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The evolution of Saharan dust input on Lanzarote (Canary Islands) – influenced by human activity in the Northwest Sahara during the early Holocene?

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Abstract: An overall Holocene increase of Saharan dust input to the Canary Islands and to the North Canary Basin is accompanied by a strong coarsening of Saharan dust in loess-like sediments deposited on Lanzarote from ~7–8 ka. No similar coarsening events are indicated in investigations of the sedimentological record for the last 180 ka, a period showing several dramatic climate changes. Therefore a mobilisation of Holocene dust by anthropogenic activity in the northwest Sahara east of the Canary Islands is assumed. Although scarce archaeological data from the coastal area of that region does not point to strong anthropogenic activity during the early Holocene, a high density of unexplored archaeological remains is reported from the coastal hinterlands in the Western Sahara. Thus, the hypothesis of early anthropogenic activity cannot be excluded.

Key words: Canary Islands, Saharan dust, geoarchaeology, early Holocene, Western Sahara, desertification.

Introduction

Sediments derived from aeolian dust can bear witness to past environmental changes occurring in dust mobilisation areas. Generally, these dust source areas are characterised by arid to semi-arid or periglacial conditions with a lack of palaeoenvironmental archives, due to their destruction by very active geomorphic processes (Krissek and Clemens, 1992; Stuut et al., 2002; Frechen et al., 2003). Accordingly, numerous marine studies off the coast of Northwest Africa demonstrate that sediments originating from Saharan dust are excellent archives of palaeoclimate conditions in the Sahara, as well as of their transporting winds (Matthewson et al., 1995; Moreno et al., 2001, 2002).

The Canary Islands are situated at the northern fringe of the recent Saharan dust plume towards the Atlantic (Figure 1), and annually receive dust derived from the Sahara (Coudé-Gaussen et al., 1987; Criado and Dorta, 2003; Menéndez et al., 2007). Saharan dust deposited in the Canary Islands consists mainly of clay and silt. Its mineralogy is dominated by quartz, feldspars, calcite and clay minerals (e.g. illite and kaolinite) (Stuut et al., 2005; Menéndez et al., 2007). Quartz, a mineral not authigenically formed by the alkaline volcanism of the islands, is exclusively brought by Saharan dust. Thus, it can serve as a proxy for Saharan material (Mizota and Matsuhisa, 1995). In Lanzarote, Saharan dust forms stacked sequences with thicknesses of several decameters, classified as "Saharan dust of proximal character" (Coudé-Gaussen, 1991). Former investigations demonstrated that these sequences are useful archives of local palaeoenvironmental conditions on the island (Zöller et al., 2003; Suchodoletz et al., 2009a). Furthermore, it was possible to derive quantitative estimates of Saharan dust sedimentation for different time slices from these archives (Suchodoletz et al., 2009b).

In this article, we will show that in Lanzarote there was a strong qualitative and quantitative change of Saharan dust sedimentation during the early and middle Holocene. Several scenarios explaining the observed pattern will be discussed, including possible links to anthropogenic activity in the Western Sahara and northern Mauritania.

Study area and sites

The Canary Islands are a volcanic archipelago situated off the Northwest African coast in the subtropical northeast Atlantic (Figure 1). During most of the year, the islands are under the influence of marine trade winds. Sparse precipitation is brought during winter by westerly cyclones occasionally following southern tracks and breaking the trade wind air layer over the islands. On the orographically higher western islands, this kind of rainfall is supplemented by humidity from rising trade wind air. Saharan dust is transported towards the Canary Islands mainly through two different pathways. During winter, dust is entrained by so-called “Calima” winds, low-level continental African trade winds (Harmattan) deflected towards the northwest by Atlantic cyclones (Criado and Dorta, 2003) (Figure 1, I and II). During summer, dust is transported to latitudes north of the Canary Islands by the northern branch of the high altitude Saharan Air Layer (SAL) (Figure 1). Here, the material brought at high altitude that sinks into the lower atmosphere is finally transported towards the islands via the northeast trade winds (Koopmann, 1981; Bozzano et al., 2002). The dust is deposited either in dry or wet form (Criado and Dorta, 2003; Menéndez et al., 2007).

Lanzarote, the northeasternmost of the Canary Islands, is located ~130 km off the Northwest African coast and has several old valleys dammed by younger volcanic activity during the Quaternary (locally called vegas). In these valleys, local volcanic material as well as Saharan dust have been trapped, forming stacked deposits with total thicknesses of up to 50 m, in places outcropped by local population.

The sediments of two of these valleys in the north (Teguise, Guatiza) and one in the south of Lanzarote (Femés) were investigated in order to reveal changes in Saharan dust input (Figure 1, inset). These valleys are developed in Miocene to Pliocene volcanites and were dammed by volcanic material originating from the Early to Middle Pleistocene (Suchodoletz et al., 2009b). Sediment thicknesses in the valley bottoms reach up to several decameters, while slopes are strongly eroded and covered by thick calcretes containing some remnants of soil material. Two of the vegas (Teguise and Guatiza) are not completely dammed, whereas the vega of Femés was probably completely dammed during the whole period of 1 Ma. Thus, this vega should contain the complete amount of material deposited since the Early Pleistocene. Properties of the investigated vegas are listed in Table 1.

Marine sediment core GeoB11804-4 (30°50.73’N, 10°05.90’W) was retrieved using the push-core device of the drilling-rig MeBO (MARUM, Germany) on board the R/V Maria S. Merian (cruise MSM04-4a) at 374 m water depth off Cape Ghir (Morocco) (Figure 1). The partly filled barrels contain hemipelagic silty clays that gradually change in colour at ˜300 cm from reddish to greenish-grey.

Methods

Chronostratigraphies of the vegas are based on optically stimulated luminescence (OSL) dating using fine (4–11 µm) and coarse (63–200 µm) quartz grains, as well as on infrared stimulated luminescence (IRSL) dating of fine-grained feldspar. Sample preparation was done under subdued red light (wavelength 640 ± 20 nm) in the Bayreuth luminescence laboratory (Germany). Preparation steps followed standard methods, including etching with HCl and H_2O_2 to remove carbonate and organic matter, as well as sieving and sedimentation in settling tubes to separate fine and coarse grains. In order to obtain coarse quartz grains, density separation with a lithium heteropolytungstate solution and etching with HF were carried out. Fine-grained quartz was separated by etching with hexafluorosilicic acid (Fuchs et al., 2005). Luminescence measurements were carried out using two Risø-Readers TL/OSLDA-15, applying the single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) for oarseand fine-grained quartz (OSL), and the protocol of Lang et al. (1996) for fine-grained quartz (IRSL). Dose rates were determined by thick source α-counting at the University of Bayreuth (Germany) and by inductively coupled plasma source mass spectrometry (ICP-MS) at the Bayreuth Center for Ecology and Environmental Research (BAYCEER, Germany), as well as by atomic adsorption spectrometry (AAS) at the University of Marburg (Germany). Chronostratigraphies were further corroborated by interprofile correlations and correlations of kaolinite contents from the vegas with proxies from nearby marine cores (Suchodoletz et al., 2008).

For a high-resolution grain size record of fine sand, 8 to 10 g of dry material were sampled at a spacing of 5 cm. Sample pre-treatment followed the procedure given in Konert and Vandenberghe (1997). Carbonate was destroyed by 10 and 30% chloric acid at 65°C. Organic material was removed using 30% hydrogen peroxide. After drying and weighing, the remaining mineralic fraction was sieved with 63 and 125 μm mesh width. The obtained grain size fraction of 63–125 μm was dried, weighed and related to the original sample weight.

