmos Chem* 2006, 53 (1), 63-90.

[21] Kaufman, Y.J.; Koren, I.; Remer, L.A.; Tanre, D., Ginoux, P.; Fan, S. Dust transport and deposition observed from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) spacecraft over the Atlantic Ocean. *J Geophys Res* 2005, 110, D10S12.

[22] Dorta, P. Et Al. Selección de tipos de tiempo en Canarias. Un ejemplo: las invasiones de aire sahariano. In Proceedings of the 1er Encuentro sobre Meteorología y Atmósfera de Canarias; Ministerio de Medio Ambiente: *Santa Cruz de Tenerife*, 2003, pp. 77-79.

[23] Alonso-Perez, S.; Cuevas, E.; Querol, X.; Viana, M.; Guerra, J.C. Impact of the Saharan dust outbreaks on the ambient levels of total suspended particles (TSP) in the marine boundary layer (MBL) of the Subtropical Eastern North Atlantic Ocean, *Atmos Environ* 2007, 41, 9468-9480.

[24] Torres-Padrón, M.E.; Gelado-Caballero, M.D., Collado-Sánchez, C.; Siruela-Matos, V. F.; Cardona-Castellano, P. J.; Hernández-Brito, J. J.; Variability of dust inputs to the CANIGO zone. *Deep-Sea Res Pt II* 2002, 49 (17), 3455-3464.

[25] Criado, C.; Dorta, P. An unusual "blood rain" over the Canary Islands (Spain). The storm of January 1999. *J Arid Environ* 2003, 55, 765-783.

[26] Middleton, N. Desert dust. In: Arid Zone Geomorphology Process. Form and Change in Drylands. David S.G. Thomas Eds.; *Whiley: Chichester*, 1997, pp. 413-436.

[27] Middleton, N.J.; Goudie, A.S. Saharan dust: sources and trajectories. *T I Brit Geogr* 2001, 26, 165-181.

[28] Arimoto, R. Eolian dust and climate: relationships to sources, tropospheric chemistry, transport and deposition. *Earth-Sci Rev* 2001, 54, 29-42.

[29] Prospero, J.M.; Ginoux, P.; Torres, O.; Nicholson, S.E.; Gill, T.E. Environmental Characterization of Global Sources of Atmospheric Soil Dust Identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) Absorbing Aerosol Product. *Rev Geophys* 2002, 40,1.

[30] Gelado, M.D.; Dorta, P.; Torres, M.E.; Hernández, J.J.; Collado, C.; Siruela, V.F.; Cardona, P.; Rodríguez, M.J. Caracterización del aerosol sahariano en Gran Canaria". In Proceedings of the 1er Encuentro sobre Meteorología y Atmósfera de Canarias; Ministerio de Medio Ambiente: *Santa Cruz de Tenerife*, 2003, pp. 155-157.

[31] Amato, T.E.; Heidinger, A.K.; Knippertz, P. Analysis of winter dust activity off the coast of West Africa using a new 24-year over-water advanced very high resolution radiometer satellite dust climatology. *J Geophys Res* 2006, 111, D12210.

[32] Hernández, F.; Alonso-Pérez, S. Hernándes-Armas, J.; Cuevas, E. Influence of major African dust intrusions on the 137Cs and 40K activities in the lower atmosphere at the Island of Tenerife. *Atmos Environ* 2005, 39 (22), 4111-4118.

[33] Hernandez, F.; Rodríguez, S.; Karlsson, C.L.; Alonso-Pérez, S. López-Pérez, M.; Hernandez-Armas, J.; Cuevas, E. Origin of observed high 7Be and mineral dust concentrations in ambient air on the Island of Tenerife. *Atmos Environ* 2008, 42 (18), 4247–4256

[34] Mizota, C.; Matsuhisa, Y. Isotopic evidence for the eolian origin of quartz and mica in soils developed on volcanic materials in the Canary Archipelago. *Geoderma* 1995, 66, 313-320.

[35] Schwaighofer, B. Zur Verwitterung vulkanischer Gesteine - ein Beitrag zur Halloysit-Genese. Mitt. *Geol. Gesellsch. Wien*, 1973/74, 66/67, 221-236.

[36] Jahn, R. Böden Lanzarotes. PhD-thesis, *Stuttgart-Hohenheim*, 1988.

