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Geomorphological investigations of sediment traps on Lanzarote (Canary Islands) as a key for the interpretation of a palaeoclimate archive off NW Africa

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Abstract
On Lanzarote (Canary Islands) Late Quaternary Saharan dust and volcanic material were trapped in Miocence to Pliocene valleys dammed by volcanic lava flows. These trapped sediments are potentially interesting as they can be natural archives useful to reconstruct the terrestrial palaeoclimate history of the NW African margin. Nevertheless, slope wash processes altered the primarily eolian deposits, making climatic interpretation not straightforward. Geomorphological mapping, GIS calculations and sedimentological investigations were used to unravel these processes influencing the temporal resolution of the palaeoclimatic archive, demonstrating that they average the palaeoclimatic signal by some ka. Thus, despite the colluvial geomorphic environment, the valley fillings can be used for palaeoclimatic interpretation of events with a length of at least some ka. The youngest sediments, deposited since at least 2.5 ka, are anthropogenically triggered and thus cannot be used for palaeoclimatic interpretation. The results show that the input of Saharan dust at Lanzarote increased during the last 1.0 Ma and especially during the Early/Middle Holocene.

1. Introduction

Loess–palaeosol sequences are an important type of terrestrial palaeoclimate archive. Such sequences have been used in both hemispheres to derive terrestrial climate variations during past few million years including changing wind dynamics and moisture regimes (e.g. Issar and Bruins 1983; Dodonov and Baiguzina 1995; Antoine et al., 2001; Berger et al., 2001; Markovic et al., 2006; Schellenberger and Veit 2006; Mason et al., 2007). Accordingly, loess–palaeosol sequences derived from Saharan dust were investigated in the Mediterranean area and are regarded as valuable palaeoclimate archives (e.g. Yaalon and Bruins 1977; Coudé-Gaussen 1991; Dearing et al., 2001).
Lanzarote (Canary Islands) is situated on the northern fringe of the Saharan dust plume over the Atlantic Ocean and annually receives eolian material derived from the Sahara (e.g. Jahn, 1995). This study investigates valleys dammed by volcanic activity representing sediment traps, where continuous sedimentation of Saharan dust and volcanic material occurred over a longer time span during the Quaternary (Zöller et al., 2003). The layered deposits filling the valleys show continuity and therefore could be used as palaeoenvironmental archives (Fig. 1). However, steep and strongly eroded slopes of the valleys indicate that colluvial input contributed to the infilling of the valleys (Fig. 2). When sediments were only partly directly deposited by eolian input and another part was later reworked by colluvial processes, the understanding of the link between erosional and depositional area and the type of material transport (high frequency/low magnitude or low frequency/high magnitude) becomes important for palaeoenvironmental interpretation. These issues are important since a weak link and low frequency/high-magnitude processes can cause a time lag between environmental signal and time of deposition or destroy older sediments (e.g. Lang, 2003; Fuchs et al., 2004; Rommens et al., 2006). Hence, the interpretability of a colluvial sedimentary archive depends on the way of transport, making its investigation a crucial prerequisite for a subsequent palaeoenvironmental interpretation of the archive.
Consequently, in order to know whether the sediments trapped on Lanzarote bear useful palaeoenvironmental information about the regional climate of the NW African region and to what extent they can be stratigraphically and palaeoclimatologically interpreted, our

investigation of the sedimentation path focussed on the link between erosional and depositional areas as well as the frequency–magnitude relation of colluvial transport. For this, we use geomorphological mapping and GIS calculations supported by luminescence dating and sedimentological analyses. The investigations allow the development of different sedimentation scenarios, which can serve as a base for further palaeoclimatic interpretation of these deposits. Furthermore, quantitative estimations from a selected sediment trap allow evaluating the dynamics of Saharan dust input during the Quaternary as well as the influence of anthropogenic activity on the local semiarid ecosystem.