For selected samples with a prominent 63–125 μm peak, the quartz content was determined by x-ray diffraction (XRD). Prior to the XRD analysis, the samples were ground in an agate mortar and 5% Md-IV-sulphide was added as an internal standard (Krischner, 1990). Measurements were done in a Siemens D 5005 diffractometer with 2 s/point from 12–30°2θ at the University of Potsdam, Germany. For data evaluation (software Mac Diff 4.2.5., Petschick (2000)), the Md-IV-sulphide-peak at 14.42°2θ and the quartz peak at 26.66°2θ were used. In order to obtain absolute quartz contents, a calibration curve was constructed, using 11 increasing amounts of quartz in an artificial composite of feldspars, muscovite and olivine spiked with 5% Md-IV-sulphide. The linear regression yields the equation 0.1375*x + 3.07 ($R^2 = 0.9869$), with the intersect >0 indicating that a main peak of muscovite is located close to the investigated quartz peak (Figure 2). Given that the mineral composite was always the same, this effect could be neglected and for calculations the regression quartz/sulphide was used. Relating measured ratios of the peaks of Md-IV-sulphide and quartz with the calibration curve yielded the percentage of quartz. Multiplying this percentage with the mass of the grain size fraction 63–125 μm, the absolute amount of quartz in this fraction was obtained.

For marine core GeoB11804-4, magnetic susceptibility (in 10^{-6} SI) was measured on-board, using a Bartington susceptibilimeter (equipped with a point sensor) mounted on a GEOTEK multisensor core logger. The hard isothermal remanent magnetisation (HIRM, in mA/m) was obtained by adding the saturation IRM (imparted at 0.7 T) and the backfield IRM (imparted at –0.3 T), both measured on discrete samples using a cryogenic magnetometer (2G 755R) at the Geophysics Department, University of Bremen (Germany). Bulk elemental contents (titanium and calcium in g/kg) were measured after full digestion of the sediments, using an inductively coupled plasma optical emission spectrometer (ICP-OES Perkin Elmer Optima 3300 R) at the Geochemistry Department, University of Bremen (Germany).

Results

Aggregation and iron staining of Saharan dust grains, often reported in former studies (Koopmann et al., 1981; Evans et al., 2004), lead to luminescence age overestimations, some up to ka, for fine-grained (4–11 μm) quartz and feldspar. For coarse quartz grains (63–200 μm), age overestimations were much less due to a transport of this grain size fraction as single grains. Fine grain IRSL-ages of feldspar are further biased due to strong anomalous fading (a not predictable loss of the luminescence signal with time) and were thus regarded with caution. Consequently, the technique of choice was OSL based on coarse quartz grains. The luminescence of coarse quartz grains was not completely bleached during fluvial transport into the valley bottoms after aeolian deposition, as can be seen in the distribution of equivalence doses of small sub-aliquots of a sample (see example in Figure 3). This effect could be corrected using the statistical technique of Juyal et al. (2006), modified by Fuchs et al. (2007). However, since errors of Holocene coarse grain dating were in the range of 10–13% (in Pleistocene parts of the sequences up to 31%), this caused a total error of 0.07–0.8 ka for the Holocene samples.

Chronostratigraphies of the investigated vega sections show that sediment ages range between Middle Pleistocene and Holocene in Femés and Teguise, and between Upper Pleistocene and Holocene in Guatiza III. The highest average sedimentation rate was recorded in Guatiza III, followed by Femés and Teguise. All vegas show a hiatus between ~15 and 30 ka, coeval with a "geomorphological crisis" described by Rognon and Coudé-Gaussen (1987) on Fuerteventura and in northwest Morocco. Chronostratigraphies are described in detail in Suchodoletz et al. (2008) (Figure 4).

The Holocene period includes a distinctive yellow-brownish loess-like layer found in all vegas (Figure 4, Table 2). Coarse quartz grain luminescence dating shows that this layer was coevally deposited during the early to middle Holocene in all vegas (Figure 5). The precise end of its sedimentation is questionable, since the timing of the start of anthropogenic colluvial sedimentation overlying the loess-like layers is unclear. Luminescence dating indicates that anthropogenic sedimentation probably started between c. 5 and 2.5 ka in Teguise and Femés and in Guatiza III between ca. 2.5 and 2 ka (Figures 4 and 5). In contrast to the sediments of non-anthropogenic origin, anthropogenic sediments are characterised by pebbly, heterogeneous material containing broken snail shells and partly ovicaprid bones (Table 2, Figure 4). The loess-like layer is underlain by reddish palaeosol sediments found in all vegas, characterised by a high clay content and vertic properties (Table 2, Figure 4) (cf. Suchodoletz et al., 2009a). These palaeosol sediments were formed by pedogenesis mostly on the slopes, and afterwards eroded and transported into the valley bottoms by fluvial processes (Suchodoletz et al., 2009b). The end of the pedogenesis and the subsequent start of the loessic sedimentation are thought to have taken place at c. 8.5 ka. This is based on a parallel rise of sea surface temperatures in the Canary current and/or a possible retreat of the African summer monsoon from this area during that period (Zhao et al., 1995; Boessenkool, 2001; Kuhlmann, 2003), which is most likely responsible for the end of more humid conditions and thus of more intensive pedogenesis in the vegas (Suchodoletz et al., submitted).

When related to the total mineralic sediment mass, Pleistocene and Holocene values of bulk fine sand (63–125 μm) vary between 0.06 and 1.49% in Femés, between 0.01 and 2.14% in Teguise and between 0.01 and 5.5% in Guatiza III. Regarding only quartz fine sand (63–125 μm), values vary with irregular fluctuations between 0.03 and 0.42% in Femés, 0.06 and 1.04% in Teguise and 0.11 and 0.77% in Guatiza III during the Pleistocene. In contrast, fine quartz sand contents dramatically increase during the Early and Middle Holocene, reaching maximal values of 0.9% in Femés, 1.83% in Teguise and 2.88% in Guatiza III. In overlying Late Holocene anthropogenic layers, values strongly decrease again in all vegas (Figure 6).

For marine core GeoB11804-4, the magnetic parameters (magnetic susceptibility and HIRM) and the ratio titanium/calcium (Ti/Ca) increase from the bottom to the top of the core. The sedimentation rate (calculated using a polynomial fit through 25 ^{14}C ages on mixed benthic foraminifera, Blanchet et al. (2009)) is higher at the bottom and at the top of the core (Figure 8).

Discussion

Suchodoletz et al. (2009b) show that average dust sedimentation on Lanzarote increased in several steps during the last 1.0 Ma: 0.67 cm/ka between 1.0 Ma and 180 ka, 1.0 cm/ka between 180 ka and 8.5 ka and 1.1–1.8 cm/ka between 8.5 and 5 (or latest 2.5 ka), before reaching the values of 1.5–3.0 cm/ka observed today (Herrmann et al., 1996; Menéndez et al., 2007) (Figure 7). This pattern could be biased by the comparison of different timescales during the investigated period, where short periods of high dust input could be included in the Pleistocene time slices. However, such periods of high dust sedimentation would have lowered the average dust sedimentation rate for the majority of the Pleistocene, so that the observed overall increase of dust input from the Pleistocene–Holocene transition until the middle Holocene is not an artefact.