[37] Herrmann, L.; Jahn, R.; Stahr, K. Identification and quantification of dust additions in perisaharan soils. In The impact of desert dust across the Mediterranean; Guerzoni, S.; R. Chester Eds.; Kluwer Academic Publishers: Netherlands, 1996, pp. 133-151.

[38] Fúster, J.M.; Cendrero, A.; Gastesi, P., Ibarrola, E.; López-Ruiz, J. Geología y volcanología de las Islas Canarias, Lanzarote. Instituto "Lucas Mallada", *Consejo Superior de Investigaciones Cientificas:* Madrid, 1968, pp. 1-239.

[39] Edwards, N.; Meco, J. Morphology and palaeoenvironment of brood cells of Quaternary ground-nesting solitary bees (Hymenoptera, Apidae) from Fuerteventura, Canary Islands, Spain. *P Geologist Assoc* 2000, 111, 173-183.

[40] Criado, C.; Guillou, H.; Hansen, A.; Hansen, C.; Lillo, P.; Torres, J.M.; Naranjo, A. 2004 Geomorphological evolution of parque natural de Las Dunas de Corralejo

(Fuerteventura, Canary Islands). In Contribuciones recientes sobre geomorfología. Actas de la VIII Reunión de Geomorfología, Toledo; Benito, G. & A. Diez-Herrero Eds.*; SEG & CSIC: Madrid.*, 2004, pp. 291-297.

[41] Coudé-Gaussen, G. Les poussières sahariennes. Edition *John Libbey Eurotext, Paris*, 1991; 485 pp.

[42] Grousset, F.E.; Rognon, P.; Coudé-Gaussen, G.; Pédernay, P. Origins of peri-Saharan dust deposits traced by their Nd and Sr isotopic composition. *Palaeogeogr Palaeocl* 1992, 93, 203-212.

[43] Zöller, L.; Suchodoletz, H. von; Küster, N. Geoarchaeological and chronometrical evidence of early human occupation on Lanzarote (Canary Islands). *Quaternary Sci Rev* 2003, 22, 1299-1307.

[44] Menéndez, I.; Cabrera, L.; Sánchez-Pérez, I.; Mangas, J.; Alonso, I. Characterization of two fluvio-lacustrine loessoids deposits in Gran Canaria Island, Canary Islands. *Quatern Int* 2008, in press, doi:10.1016/j.quaint.2008.05.011.

[45] Zöller, L.; Suchodoletz, H. von; Blanchard, H.; Faust, D.; Hambach, U. Reply to the comment by J.C. Carracedo et al., on 'Geoarchaeological and chronometrical evidence'. *Quaternary Sci Rev* 2004, 23, 2049-2052.

[46] Suchodoletz, H. von; Fuchs, M.; Zöller, L. Dating Saharan dust deposits at Lanzarote (Canary Islands) by luminescence dating techniques and their implication for paleoclimate reconstruction of NW Africa. *Geochem Geophy Geosy* 2008a, 9, doi:10.1029/2007GC001658.

[47] Rothe, P. Kanarische Inseln. Sammlung geologischer Führer. *Gebrüder Bornträger* Berlin, Stuttgart, 1996; 307 pp.

[48] Romero, C. El relieve de Lanzarote. Rubicón. *Cabildo de Lanzarote*, 2003; 242 pp.

[49] Suchodoletz, H. von; Faust, D.; Zöller, L. Geomorphological investigations of sediment traps on Lanzarote (Canary Islands) as a key for the interpretation of a palaeoclimate archive off NW Africa. *Quatern Int* 2008b (accepted). doi:10.1016/j.quaint.2008.03.014.

[50] Langbein, W.B.; Schumm, S.A. Yield of sediment in relation to mean annual precipitation. *Transactions of the American Geophysical Union* 1958, 39 (6), 1076-1084.

[51] Suchodoletz, H. von; Kühn, P.; Hambach, U.; Dietze, M.; Zöller, L.; Faust, D. Loess-like and palaeosol sediments from Lanzarote (Canary Islands/Spain) – indicators of palaeoenvironmental change during the Late Quaternary. *Palaeogeogr Palaeocl* 2008c (resubmitted).