2. Geographical setting

Lanzarote is the northeasternmost island of the volcanic Canary islands 130 km off the coast of Southern Morocco at 28–29°N and 13–18°W (Fig. 3). Volcanism on Lanzarote started during the Miocene about 15.5 Ma ago and lasted until the Late Holocene (last volcanic eruptions 1730–36 and 1824) (e.g. Carracedo et al., 1998). Both the northern and the southern part of the island are dominated by volcanic massifs with Miocene to Pliocene age. The volcanism is basic and pyroclastics were formed (cf. Rothe, 1996). Given this basic volcanism of the island, Mizota and Matsuhisa (1995) and Jahn (1988) demonstrate that all quartz found on the island has an allochthonous origin. The relief of the island is strongly eroded so that the maximum altitude of Lanzarote is only 670m (Jahn, 1988). Slopes are generally smoothed and concave. Several phases of soil forming processes led to the formation of polygenetic calcretes, which are exposed on the slopes of the volcanoes due to erosion processes. The two volcanic complexes are separated by the central part of the island showing a smoother topography, and are dissected by numerous U-shaped valleys and smaller gullies. Some of the larger valleys were dammed by volcanic material (lava flows, pyroclastica) during the Early and Middle Pleistocene so that they served as sediment traps for Saharan dust and local volcanic material. Locally, these dammed valleys are called vegas.

The climate of the Canary Islands is maritime-semiarid. Due to the limited altitude of Lanzarote compared to the western Canary Islands, the island gets no orographic precipitation from rising trade winds. Thus, it gains only very sparse precipitation (100–250 mm) from boreal winter cyclones decreasing from higher to lower altitudes. Mean annual temperature at sea level is 19.9°C with a minimum of 17.0°C in January and a maximum of 23.0°C in August (Jahn, 1988). The vegetation has a very sparse, shrubby and dispersed character and is dominated by xerophytic and halophytic species. This kind of vegetation cover is mainly caused by anthropogenic activity (Jahn, 1988; Kunkel, 1993). Lanzarote is situated at the northern fringe of the Saharan dust plume over the North Atlantic. Today, Saharan dust is brought to Lanzarote during two different synoptic situations. During winter, dust is advected at low altitude (0–1500 m) to the archipelago by Calima-winds, continental African Trade winds (Harmattan) which are deflected towards the west by Atlantic cyclones situated close to the Canary Islands (cf. Criado and Dorta, 2003). During summer, dust is transported to the north of the Canary Islands by the northern branch of the Saharan Air Layer blowing at an altitude of about 1500–5500 m. There, the material sinks into the lower atmosphere due to changes in the geopotential fields and is finally transported towards the island by the Northeast Trade wind (cf. Koopmann, 1981; Bozzano et al., 2002).

3. Methods

Geomorphological mapping of the vega catchments and calculations with the GIS-program Arc Map 9.0 (ESRI) were used to determine the ratios between catchment area surfaces and those of the recent valley floors. The digital database of elevation contour lines was provided by GRAFCAN, Cartografía de Canarias S.A. The vector data were triangulated for the

calculation of a digital elevation model, where the height information is referenced per pixel. Due to the temporarily incomplete damming of the vegas of Teguise and Guatiza, the continuously completely closed Femés sediment trap was chosen in order to establish a semi-quantitative sediment mass balance by calculating volumes of sediment deposited in the vega bottom and temporarly stored in the catchment area (Table 1). Due to the lack of geophysical investigations, the depths of the different valley segments prior to damming were estimated using slope extrapolations from various vega transects as shown in Figs. 4 and 5. Close to the damming in the northeast, a value of about 50 m is proposed which is confirmed by the estimation of Zöller et al. (2006). Using the estimated depth of a vega transect produced a triangle-shaped cut through the sediment body. Considering a probable U-shaped valley, the triangle was horizontally cut at 75% of the depth so that the cut became trapezoid shaped, similar to most of the Miocene/Pliocene valleys found on Lanzarote today (Fig. 6). Taking into account different valley widths, the vega was subdivided into 10 different sediment bodies (Fig. 4, Table 1). To determine their lateral surfaces, the trapezoid cuts from adjacent vega transects were used, e.g. for sediment body V1 the cuts of the northward transect T-I and the southward transect T-II (Fig. 4) were taken. Sediment bodies V2–V5 were added to calculate the volume of the sediment deposited in the lower vega bottom, which is equivalent to the erosion base. The remaining sediment bodies served for calculations of the sediment trapped in small valleys and the upper vega, comprising the material that did not reach the erosion base in the lower vega bottom.
In order to estimate the volume stored in the alluvial fans, an average sediment thickness of 5 m, the average value observed during geomorphological mapping, was multiplied with the total area of the fans (Fig. 4). The partial overlapping of the fan areas with the sediment bodies is not relevant as a problem since the calculations are semi-quantitative.
Geomorphological mapping showed that all slopes are covered by thick calcretes and in the lower segments partly by soils. Thus, an average sediment thickness of 0.8 m was estimated for the remaining slopes.Consequently, the material deposited in the vega bottom was calculated by the formula