In core GeoB11804-4, magnetic susceptibility (MS) and HIRM show a step-wise increase between ˜17.8 ka and the top of the core, with remarkable steps at ~12.8 and 2 ka (Figure 8). Similarly, the Ti/Ca ratio notably increases between ~17.8 and 12.8 ka and then gradually increases towards the top of the core. MS is a tracer for magnetite (Fe_3O_4) content, which has been shown to be a major component of present-day dust samples (Menéndez et al., 2007; U. Hambach and C. Blanchet, unpublished data). HIRM is a proxy for hematite (Fe_2O_3) and goethite (FeOOH) content that might be minor components of dust (Balsam and Otto-Bliesner, 1995). The latter minerals are less sensitive to dissolution than magnetite (occurring during early diagenesis in marine sediments; Funk et al. (2004)), and the overall correlation of MS and HIRM profiles suggests a limited influence of diagenesis on the magnetite content (restricted mostly to the upper 2 ka). The Ti/Ca ratio is used as a tracer for terrigenous-biogenic content in marine sediments (Kwiecien et al., 2009), and indicates higher terrigenous contents in sediments deposited here after 17.8 ka. This further indicates that diagenetic dissolution of magnetic minerals is not the main modulator of iron oxide contents. Furthermore, this demonstrates that the increased sedimentation rate between 12.8 and 2.5 ka (Figure 8) is much more likely due to an increase in terrigenous input than to an increase in marine biogenic productivity. This massive delivery of terrigenous material to the continental margin close to Cape Ghir between 12.8 and 2.5 ka might be mainly due to higher dust input (although a fluvial contribution cannot be ruled out), since it corresponds to the dust event reconstructed in Lanzarote (see above) and to a higher ratio aeolian/fluvial input on the margin as reconstructed in a neighbouring core (GeoB6007) during the early Holocene (Holz et al., 2007).

The above conclusion clearly disagrees with the results of marine core ODP 658 (de Menocal et al., 2000). These authors report increased dust input only after 5 ka, whereas the findings from Lanzarote and from core GeoB11804-4 indicate that this increase already started some ka earlier, at the latest just prior to the Pleistocene–Holocene boundary. The time discrepancy between our results and those of de Menocal et al. (2000) could be due to geographical factors: core ODP 658 is located below the southern part of the Saharan dust plume influenced by the SAL during summer, whereas Lanzarote and the North Canary Basin are situated below the northern part of the dust plume, influenced by Calima winds during winter (Figure 1). This suggests that the transport of Saharan dust by Calima winds increased some ka earlier than the dust transport related to the SAL. A possible explanation is that the latest Pleistocene and Holocene palaeoclimatic history of the formerly monsoon-influenced southern Sahara was obviously different from that of the northern Sahara (Verschuren et al., 2004; Zielhofer et al., 2004), although large palaeoclimatic knowledge gaps exist in the northern Sahara until now (cf. Cheddadi et al., 1998).

In addition, enhanced Holocene dust sedimentation on Lanzarote was accompanied by a dramatic increase of fine quartz sand (63–125 μm) in sediments deposited during the early and middle Holocene (Figure 6). However, such a coarsening was neither detected in marine cores located ~300 km north (GeoB5559-2, GeoB6007-2; Figure 1), nor in those located ~1000 km south (CD 53-30, ODP site 658; Figure 1) of Lanzarote (Matthewson et al., 1995; de Menocal et al., 2000; Moreno et al., 2001; Holz et al., 2007). In Femés, a significant volcanic input during the Pleistocene only recorded in bulk fine sand displays that depth-dependent functions of bulk and quartz fine sand are independent from each other (Figure 6). Bulk fine sand contains both local volcanic and allochthonous aeolian material (e.g. quartz), so that the independent trends of bulk and quartz fine sand confirm a purely aeolian origin of quartz on Lanzarote. An anthropogenic cause for the strongly increased quartz fine sand content is not possible, since chaotic colluvial sediments indicating human impact on the instable semi-arid landscape of the island are not mixed with underlying loess-like layers showing higher fine quartz sand content. Unfortunately, there are only few Holocene coarse grain OSL ages. Furthermore, there are the effects of a small time-lag between aeolian sedimentation in the vega catchments and subsequent fluvial transport into the valley bottoms, which potentially cause an underestimation of the primary aeolian depositional age of the sediment during luminescence dating (Suchodoletz et al., 2009b). However, a cross-correlation of the information from different vegas demonstrates that, in spite of these uncertainties, ages are reliable; OSL dating shows that the increase of quartz fine sand in Femés and Teguise started coevally at c. 8–7 ka, with the highest values reached at c. 5–6 ka before declining dramatically (Figure 6). However, in Guatiza III, a coarse grain OSL age shows that there was a continuous increase in the amount of fine quartz sand until ~2.7 ka prior to a sharp drop of its content. Since the OSL age from Guatiza III could also be successfully corrected for insufficient bleaching prior to material deposition, this age is also regarded as reliable. Thus, the fine sand content in Guatiza III could continuously grow beyond the period 5–6 ka, reaching highest absolute values of all vegas (2.88%) ~2.7 ka, since there was no earlier disturbance of the natural sedimentation pattern by anthropogenic activity as in Teguise and Femés. Unfortunately, due to the lack of dating in the lower part of the loess-like layer, the onset of coarse dust sedimentation in Guatiza III cannot be determined exactly (Figure 5). However, all profiles are situated at a maximal distance of 30 km from each other, and the increase of fine quartz sand occurs in loess-like layers showing very similar sedimentological properties in all vegas (cf. Table 2, Suchodoletz et al., 2009a).

This strongly suggests that the sedimentation of coarse Saharan dust synchronously started in all vegas (including Guatiza III) ~7–8 ka ago. Overlying anthropogenic layers are a mixture of material of different ages, consequently showing different fine quartz sand contents. This material was deposited in protected locations of the catchment areas and was coevally mobilised by anthropogenic activity during the middle and late Holocene. Due to the mixed character of this material, fine quartz sand values drop dramatically compared to underlying loess-like layers.

Regarding boundary conditions necessary for the entrainment of mineral grains into the atmosphere, three different factors could have caused a coarsening of Saharan dust input to Lanzarote (Gillette, 1979; McTainsh et al., 1982; Tsoar and Pye, 1987; Xu, 2006):

(1) a strong increase of wind speed, allowing coarser grains to be transported into the atmosphere;
(2) an approaching of the source area of Saharan dust, diminishing the sedimentation of coarser grains prior to their arrival in Lanzarote;
(3) a destabilisation of the source area of Saharan dust, possibly by anthropogenic activity.

In the following, we will discuss these three possible causes of the observed strong coarsening of Saharan dust input on the Canary Islands during the early and middle Holocene:

(1) Increased wind speed can mobilise coarser grains and transport them over longer distances. The coarseness of early and middle Holocene dust input far exceeds all values known during the past 180 ka, a time span also including prominent stormy periods in Northwest Africa, such as termination I and II (Lézine and Denèfle, 1997; Moreno et al., 2001). Furthermore, no evidence of exceptional high wind strengths was found in records from different regions during the early and middle Holocene (O´Brien et al., 1995; Hesse and McTainsh; Xiao et al., 1999; 1999; Mayewski et al., 2004). This demonstrates that an increase of wind speed can be ruled out as a cause of coarse dust input to Lanzarote during the early and middle Holocene.

(2) A marine regression would cause part of the Northwest African shelf to fall dry and thus offer its sediments to mobilisation by aeolian processes. However, global sea level during the early and middle Holocene between 8 and 7 ka had almost reached modern values and was only reduced by a maximal amount of ~10 m (Peltier, 2002). Thus, only a small strip of the African shelf was uncovered by water during that period. This indicates that this area was not a prominent source area of Saharan dust during the early and middle Holocene.

(3) An anthropogenic destabilisation of nearby African landscapes upwind of the Canary Islands. This would expose sediments of those areas to aeolian uptake and thus virtually approach the source of Saharan dust to the depositional area on Lanzarote, whereas the relative contribution of (finer) dust transported over longer distances is reduced (McTainsh et al., 1997). Regarding the time span 180–8.5 ka, significant landscape change was exclusively caused by natural phenomena. In contrast, anthropogenic activity, such as early Neolithic land use causing negative effects on landscape stability, only started during the Holocene (Fuchs, 2007; Dearing, 2008). This offers a possibility to explain the unprecedented strong coarsening of Saharan dust input 8–7 ka ago by early anthropogenic activity.