[52] Moreno, A.; Cacho, I.; Canals, M.; Prins, M.A.; Sanchez-Goni, M.-F.; Grimalt, J.O.; Weltje, G.J. Saharan dust transport and high latitude glacial climatic variability: the Alboran Sea record. *Quaternary Res* 2002, 58, 318-328.

[53] Moreno, A.; Canals, M. The role of dust in abrupt climate change: insights from offshore Northwest Africa and Alborean Sea sediment records. *Contributions to Science* 2004, 2 (4), 485-498.

[54] Holz, C.; Stuut, J.B.; Henrich, R. Variability in terrigenous sedimentation processes off NW Africa and its relation to climate changes: inferences from grain-size distributions of a Holocene marine sediment record. *Sedimentology* 2004, 51 (5), 1145-1154.

[55] Menéndez, I.; Díaz-Hernández, J.L.; Mangas, J.; Alonso, I.; Sánchez-Soto, P.J. Airborne dust accumulation and soil development in the North-East sector of Gran Canaria (Canary Islands, Spain). *J Arid Environ* 2007, 71, 57-81.

[56] Moreno, A.; Taragona, J.; Henderiks, J.; Canals, M.; Freudenthal, T.; Meggers, H. Orbital forcing of dust supply to the North Canary Basin over the last 250 kyr. *Quaternary Sci Rev* 2001, 20, 1327-1339.

[57] Maher, B.A. Magnetic properties of modern soils and Quaternary loessic paleosols: paleoclimatic implications. *Palaeogeogr Palaeocl* 1998, 137, 25-54.

[58] Matasova, G.; Petrovsky, E.; Jordanova, N.; Zykina, V.; Kapicka, A. Magnetic study of Late Pleistocene loess/palaeosol sections from Siberia: Palaeoenvironmental implications. *Geophys J Int* 2001, 147, 367-380.

[59] Fernandez-Caldas, E.; Quantin, P.; Tejedor-Salguero, M.L. Séquences climatiques des sol dérivés de roches volcaniques aux Iles Canaries. *Geoderma* 1981, 26, 47-62.

[60] Genise, J.F.; Edwards, N. Ichnotaxonomy, origin, and paleoenvironment of Quaternary insect cells from Fuerteventura, Canary Islands, Spain. *J Kansas Entomol Soc* 2003, 76(2), 320-327.

[61] Coello, J.; Cantagrel, J.-M.; Hernán, F.; Fúster, J.-M.; Ibarrola, E.; Ancochea, E.; Casquet, C.; Jamond, C.; de Téran, J.-R.D.; Cendrero, A. Evolution of the eastern volcanic ridge of the Canary Islands based on new K-Ar data. *J Volcanol Geoth Res* 1992, 53, 251-274.

[62] Instituto Tecnológico y Geominero de España. Mapa geológico de España, Escala 1:100.000, Memoria de la hoja geológica de la Isla de Lanzarote; 2005, *Madrid, ISBN*: 84-7840-606-9.

[63] Arimoto, R.; Duce, R. A.; Ray, B. J.; Ellis Jr., W. G.; Cullen, J. D.; Merrill, J. T. Trace elements in the atmosphere over the North Atlantic. *J Geophys Res* 1995, 100 (D1), 1199–1213.

[64] Prospero J.M.; Saharan dust transport over the North Atlantic Ocean and Mediterranean: An Overview. In The impact of desert dust from Northern Africa across the Mediterranean; S. Guerzoni and R. Chester Eds.; Kluwer *Academic Publishers: The Netherlands,* 1996, pp. 133-151.

[65] Prospero, J.M.; Barrett, K.; Church, T.; Dentener, F.; Duce, R.A.; Galloway, J.N.; Levy H.; Moody, J.; Quinn, P. Atmospheric deposition of nutrients to the North Atlantic Basin. *Biogeochemistry* 1996, 35, 27-73.

[66] Taylor, S.R.; McLennan, S.M. The continental crust: Its composition and evolution. *Blackwell Scientific Pub*., Palo Alto, CA, 1985; 328 pp.

[67] Alastuey, A.; Querol, X.; Castillo, S.; Escudero, M.; Avila, A.; Cuevas, E.; Torres, C.; Romero, P.M.; Expósito, F.; Garcia, O.; Diaz, J.P.; Dingenene, R.V.; Putaude, J.P. Characterisation of TSP and PM2.5 at Izaña and Sta. Cruz de Tenerife (Canary Islands, Spain) during a Saharan dust episode (July 2002). *Atmos Environ* 2005, 39, 4715-4728.