$$V_{vega} = V_2 + V_3 + V_4 + V_5$$

The material in the remaining catchment areas ($V_{catchment}$) was calculated by the formula

$$V_{catchment} = V_1 + V_6 + V_7 + V_8 + V_9 + V_{10} + V_{af} + V_s$$

where $V_{1\text{-}10}$ represent sediment bodies in the valley, V_{af} the sediment stored in alluvial fans and V_s the sediment deposited on the slopes.
Micromorphological images were interpreted after Stoops (2003) by Peter Kühn (University of Tübingen). Preparation of thin sections was executed after the method of Beckmann (1997).
Electric conductivities of sediment layers were measured by mixing 10 g of sediment with 50 ml of deionized water, and filtrating and measuring the filtrate with the conductivity electrode of a pH meter (inoLab, WAW).
Wet sieving yielded the grain size fractions of fine (63–125 µm) and coarse sand (250–2000 µm). Prior to sieving, an aliquot of 8–10 g (equidistant 5 cm) was treated with HCl and H_2O_2 to remove carbonate and organic matter. After sieving, dried fractions were weighed and related to the total mass of the sample.
Quartz contents determined by ***X-ray diffraction (XRD) analyses*** were used to determine quartz contents. Aliquots of 5 g (equidistance 10 cm) were ground in an agate mortar. Subsequently, carbonate was dissolved using 10% acetic acid at room temperature. Afterwards, the material was washed, dried, ground again and 2% Md-IV sulfide were added

as a standard (Krischner, 1990). Measurements were executed at a Siemens D 5005 diffractometer at the University of Potsdam (2s/point, 4–42°2θ, Cu-tube FLCu-4KE), results were interpreted using the program MacDiff 4.2.5. on a Macintosh computer (Petschick, 2000). For analysis, the highest peaks of Md-IV-sulphide (molybdenite) and quartz were used: for Md-IV-sulfide the peak at 14.39°2θ and for quartz the peak at 26.67°2θ. Absolute quartz contents were obtained applying a calibration curve consisting of 11 well defined quartz contents in an artificial mineral composite (feldspars, muscovite, olivine), spiked with 5% Md-IVsulphide.
Age determinations used luminescence dating, as discussed elsewhere (Suchodoletz et al., 2008).

4. Studied sites

Three dammed palaeovalleys (vegas) were investigated on Lanzarote (Fig. 3). The flat valley slopes underwent a long-term alteration with several soil forming periods as could be seen in polygenetic calcretes (Fig. 2). The valley bottoms are filled with quartz-rich sediments, thus indicating that they mainly consist of Saharan dust and to a minor degree of volcanic material including bombs, lapilli and ashes (Jahn, 1988; Zöller et al., 2004).

4.1. Vega of Femés

The vega of Femés is a SW to NE oriented palaeovalley with a length of about 3 km in the Los Ajaches Massif in the south of Lanzarote (Fig. 3). According to datings of volcanites originating from the same volcanic group as those that form the damming of the vega (Coello et al., 1992, Instituto Tecnológico y Geominero de España, in press), this damming occurred about 1.0 Ma ago and lasted until recent time. The valley bottom is situated about 300 m a.s.l. The catchment area extends about 5.07 km^2 whereof 18.4% are covered by the recent valley floor, giving a ratio of 5.4:1 (Fig. 3). The northwestern slopes are on average two times higher than the southeastern ones and reach up to 200 m relative height above the valley bottom. The topography is characterized by steep slopes, a nearby erosion base and relatively simple catchment topography. Although most of the valley bottom is filled up with horizontally deposited sediments, alluvial fans are common along the margin. The contact between valley bottom and slopes is abrupt. However, lower footslopes even in case of steep slope angles are covered by well preserved soils, which thin out upslope within a few metres.