Although Middleton et al. (2001) report a possible transport of large grains over long distances as part of a “giant aeolian fraction”, we think that a transport of “giant” quartz grains from Africa to Lanzarote over hardly 160 km by Calima winds is much more probable than a transport by the hook-shaped SAL, with a distance of at least 1000 km (Figure 1). This is further supported by the lack of early–middle Holocene coarse dust input in marine records, situated about 1000 km south of Lanzarote off Cape Blanc directly below the transport path of the high-altitude SAL (cores CD 53-30 and ODP site 658; Figure 1) (Matthewson et al., 1995; de Menocal et al., 2000). However, no similar coarsening was observed in marine cores off Cape Ghir, situated in an area some 300 km north of Lanzarote, although this region is also strongly influenced by Calima winds (Moreno et al., 2001; Holz et al., 2007) (Figure 1) and shows a general increase of dust input during the latest Pleistocene and early Holocene, as described above.

Thus, the lack of coarsening in marine cores, located some 100 km both north and south of Lanzarote, indicates that the cause of coarse dust mobilisation was probably located in a very confined area upwind of Lanzarote, not delivering dust to the region off Cape Ghir during Calima events. Such an area could be located in the Saharan coastal region opposite to Lanzarote (Cape Yuby) and its hinterland in the Western Sahara or northern Mauritania (Figure 1), regions that are main dust sources for the Canary Islands today (Criado and Dorta, 2003;Alonso-Pérez, 2007). Data outlining the settlement history of the coastal region are rather scarce; however, they do not show strong anthropogenic activity during the period 8–7 ka ago. Whereas a single Neolithic settlement is reported by Zielhofer and Linstädter (2006) during this time, other studies show that the region around Cape Yuby (site Izriten) and the Western Sahara were generally occupied by dispersed settlements of the epipalaeolithic Foum Arguin culture of nomadic hunters (Charon et al., 1973; Vernet, 2004). It was only during the middle Holocene that people migrated from desiccated Saharan ergs towards the Atlantic oast (Nehren, 1992). A corresponding Saharan influence on Neolithic sites in northern Morocco, as well as an increase of Neolithic settlements in the region of Cape Yuby, are consequently reported only after ~6–5 cal ka BP (Daugas et al., 1989; Debénath, 2000; Zielhofer and Linstädter, 2006). However, also after the introduction of a Neolithic lifestyle into the coastal area of the Western Sahara and southern Morocco during the middle Holocene, this was dominated by hunter-gatherer and fisher cultures. Ceramics and grind mills (from ~4–3 ka), testifying to a middle Holocene Neolithic economy including tilling and stock farming activities, are almost exclusively found southwards towards Mauritania in more humid areas

(Petit-Maire, 1979a; Hassan, 2002). North of Cape Blanc, this kind of economic activity was mostly lacking. Looking at landscape stability in the coastal area opposite to the Canary Islands, Ortlieb (in Petit-Maire, 1979b) describes the region as generally protected against surface erosion by a widespread Quaternary calcrete overlying more erodible sediments, whereas dunes are only found in a small strip along the littoral. Furthermore, local Neolithic activity obviously stabilised these coastal dunes by a cover of marine shells, rather than strongly altering their stability (Petit-Maire, 1979a). In summary, archaeological findings in the coastal area opposite to the Canary Islands do not point to human destabilisation during the early and middle Holocene. In contrast, the West Saharan and Mauritanian hinterland of the coastal area is largely unexplored in respect to archaeology. Here, Brooks et al. (2003, 2006) describe a wealth of Holocene archaeological remains. They suspect that this area had served as a refuge for people fleeing the desiccated Sahara, due to relatively advantageous conditions compared to regions further to the east; although the timing of initial settlement is not known. Thus, inappropriate land use activities could have led to large-scale landscape instability in the hinterland, providing a possible explanation for the observed coarse dust input in Lanzarote during the early and middle Holocene.

Conclusion

A general increase of Saharan dust input to the area of the Canary Islands during the Holocene is accompanied by a strong coarsening in dust-borne sediments on Lanzarote from c. 8–7 ka ago. This coarsening is neither coincident with a period of strong winds nor with a low sea level allowing sediments to be blown out from the African shelf. Several studies report a strong enhancement of dust export from semi-arid areas caused by a destabilisation of surfaces by human and animal activity, accompanied by a mobilisation of coarse grain sizes (McTainsh et al., 1997; Neff et al., 2008). This strongly suggests an anthropogenic rather than a natural cause of coarse dust input into Lanzarote during the early and middle Holocene, by virtue of human influence on landscape stability in areas of dust mobilisation on a scale never seen before. No parallel coarsening of Saharan dust input is observed in marine records both north and south of the Canary Islands. Thus, a confined local dust source in the area upwind to Lanzarote during Calima events is assumed, comprising parts of Western Sahara and northern Mauritania. Although no large-scale anthropogenic activity is known from the coastal area during the early and middle Holocene today, the described general wealth of archaeological remains together with the scarcity of archaeological studies of the coastal hinterland does not exclude an anthropogenic trigger for the observed coarse dust input on Lanzarote. Therefore, the conclusions presented here, based on sedimentological analyses of Saharan dust deposits, raise more questions and thus ask for indispensable archaeological investigations in the West Saharan and north Mauritanian region.

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Figures

Figure 1

Location of the Canary Islands off Northwest Africa. Dust-bearing winds are indicated by transparent arrows. The SAL splits off Northwest Africa into a western and a hook-shaped northern part, the latter influencing the Canary Islands. The way of Calima winds is differentiated between that of Calima arriving in the North Canary Basin (I) and that arriving in Lanzarote (II). The northeast trade wind is shown by hatched arrows. The main area of dust export towards the Atlantic (after Windom, 1975) is limited by a dotted line. Marine core GeoB11804-4 presented in the text is marked with a star off Cape Ghir. Marine cores mentioned in the text are shown by filled circles with numbers: GeoB 5559-2 =Moreno et al. (2001); GeoB 6007-2 = Holz et al. (2007); ODP-site 658 = de Menocal et al. (2000); CD 53-30 = Matthewson et al. (1995).
The inset shows Lanzarote with investigated sites.