[68] Gelado, M. D.; Torres-Padrón, M. E.; Hernández-Brito, J. J.; Herrera-Melián J. A.; Pérez-Peña J. Aluminium distributions in Central East Atlantic waters (Canary Islands). *Mar Chem* 1996, 51 (4), 359-372

[69] Neuer, S.; Torres-Padrón, M. E.; Gelado-Caballero, M. D.; Rueda, M. J.; Hernández-Brito, J.; Davenport, R.; Wefer G. Dust deposition pulses to the eastern subtropical North Atlantic gyre: Does ocean's biogeochemistry respond? *Global Biogeochem Cy* 2004, 18, GB4020.

[70] Viana, M.M.; Querol, X.; Alastuey, A.; Cuevas, E.; Rodriguez, S. Influence of African dust on the levels of atmospheric particulates in the Canary Islands air quality network. *Atmos Environ* 2002, 36, 5861-5875.

[71] Neuer, S.; Ratmeyer, D.; Davenport, R.; Fischer, G.; Wefer, G. Deep water particle flux in the Canary Island region: seasonal trends in relation to long-term satellite derived pigment data and lateral sources. *Deep-Sea Res Pt I* 1997, 44, 1451-1466.

[72] Buat-Menard P.; Davies, J.; Remoudaki, E.; Miquel, J.; Bergametti, C. G.; Lambert, C. E.; Etzat, U.; Quetel, C.; Rosa, J. L.; Fowler, S. W. Non-steady-state biological removal of atmospheric particles from Mediterranean surface waters. *Nature* 1989, 340, 131-134.

[73] Hamm, C.E. Interactive Aggregation and Sedimentation of Diatoms and Clay-Sized Lithogenic Material. *Limnol Oceanogr* 2002, 47 (6), 1790-1795

[74] Ratmeyer V.; Fischer, G.; Wefer, G. Lithogenic particle fluxes and grain size distributions in the deep ocean off northwest Africa: Implications for seasonal changes of aeolian dust input and downward transport. *Deep-Sea Res Pt II* 1999, 46, 1289-1337.

[75] Henderiks, J.; Freudenthal, T.; Meggers, H.; Nave, S.; Abrantes, F.; Bollmann, J.; Thierstein, H. Glacial-interglacial variability of particle accumulation in the Canary Basin: a time-slice approach. *Deep-Sea Res Pt II,* 2002, 49, 3675-3705.

[76] Kandler K.; Benker, N.; Bundke, U.; Cuevas, E.; Ebert, M.; Knippertz, P.; Rodriguez, S.; Schütz, L.; Weinbruch, S. Chemical composition and complex refractive index of Saharan Mineral Dust at Izaña, Tenerife (Spain) derived by electron microscopy. *Atmos Environ* 2007, 41 (37), 8058-8074.

[77] Maring, H.; Savoie, D. L.; Izaguirre, M. A.; Custals, L.; Reid, J. S. Mineral dust aerosol size distribution change during atmospheric transport, *J Geophys Res* 2003, 108 (D19), 8592.

[78] Pichevin, L.; Cremer, M.; Giraudeau J.; Bertrand, P. A 190ky record of lithogenic grain-size on the Namibian slope: forging a tight link between past wind-strength and coastal upwelling dynamics. *Mar Geol* 2005, 218, 81-96

[79] [79] Carracedo, J.C.; Pérez Torrado, F.J.; Ancochea, E.; Meco, J.; Hernán, F.; Cubas, C.R.; Casillas, R.; Rodríguez Bardiola, E.; Ahijado, A. Cenozoic volcanism II: The The Canary Islands. In The geology of Spain; W. Gibbons and T. Moreno Eds.; The Geological Society: London, 2002; pp. 439-472.

[80] Claquin T., Schulz, M., Balkanski Y.J. Modelling the mineralogy of atmospheric dust sources. *J Geophys Res* 1999, 104 (D18), 22243-22256.

[81] Holz, C.; Stuut, J.B.; Henrich, R.;.Meggers, H. Variability in terrigenous sedimentation processes off northwest Africa and its relation to climate changes: Inferences from grain-size distributions of a Holocene marine sediment record. *Sediment Geol* 2007, 202, 499-508.