4.2. Vega of Teguise

The Teguise sediment trap (vega de San José) is a 3 km long north–south directed palaeovalley at the southern margin of the Famara Massif in the north of Lanzarote (Fig. 3). Volcanic damming in the south occurred about 1.2 Ma ago (Instituto Tecnológico y Geominero de España, in press) and was not complete, as was detected during geomorphological mapping. The valley bottom is situated at about 300 m a.s.l. Surrounding slopes reach about 100 m above the bottom. They are obviously gentler and the topography is simpler compared with the geomorphic situation in Femés. The contact between valley bottom and slopes is gentle. However, the slope toes are covered with clayey reddish soil sediments, which thin out upslope within a few meters. The catchment area extends over 3.8 km^2, whereof 35% are covered by the recent valley floor yielding a ratio of 2.9:1 (Fig. 3). Due to incomplete damming, temporarily discharge of sediments happened and the sedimentary sequences show a conspicuous hiatus, close to the damming in the south of the vega.

4.3. Vega of Guatiza

The vega of Guatiza in northern Lanzarote is a flat area situated at the southeastern foot of the Famara Massif close to the mouth of a canyon draining the highest parts of the volcanic complex reaching about 670 m a.s.l. (Fig. 3). The valley bottom is at about 100 m a.s.l. To the east, the vega was dammed by a chain of younger volcanoes whose ages are described as Holocene (Instituto Tecnológico y Geominero de España, in press). However, thermoluminescence (TL) dating of heated palaeosols point to a damming 170 ka ago (unpublished data). Since damming was not complete to the north, the calculation of the ratio catchment-vega bottom is an approximation. A rough estimation yields a catchment area of about 10 km^2 whereof the valley bottom covers approximately 16%, resulting in a ratio of 6.2:1 (Fig. 3). Since this ratio is even higher than that in Femés, the sedimentation rate would be the highest of the three studied vegas. However, due to incomplete damming hiatae could be expected which would lower the sedimentation rate.

5. Results and discussion

5.1. Sedimentation system of the vegas

5.1.1. Connection between areas of erosion and deposition

Geomorphological mapping of the whole catchment areas, supported in Femés by the sediment–mass balance of the vega system, demonstrates that depending on their geomorphology the coupling between erosional and depositional area is different in the three valleys.

In Femés, intermediate storage within the sedimentation pathway is limited to slopes covered by calcretes, foot slope positions, slope flattenings, tributary valley bottoms, the upper parts of the alluvial fans and most of the upper part of the main vega itself. Thus, from a total volume of about 34 million m^3 of sediment deposited in the vega system since damming 1.0 Ma ago a volume of 19.5 million m^3 was deposited in the vega bottom, whereas 14.5 million m^3 were deposited in storage positions of the catchment areas (see Table 1). This means that only 42.6% of the material deposited in the catchment area is temporarily stored, whereas about 57.4% has definitely accumulated at the vega bottom. Since only 18.4% of the total material could have been deposited in the area of the vega bottom itself as in situ aeolian fallout, there must have been a significant contribution of colluvial material from the slopes in order to get the recent proportion of 57.4% of total sediment stored in the valley btoom. This yields a sediment delivery ratio from the remaining catchment area (without the valley bottom itself) into the valley bottom of around 48%, indicating that almost half of the sediment originally deposited on the slopes was reworked and is found in the vega bottom today, here forming 68.6% of the total vega bottom sediments. This demonstrates a high slope–vega connectivity.

In Teguise, sediment storage on the slopes is negligible apart from calcretes inherited from older soil forming processes. Thus, the sediment path leads more directly into the valley bottom than in Femés. As a consequence of the close slope–bottom connection, it is estimated that about 75% of the mobilized sediment from the catchment was deposited in the valley bottom.

Guatiza has a relatively large and branched catchment area with comparatively large flat areas. On the other hand, it shows steep topography (450 m difference in altitude). It is assumed that slightly less than 50% of all mobilized sediments reach the vega bottom so that the coupling between erosional and depositional area is the least in this vega.