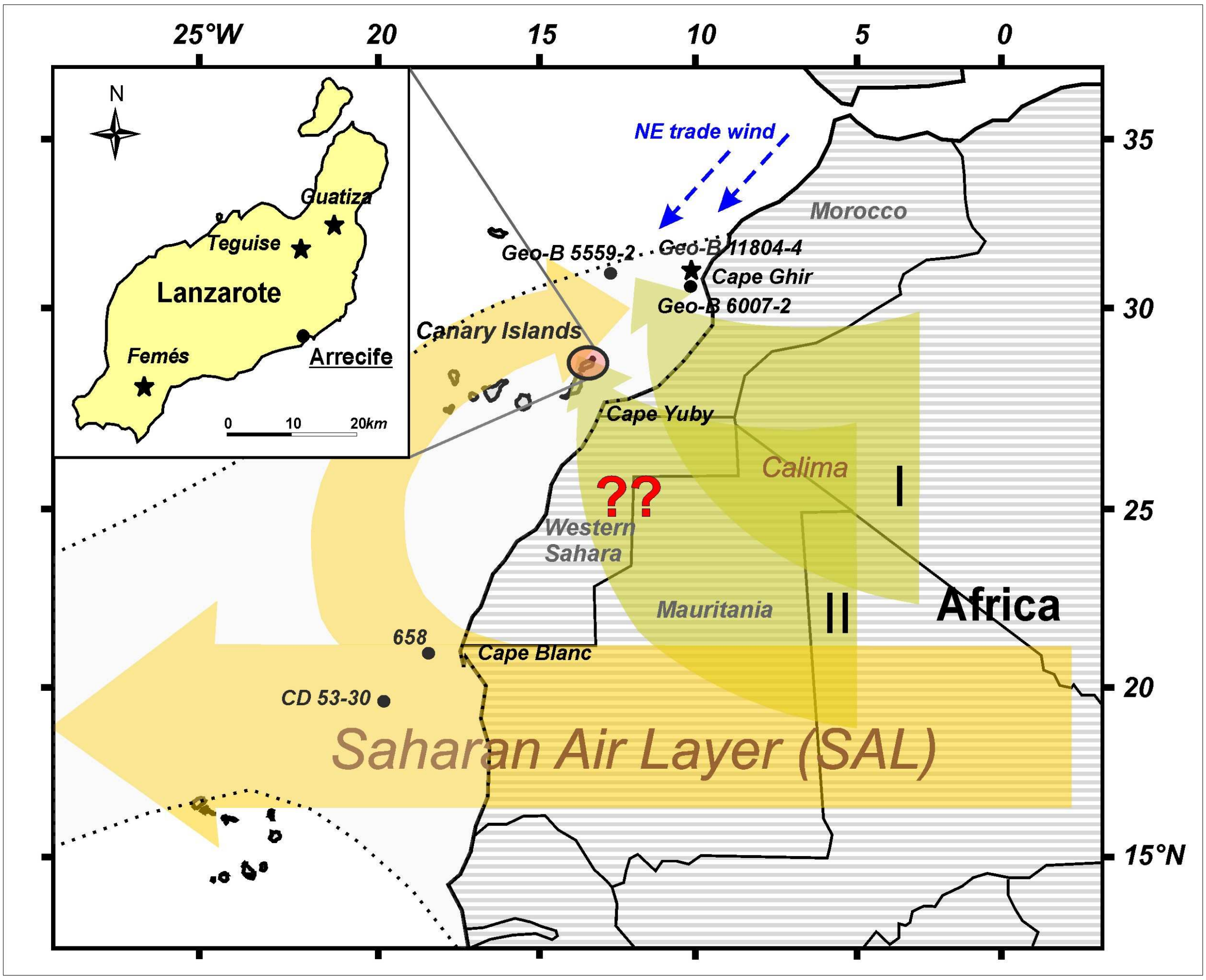


Figure 2

Calibration curve used for the determination of absolute quartz contents during XRD analyses. The intercept of the linear regression curve with the y-axis >0 was caused by the fact that a main peak of muscovite is close to the investigated quartz peak. Given that the mineral composite was always identical, this effect could be neglected for further calculations.

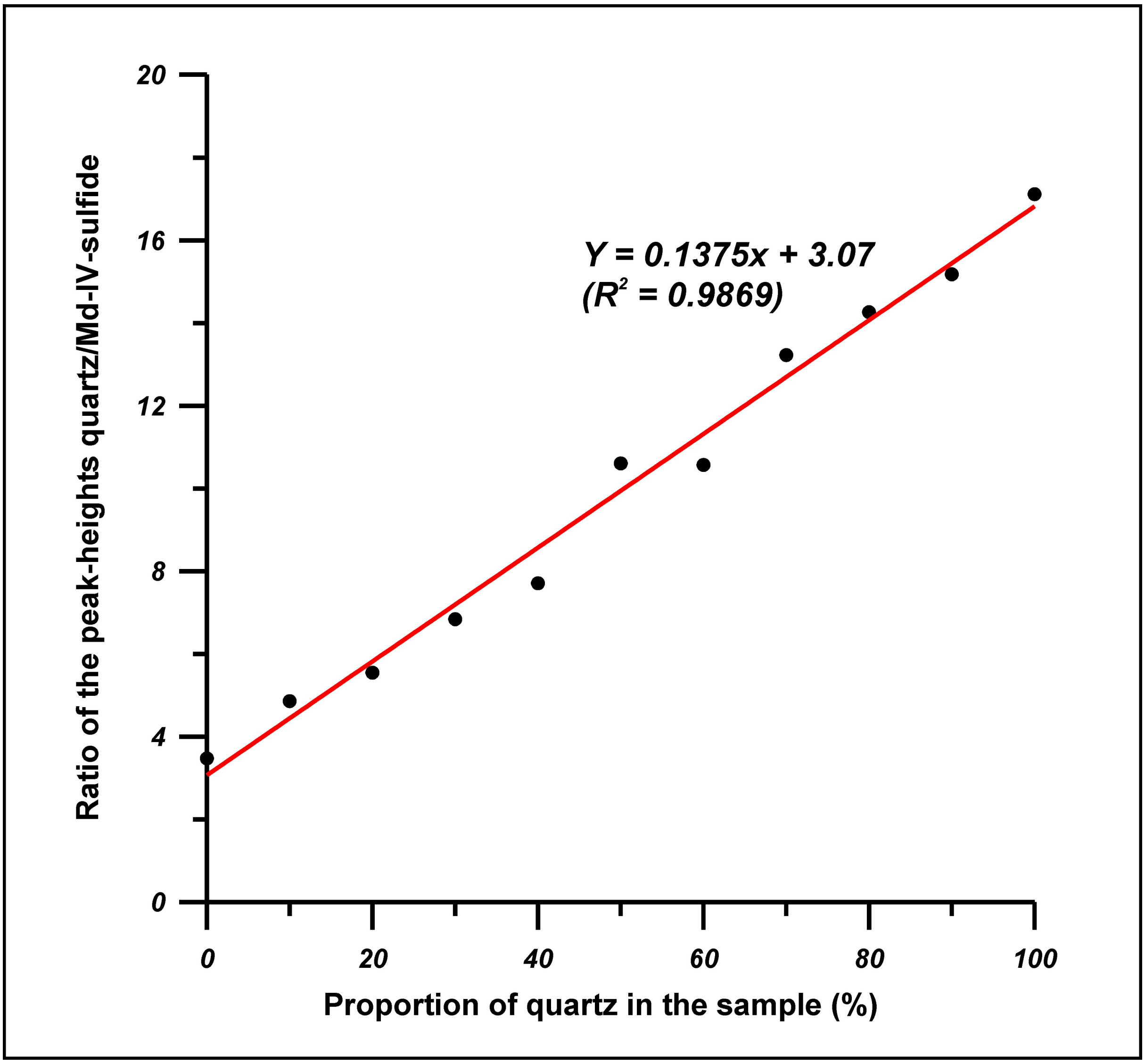


Figure 3
Equivalence dose histogram of coarse grain OSL sample Teguise 80 cm (cf. Figure 4). Due to insufficient bleaching of some parts of the material during fluvial transport into the vega bottom, following primary aeolian deposition in the catchment area, the histogram shows a left skewed distribution.