[82] Derbyshire, E. Natural aerosolic mineral dusts and human health: potential effects. In Essentials of Medical Geology; Selinus, O., Alloway, B., Centeno, J.A., Finkelman, R.B., Fuge, R., Lindh, U., Smedley, P. Eds. *Elsevier Academic Press: Amsterdam*; 2005, Chapter 18, 459-480

[83] Fubini B.; Fenoglio, I. Toxic potential of mineral dusts. *Elements* 2007, 3:407-414.

[84] Horwell, C.J.; Fenoglio, I.; Ragnarsdottir. K.V.; Sparks, R.S.J., Fubini. B. Surface reactivity of volcanic ash from the eruption of Soufrière Hills volcano, Montserrat, West indies with implications for health hazards. *Environ Res* 2003, 93, 202-215.

[85] Fubini, B.; Hubbard, A. Reactive oxygen species (ROS) and reactive nitrogen species (RNS) generation by silica in inflammation and fibrosis. *Free Radical Bio Med* 2003, 34, 1507-1516.

[86] Tegen, I. Modelling the mineral dust aerosol cycle in the climate system. *Quaterary Sci Rev* 2003, 22, 1821-1834.

[87] Fubini, B. Surface chemistry and quartz hazard. *Ann. Occup. Hyg.* 1998, 42, 521-530.

[88] Clarke, J. The occurrence and significance of biogenic opal in the regolith. *Earth-Sci Rev* 2003, 60, 175-194

[89] Kellogg, C.A., Griffin, D.W., Garrison, V.H., Peak, K.K., Royall, N., Smith, R.R., Shinn, E.A. Characterization of aerosolized bacteria and fungi from desert dust events, in Mali, West Africa. *Aerobiologia* 2004, 20, 99-110.

[90] Howitt, M.E.; Naibu, R.; Roach, T.C. The prevalence of childhood asthma and allergy in Barbados. *Am J Respir Crit* 1998, 157, A624.

[91] Griffin, D.W.; Kellogg, C.A.; Garrison, V.H.; Shinn, E.A. The global transport of dust. *Am Sci* 2001, 90: 228–235.

[92] Gyan, K.; Henry, W.; Lacaille, S.; Laloo, A.; Lamsee-Ebanks, C.; McKay, S.; Antoine, R.M.; Monteil, M.A. African dust clouds are associated with increased paediatric asthma accident and emergency admissions on the Caribbean island of Trinidad. *Earth Environ Sci* 2005, 49, 371-376.

[93] Griffin, D.W. Atmospheric movement of microorganisms in clouds of desert dust and implications for human health. *Clin Microbiol Rev* 2007, 20, 459-477.

[94] Griffin, D.W.; Kellogg, C.A.; Garrison, V.H.; Lisle, J.T., Borden, T. C.; Shinn, E.A. Atmospheric microbiology in the northern Caribbean during African dust events. *Aerobiologia* 2003, 19: 143-157.

[95] Griffin, D.W.; Kellogg, C.A. Dust Storms and Their Impact on Ocean and Human Health: Dust in Earth's Atmosphere. *EcoHealth* 2004, 1, 284-295.

[96] Querol X.; Alastuey, A.; Rodríguez, S.; Viana, M.M.; Artiñano, B.; Salvador, P.; Mantilla, E.; García do Santos, S.; Fernández Patier, R.; de La Rosa, J.; Sánchez de la Campa, A.; Menéndez, M. J.; Gil., J.I. Levels of particulate matter in rural, urban and industrial sites in Spain. *Sci Total Environ* 2004, 334-335, 359-376.

[97] Querol X.; Alastuey, A.; Viana, M.M.; Rodríguez, S.; Artiñano, B.; Salvador, P.; García do Santos, S.; Fernández Patier, R.; Ruiz, C.R.; de la Rosa, J.; Sánchez de la Campa, A.; Menéndez, M.; Gil, J.I. Speciation and origin of PM10 and PM2.5 in Spain. *J Aerosol Sci* 2004, 35, 1151-1172.

[98] Kellogg, C.A., Griffin, D.W. Aerobiology and the global transport of desert dust. *Trends Ecol Evol* 2006, 21 (11), 638-644.