These results demonstrate that due to very steep vega morphologies a system of sediment cascades as observed in larger catchment areas generally plays a minor role in valley bottom sediment supply (e.g. Faust and Herkommer (1995) calculated a delivery ratio of only 8% in a catchment of Lower Andalusia). Due to the generally high slope–vega bottom connectivity the amount of sediment never exceeded the potential sediment transport capacity, so that calculations of the dependencies between geomorphologic features of the vegas and sedimentation in the vega bottoms are possible. Hence, the sedimentation rate in the vega bottom sediments directly increases with increasing catchment area when compared to the size of the vega bottom. This means that time resolution in the vegas is directly linked to the ratio catchment area/vega bottom surface. As an example, the much smaller ratio catchment area–vega bottom in Teguise compared to Femés means that the sedimentation rate in the vega bottom should be much smaller in Teguise. Hence, a sediment package in the same depth with a comparable thickness is much older and should have a lower time resolution in Teguise when compared to Femés.

5.1.2. Types of vega sediments and colluvial transport

The material filling the valleys consists of two different components:

- Saharan dust either brought by Calima winds or by the Saharan Air Layer (SAL)
- Volcanic material originating from local sources in form of ashes, lapilli and bombs

This material was originally deposited on the slopes and in the valley bottom. However, the valley bottom additionally received colluvial sediments (soils, volcanic material and Saharan dust) reworked from the slopes, in the case of Femés almost 70% of total deposited sediment as shown in the calculations above. The importance of colluvial input during the studied periods is documented by several thin sections taken from different horizontally stratified sedimentary layers in the Vegas, since all show comparable colluvial characteristics (Fig. 7). After deposition in the vega bottoms, sediments underwent postsedimentary overprinting (swelling and shrinking, secondary carbonate and iron–manganese precipitation, formation of soil aggregates, bioturbation). Hence, neither quantification of colluvial material in an individual layer nor discrimination between in situ and colluvial sediment layers is possible in the vega bottom sediments today.

Looking at horizontally stratified layers across the valley bottoms reveals that a general sorting from proximal to distal positions—relative to the surrounding slopes—took place during the erosional process. Thus the layer material is generally coarse near the slope but rapidly becomes finer (clayey-silty) towards the vega centre, independent of the magnitude of the erosional event. Thus, discrimination between material deposited in situ as aeolian and reworked material derived from colluvial input processes of different intensity is not possible in a more distal position from the slopes. This is demonstrated by the example from Femés shown in Fig. 8, where the depth plot of the fine sand content (63–125 µm) is similar to that of the total quartz content. Since quartz has an exclusively eolian origin, variations of fine sand must be mainly controlled by Saharan dust whereas the erosional dynamics is not reflected here. Occasionally, this dust signal is overprinted by volcanic fallout, as can be seen between 220 and 400 cm (with strongest influence between 280 and 315 cm) where lapilli and volcanic ash caused two peaks in the fine sand depth plot (63–125 µm) which are paralleled by peaks in the coarse sand fraction (250–2000 µm) (Fig. 8). This demonstrates that grain sizes in the distal vega bottom sediments only display the variability of arid and humid periods (variations of clay and silt) and the dynamics of eolian dust input (fine sand), whereas the erosional dynamics is not impacting here.

When looking at the vega bottom sediments proximal to the slopes in order to reveal the erosional dynamics, it is conspicuous that in silty layers probably deposited during drier periods coarse volcanic material with a diameter of up to 10 cm is found. This material was probably eroded from the slopes since it thins towards the vega bottom as described above. In contrast, in clayey horizons probably originating from more humid periods the content of coarse, pebbly material is systematically negligible. This could indicate that erosional processes during drier periods were more intensive than those during more humid ones.

However, this differentiation could at least partly be caused by the upward transport of pebbles to the palaeosurface in clayey, swellable material similar to processes occurring in Bt horizons of desert pavements. Once the sedimentation of clayey material stopped, the stones were stuck in the silty, not-swellable material where this process could not be active, thus generating the observed distribution of stone-rich layers (e.g. Springer, 1958; Dan et al., 1982). Desert pavements, possessing a largely stone-free Bt-horizon underneath of the surface stone layer, cover large parts of Lanzarote today and thus prove the existence of such processes under local conditions.