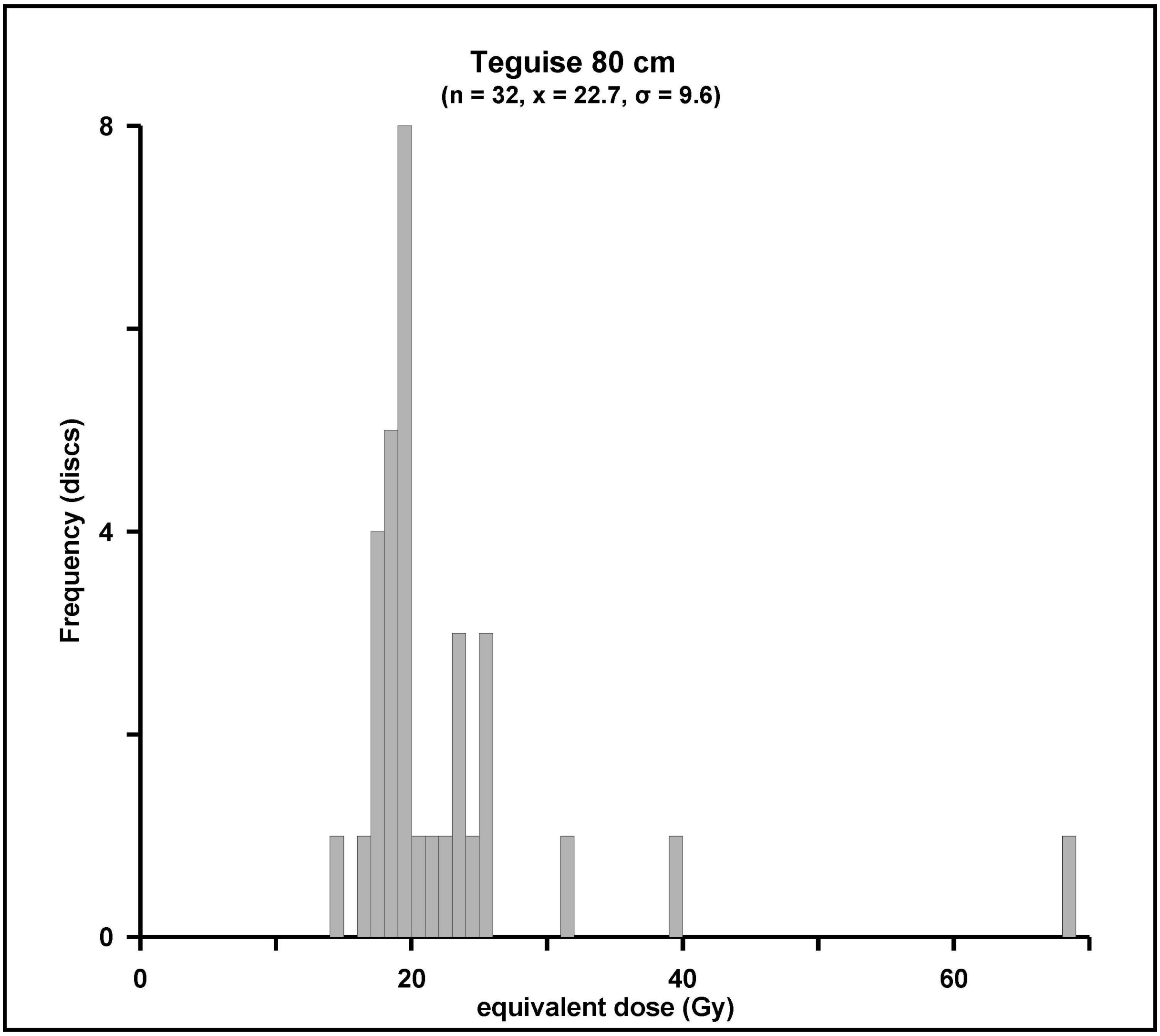


Figure 4

Stratigraphies of investigated vegas with luminescence ages and chronological frame. Upper horizons contain anthropogenically triggered colluvia of various thicknesses (55–420 cm) that cannot be used for palaeoenvironmental inferences.

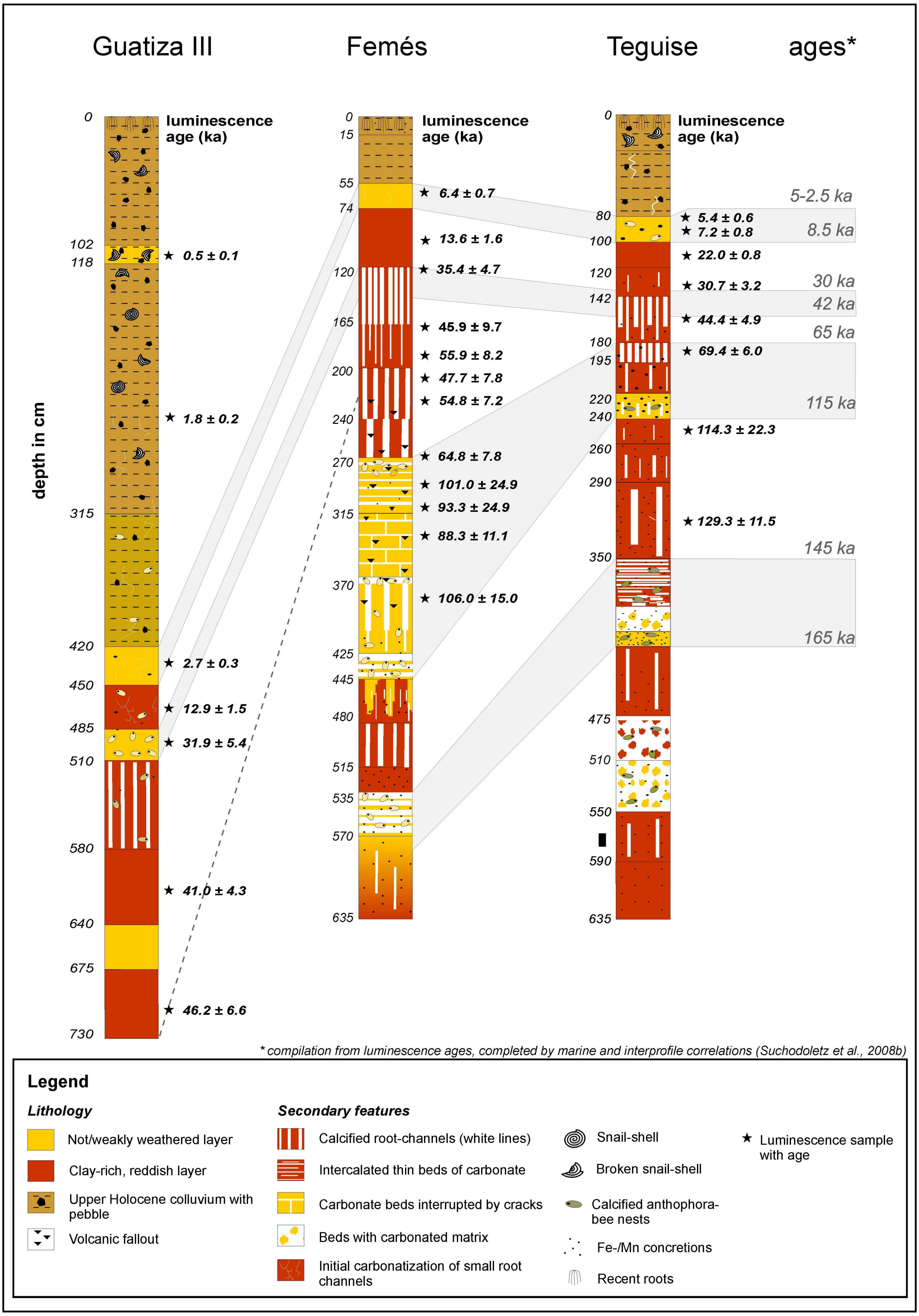


Figure 5

The loess-like Holocene layer present in all vegas (light grey), underlain by soils/soil sediments (middle grey) and overlain by anthropogenic colluvia (dark grey). Coarse grain OSL ages are shown as filled circles with error bars. The start of loess-like sedimentation ~8.5 ka is determined by the concomitant increase of SSTs in the Canary current and a possible retreat of the African summer monsoon, both assumed to have stopped pedogenesis in Lanzarote (Suchodoletz et al., submitted).