[99] Rodríguez, S.; Querol, X.; Alastuey, A.; de la Rosa, J. Atmospheric particulate matter and air quality in the Mediterranean: a review. *Environ Chem Lett* 2007, 5, 1-7.

[100] Escudero, M.; Querol, X.; Pey, J.; Alastuey, A.; Ferreira, F.; Cuevas, E.; Alonso-Pérez, S. A methodology for the quantification of the net African dust load in air quality monitoring networks. *Atmos Environ* 2007, 41, 5516-5524.

[101] Derbyshire, E. Natural minerogenic dust and human health. *Ambio* 2007, 36, 74-78.

[102] Gelado. M.D.; Dorta. P.; Hernández. J.J.; Collado. C.; Rodríguez, M.J.; Cardona P.; Siruela, V. Characterisation of African dust outbreaks in Gran Canaria (Canary Islands). *Geophys Res Abstr* 2004, 6, 05227.

[103] Daniel, N.L.; Mao, Y.; Wang, C.-T.; Markey, C.J.; Markey, S.P.; Shi, X.; Saffiotti, U. DNA strand breakage, thymine glycol production, and hydroxyl radical generation induced by different samples of crystalline silica in vitro. *Environ Res* 1995, 71: 60-73.

[104] Donaldson, K.; Borm, P.J.A. The quartz hazard: a variable entity. *Ann occup Hyg* 1998, 42, 287-294.

[105] Matthewson, A.P.; Shimmield, G.B.; Kroon, D. A 300 kyr high-resolution aridity record of the North African continent. *Paleoceanograph*y 1995, 10/3, 677-692.

[106] Bozzano, G.; Kuhlmann, H.; Alonso, B. Storminess control over African dust input to the Moroccan Atlantic margin (NW Africa) at the time of maxima boreal summer insolation: a record of the last 220 kyr. *Palaeogeogr Palaeocl* 2002, 183, 155-168.

[107] Zhao, M.; Dupont, L.; Eglinton, G.; Teece, M. n-Alkane and pollen reconstruction of terrestrial climate and vegetation for N.W. Africa over the last 160 kyr. *Org Geochem* 2003, 34, 131-143.

[108] Kuhlmann, H.; Meggers, H.; Freudenthal, T.; Wefer, G. The transition of the monsoonal and the N Atlantic climate system off NW Africa during the Holocene. *Geophys Res Lett* 2004, 31, L22204.

[109] Pons, A.; Reille, M. The Holocene- and upper Pleistocene pollen record from Padul (Granada, Spain): *A new study. Palaeogeogr Palaeocl* 1988, 66, 243-263.

[110] Shanahan, T.M.; Overpeck, J.T.; Winston Wheeler, C.; Warren Beck, J.; Pigatie, J.S.; Talbot, M.R., Scholz, C.A.; Peck, J.; King, J.W. Paleoclimatic variations in West Africa from a record of late Pleistocene and Holocene lake level stands of Lake Bosumtwi, Ghana. *Palaeogeogr Palaeocl* 2006, 242, 287-302.

[111] Yan, Z.; Petit-Maire, N. The last 140 ka in the Afro-Asian arid/semiarid transitional zone. *Palaeogeogr Palaeocl* 1994, 110, 217-233.

[112] deMenocal, P.; Ortiz, J.; Guilderson, T.; Sarnthein, M. Coherent high- and low-latitude climate variability during the Holocene warm period. *Science* 2000, 288, 2198-2202.

[113] Verschuren, D.; Briffa, K.R.; Hoelzmann, P.; Barber, K.; Barker, P.; Scott, L.; Snowball, I.; Roberts, N.; Battarbee, R.W. Climate variability in Europe and Africa: A PAGES-PEP III time stream I synthesis. *In Past climate variability through Europe and Africa;* Battarbee, R.W.; Gasse, F.; C.E. Stickley Eds.; Springer: Dordrecht, 2004; chapter 19, pp. 567-582.

[114] deMenocal, P.B.; Ruddiman, W.F.; Pokras, E.M. Influences of high- and low-latitude processes on African terrestrial climate: Pleistocene eolian records from Equatorial Atlantic Ocean Drilling Program site 663. *Paleoceanography* 1993, 8(2), 209-242.