5.1.3. Case studies for sediment accumulation

In order to better understand the sedimentation process of in situ aeolian and colluvial material into the vega bottom, different scenarios were constructed. The vega of Femés, due to its complete damming from the beginning, offers the best model conditions. It seems that comparable erosion and sedimentation processes took place in all other dammed vegas of Lanzarote. The scenarios assume that dust and ash fallout happened all over the catchment area at similar ratios. Subsequently, soils and/or fresh material were eroded and transported into the vega bottom. All scenarios are based on the ratio total catchment area/valley bottom of 5.4:1. That means, taking into account the ratio of 48% of eroded sediment reaching the valley bottom, that 32% of the sediment in the vega bottom was deposited here as in situ fallout. The remaining 68% of the material were eroded from the catchment area, yielding a ratio in situ/reworked sediment of 1:2.2. In situ and colluvial sediments cannot be distinguished in singular thin layers due to postsedimentary processes. Based on luminescence dates (Suchodoletz et al., 2008), the average sedimentation rate in the valley bottom of Femés between about 180 and 2.5 ka is ca. 3.2 cm/ka. Supposing a period of 10 ka, the whole sediment package would thus have a thickness of 32 cm of which 10 cm are in situ material and 22 cm are transported and deposited above. For this 10 ka- period, three different cases are proposed.

5.1.3.1. Scenario I. During a period of dry climate, material deriving from Saharan dust and to a minor degree from volcanic ash is deposited in the vega bottom and on the slopes. During this time no soil forming processes took place. As a consequence of erosion, the vega bottom will be covered with unweathered in situ material (Av) and unweathered transported material (As) in a ratio of 1:2.2. The profile would exclusively contain sediments indicating arid conditions (Fig. 9a).

In this scenario, the frequency of erosion is supposed to be very high, as slopes in such an arid environment (recent precipitation in the vega catchment areas ca. 150–250 mm) are unstable over the whole period as shown in Fig. 10. This results in closely interbedded strata of in situ and colluvial unweathered material.

5.1.3.2. Scenario II. During a wetter climatic period, aeolian material is deposited in the vega bottom as well as on slopes. Soil formation happened synsedimentarily in the vega bottom and on slopes. After erosion, the sediment package in the vega bottom consists of in situ soil material (Bv) below redeposited soil sediment deriving from the slopes (Bs) in the ratio of 1:2.2. Both kinds of sediment indicate a wetter climate, but due to peloturbation they cannot be distinguished (Fig. 9b).

In contrast to scenario I, slopes would be vegetated and consequently more stable so that the frequency of erosion events should be reduced. Nevertheless, elevated precipitation compared to today also falls in a range of low geomorphic stability (Fig. 10). Furthermore, palaeoenvironmental research indicates that stable conditions in the northwest African area over a time span of more than 10 ka would not be expected. Thus, a strong influence of climatic cycles like Heinrich-events and D-O cycles occurring with a high frequency of some ka on this region is reported from several studies (Cacho et al., 1999; Moreno et al., 2002, Moreno and Canals 2004), which play an important role in this geomorphic environment instable even during generally wetter periods. Furthermore, high electric conductivity of the sediments (e.g. in Femés up to 571 and in Teguise to 2400 µS/cm) caused by the adjacency of the vegas to the sea permitted a dispersion of clayey material during the slightest runoff and thus soil sediments are easily mobilized. Consequently, although the frequency of erosion should be lower than in scenario I, steady state conditions over a time span of 10 ka are not assumed.

5.1.3.3. Scenario III. This case assumes that climate changes from dry to wet or vice versa occurred during a 10 ka lasting period. These cases are regarded in scenarios III–I and III–II.

> (I) Assuming that climate will change from dry to wetter conditions, soils will be formed synchronously in the vega bottom and on the slopes during the wetter period. When erosion occurs, interbedded strata in the vega bottom form, consisting of unweathered in situ and colluvial material (Av and As) below in situ soil (Bv) covered by eroded soil sediment (Bs). As mentioned above, the in situ soil will mix with the overlying soil sediment. As a result, unweathered material (Av,s) will be covered by soil material (Bv,s) in a ratio depending on the duration of each period (Fig. 9c).
>
> (II) When climate changes from wetter to drier conditions, first soils will develop synsedimentarily in the deposited sediments in the vega bottom as well as on the slopes, whereas the latter is regularly eroded into the vega bottom. After climate changed, aeolian sediment will be deposited everywhere and not be overprinted by pedogenesis, and slope material will immediately be transported into the valley bottom. As a result, the vega bottom will have a layer consisting of in situ and colluvial soil (Bv,s) mixed by peloturbation below interbedded unweathered in situ and colluvial material (Av,s). As in scenario III-I, the ratio between soil (Bv,s) and unweathered material (Av,s) depends on the duration of each period (Fig. 9d).