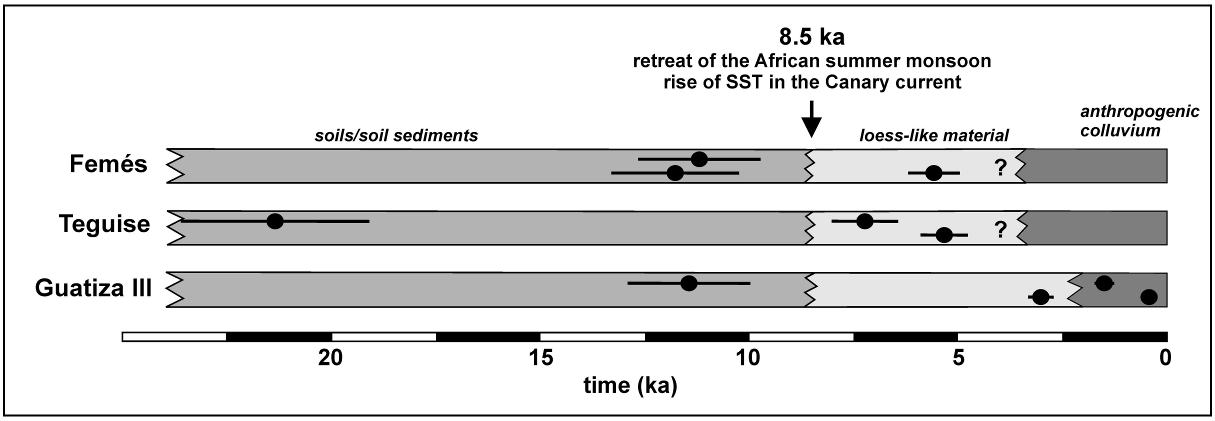


Figure 6
Chronological depth plots of bulk (hatched line) and quartz fine sand (continuous line) contents in all vegas. The Pleistocene period is indicated in light grey, whereas the Holocene is shown in dark grey. Insets show the younger parts of the depth plots in their stratigraphic context not adapted to absolute chronology. The Holocene loess-like layer is shown in light grey, underlying soils/soil sediments in middle grey and overlying anthropogenic colluvia in dark grey. Coarse grain quartz OSL-ages are shown as filled circles with error bars. For the lithological features, see legend of Figure 4.

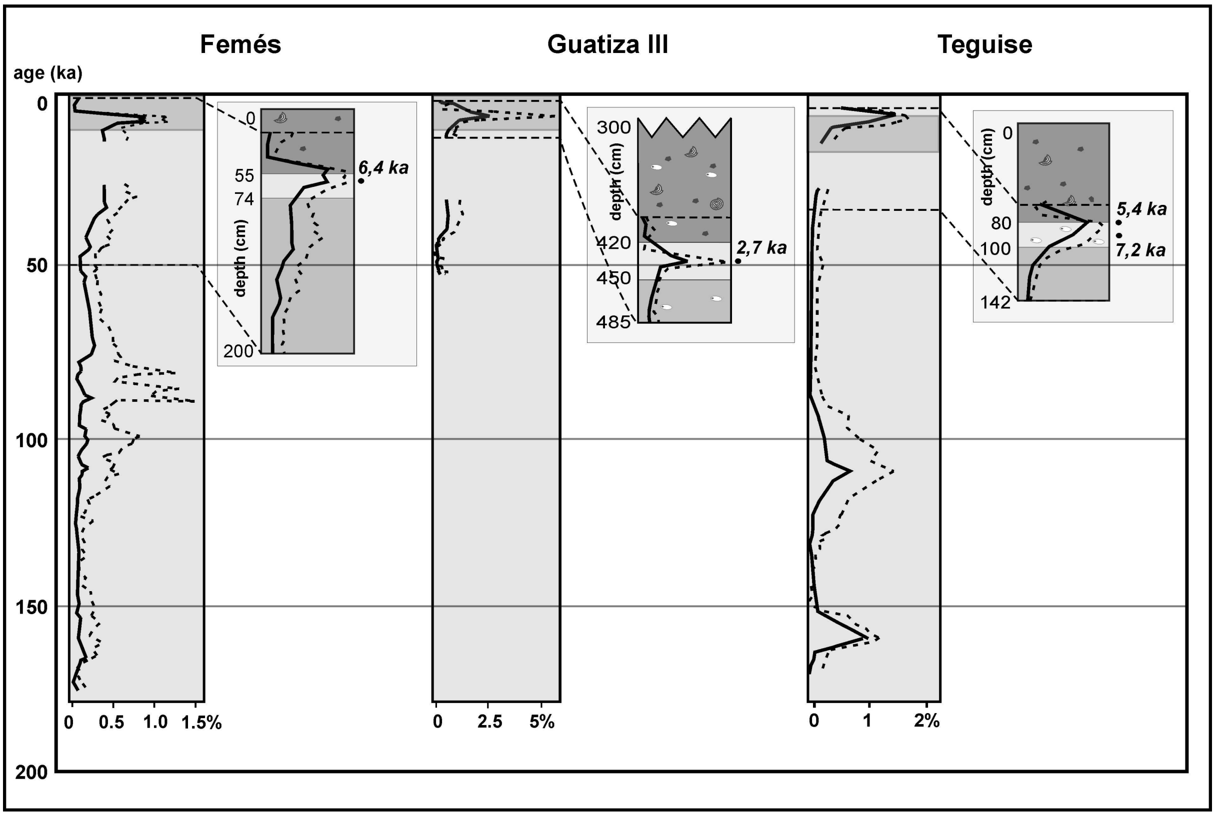


Figure 7

Evolution of dust input on Lanzarote based on the sediment mass balance of the Femés vega (after Suchodoletz et al. 2009b). Dashed lines indicate the incertainty of calculations for the Holocene and the recent period (Herrmann et al., 1996; Menéndez et al., 2007). Much lower values of 0.46 cm/ka reported for the recent period by Prospero (1996) are not included, since the author itself points to the uncertainty of this estimation due to methodological problems. During the periods 180–8.5 ka and 1.0Ma–180 ka, dust input was probably lower than derived from the sediment mass balance, when accounting for the fact that during these periods high input of volcanic material is most likely.A30-cm-layer, almost exclusively composed of lapilli and tephra found in a drill-hole below the recent surface of the outcrop, suggests that this reduction was probably strongest during the period 1 Ma–180 ka (Zöller et al., 2003). In difference, no Holocene volcanic eruptions causing volcanic fallout into the vega are known from Lanzarote between 21 ka and the 18th century AD. (Carracedo et al., 2003; Instituto Tecnológico y Geominero de España, 2005), so Holocene values can be regarded as close to the real quantity of dust input. A significant effect of sediment compaction can be excluded, since the proportion of pores in the sediment matrix fluctuates irregularly throughout the upper 6.3 m of the sediment between 20 and 35%, as seen by soil micromorphology (Sauer and Zöller, 2006).