5.2. Palaeoenvironmental interpretation

Knowledge about sedimentation processes and sediment budget of the vegas is useful when addressing different items of palaeoenvironmental research on Lanzarote.

5.2.1. Limitations of the resolution of palaeoclimatic events in vega sediments

Understanding the interaction between in situ and colluvial sedimentation is crucial for correct palaeoclimatic interpretation, and even more important when considering the time resolution of palaeoclimatic events. The chronology of the vega sediments was established using optical and infrared stimulated luminescence, where partial insufficient bleaching during colluvial transport caused inaccurate zero setting of the luminescence signal. In consequence, dating errors are up to 10%, so that an age of 100 ka yields an error of about 10 ka (Suchodoletz et al., 2008). Although these luminescence ages are supported by correlations between similar proxies from the vegas and nearby marine cores as well as a stratigraphic correlation between different profiles (Suchodoletz et al., 2008), a climatic interpretation of sediments could only have a coarse temporal resolution. For younger sediments, due to smaller numerical dating errors of luminescence ages, climatic interpretability becomes naturally better. However, this improvement of time resolution for younger sediments has an intrinsic limit caused by the colluvial sedimentation process including time lags between sedimentation and colluvial transport as shown above. Therefore, resolution in scenario III including climatic shifts shorter than 10 ka (e.g. D-O cycles, Heinrich-events) is almost

impossible. Consequently, due to regular colluvial input climatic proxies are expected to average the palaeoclimatic information of a level of some ka. Thus, only palaeoclimatic events that encompass at least this time span offer good possibilities for identification and interpretation.
Youngest sediments overlying an Early/Middle Holocene dust layer which were deposited since at least 2.5 ka are characterized by an extreme rate of material delivery into the valley bottom of Femes. In the central basin of the vega these sediments have a thickness of up to 75 cm as shown in Fig. 11, and reach up to 420 cm in the vega of Guatiza. Geoarchaeological studies (e.g. Atoche-Peña et al., 1995) report an intensified Roman colonization with strong pasturing of the slopes from ca. 2 ka BP. The intensive pasturing triggered accelerated erosion including a mobilization of material from sediment storages (filled during longer periods of the past) due to the high vulnerability of the instable semiarid ecosystem to anthropogenic activity. Since the anthropogenic sediment transport mechanism is completely different from that of the period before, this recently deposited material is not useful for palaeoclimatic interpretations based on the actualistic principle.