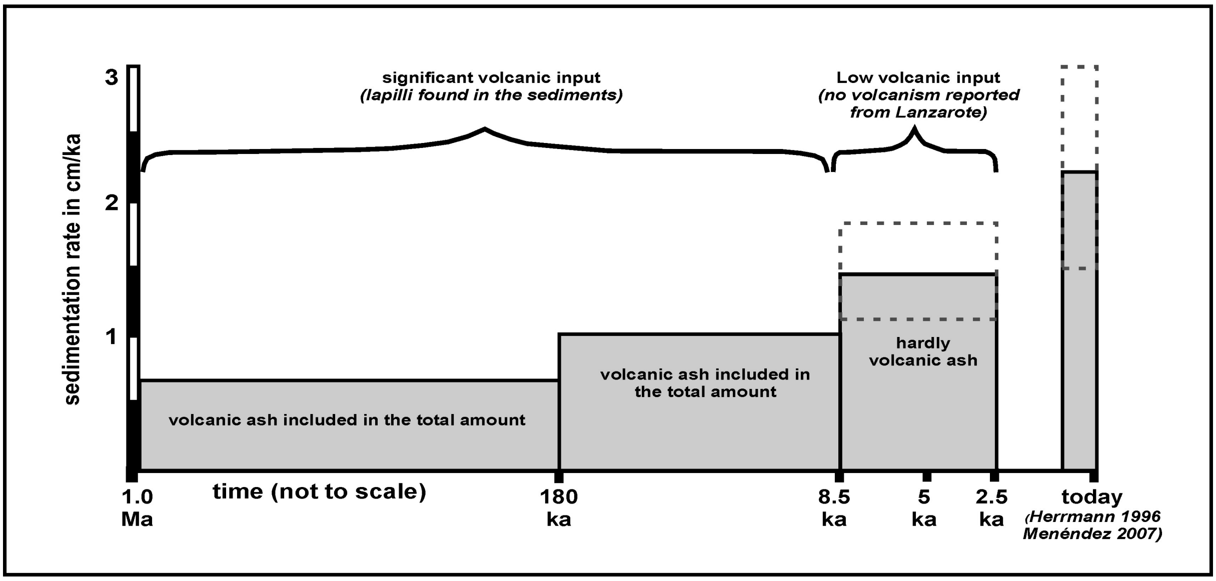
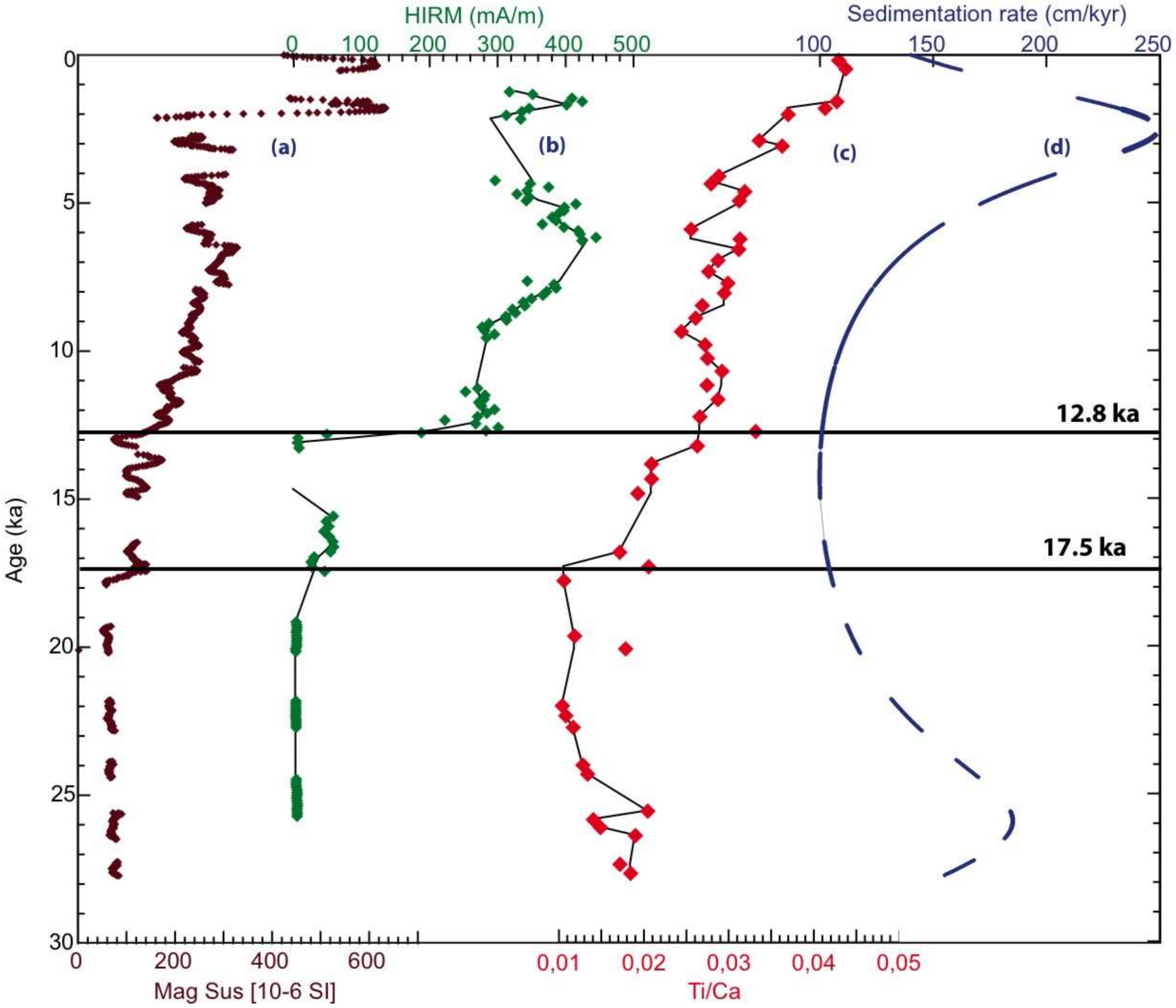


Figure 8

Magnetic and elemental record of marine core GeoB11804-4, indicating changes in terrigenous input. (a) Magnetic susceptibility is used as an indicator of magnetite concentration, (b) hard isothermal remanent magnetisation (HIRM) is used as a proxy for the hematite and goethite concentration, (c) Ti/Ca ratio is used as a tracer for terrigenous/biogenic content. Average lines are moving averages over 7 points, (d) sedimentation rates calculated using a polynomial fit through 25 14C ages (Blanchet et al., 2009), which was also used to establish the age model. Terrigenous input starts to increase at 17.5 ka and steadily rises during the deglaciation. Dust delivery seems to drastically increase after 13 ka.



Tables

Table 1
Properties of studied sites on Lanzarote

	Guatiza	**Femés**	**Teguise**
latitude N	29°04´08´´	28°55´32´´	29°04´52´´
longitude W	13°29´22´´	13°45´19´´	13°30´55´´
altitude (m a.s.l.)	100	300	300
catchment area (km^2)	10.1	5.07	3.8
valley bottom (% of catchment area)	16.1	18	35
relative elevation difference in the catchment area (m)	> 550	100-200	100
time of volcanic damming	170 ka[1]	1.0 Ma[2]	1.2 Ma[3]
volcanic damming complete?	no	yes	no
thickness of anthropogenic colluvial deposits (cm)	420	55	80

[1] red thermoluminescence ages (unpublished data)

[2] Instituto Tecnológico y Geominero de España (2005), Coello et al. (1992)

[3] Instituto Tecnológico y Geominero de España (2005)

Table 2
Holocene stratigraphies of the investigated sediment sequences from Lanzarote.

	Femés	**Teguise**	**Guatiza III**
Anthropogenic colluvium			
Depth (cm)	0-55	0-80	0-420
Munsell colour	5YR 5/6	5YR 4/4	5YR 4/6
Silt (clay) content (%)	54 (45)*	-	-
Vertic properties	?	?	?
Pebbles, broken snail shells	yes (very singular)	yes	yes
Loess-like layer			
Depth	55-74	80-100	420-450
Munsell colour	5 YR 6/4	5YR 4/3	7.5 YR 4/6
Silt (clay) content (%)	74 (23)*	-	-
Vertic properties	no	no	no
Pebbles, broken snail shells	no	no	no
Soil sediments			
Depth	74-120 cm	100-120 cm	450-485 cm
Munsell colour	5YR 3/6	5YR 4/6	5YR 4/6
Silt (clay) content., (%)	36 (59)*	-	-
Vertic properties	yes	yes	?
Pebbles, broken snail shells	no	no	no

* data taken from Suchodoletz et al. (2009a)