5.2.2. Dynamics of Saharan dust input during the Quaternary

The export of Saharan dust to the North Atlantic has been a study issue for a long time. Thus, it is established that dust export from North Africa has existed since the Lower Cretaceous (Goudie and Middleton, 2001). During the Neogene, dust export increased in parallel with the desiccation of the African continent, showing prominent steps at 6–5, 2.5 Ma and between 1.6 and 1.2 Ma (Pflaumann et al., 1998; Goudie and Middleton, 2001). However, a quantitative estimation for the development of dust input to the region of the Canary Islands during the Quaternary does still not exist. This problem is addressed using the sediment mass-balance of the vega of Femés.
The recent period is obviously one of the driest during the last 180 ka at Lanzarote (unpublished results). Furthermore, the landscape shows a high degree of anthropogenic destabilization. Nevertheless, vega bottoms still have a vegetation cover, and a geoarchaeologic study reports much moister conditions with a denser vegetation prior to Spanish influence starting from the 15th century (Santana-Santana, 2003). Thus, remobilization of dust from the vega bottoms did probably not play an important role during most of the Quaternary, so that calculated dust deposition rates should correspond to real values. Assuming a continuous input for the whole period of 1.0 Ma, a total volume of 34 000 m^3 was in average deposited during 1 ka (cf. Chapter 5.1.1.). Converted to thickness (total catchment area 5.07 km^2) this yields an approximate material deposition of 0.67 cm/ka over the whole catchment area. If this value was exceeded, the valley would have been filled up by now which is not the case. The deposited material is composed of Saharan dust and volcanic material. Thus, the average yearly deposition rate of 0.67 cm/ka for the whole catchment is the theoretically maximal value of dust deposition during the last 1.0 Ma. Comparing the average material deposition of 0.67 cm/ka in the vega catchment area during the whole period of the 1.0 Ma to a value of 1.0 cm/ka for the last 180 ka (derived from the sedimentation rate of 3.2 cm/ka in the valley bottom as described in Chapter 5.1.3), the former is much lower than the value for the last 180 ka, indicating an increase of dust sedimentation during the Early or Middle Pleistocene.
A persistent layer deposited during the Early/Middle Holocene shown in Fig. 11 has a thickness of about 20 cm in Femés and was deposited within at most 6 ka in the studied vegas (from about 8.5 to latest 2.5 ka, Suchodoletz et al., 2008). This yields an average in situ accumulation rate in the whole vega catchment area of 1.1 cm/ka. This accumulation rate in the vega bottom is much higher than the average accumulation rate of 0.67 cm/ka calculated for the last 1.0 Ma and slightly higher than the average rate of ca. 1.0 cm/ka during the last 180 ka.

New dating has shifted the eruption period of the Corona-volcano system (the last volcanic event prior to the 18th century) from formerly ca. 4–6 to 21 ka (Carracedo et al., 2003). Thus, there was no strong contribution of volcanic material during the Early and Middle Holocene, meaning that the value of 1.1 cm/ka must be close to the real sedimentation rate of Saharan dust during the Early/Middle Holocene. Furthermore, luminescence dates from Femés do not exclude the possibility that the sedimentation of this layer ended already ca. 5 ka, thereby limiting the period of its formation to ca. 3.5 ka and thus yielding a maximum possible accumulation rate of 1.8 cm/ka. Hence, Saharan dust sedimentation during the Early/Middle Holocene was probably somewhat elevated compared to the average of the period from 180 ka to the Holocene. This is in contrast to a study which reports a strongly reduced export of Saharan dust during the Early/Middle Holocene from 12 to 5.5 ka due to moist conditions in the Sahel area (de Menocal et al., 2000). Thus, a high dust input on the Canary Islands could also be forced by other factors than aridity, including a change of the origin of dust or human activity connected to destablization in the dust mobilization area.
These results were compared with studies on recent Saharan dust accumulation on the Canary Islands: One study points to an actual dust accumulation rate between 1.3 and 6.6 cm/ka depending on the altitude, an average value between 4 and 2 cm/ka seems representative for the altitude of the catchment area of Femés (Menéndez et al., 2007). A pedologic study points to an accumulation rate of about 1.5 cm/ka during the last 260 a (Herrmann et al., 1996). On the other hand, model estimates indicate a recent dust fall of only 0.46 cm/ka for the geographic position of the Canary Islands (Prospero, 1996), which seems to be an underestimate. Altogether, most results confirm that dust input on the Canary Islands intensified at the latest during the Early and Middle Holocene and obviously maintained this elevated level until the recent. Hence, the Holocene is a climate period with an exceptional high dust mobilization and a comparatively high morphodynamic activity compared to former periods. Summing up, the calculations show that the dust input to the Canary Islands increased during the last 1.0 Ma, whereas the highest values were reached at the latest during the Early/Middle Holocene lasting (and probably accelerating) until today.

6. Conclusion

Geomorphologic calculations supported by sedimentologic analyses and luminescence dating established a quantitative sediment-mass budget of volcanic sediment traps on Lanzarote. These investigations demonstrate that despite the colluvial transport system of the sediment traps on Lanzarote they can serve as palaeoclimate archives, although time resolution is limited to some ka. The youngest sediments deposited since at least 2.5 ka are climatically not interpretable, as they were mobilized by human activity rather than by climatic processes. These results will serve as a base for following palaeoclimatic analyses of the trapped sediments. Furthermore, the quantitative sediment budget together with luminescence dating allows an estimation of Saharan dust input to the Canary Islands, demonstrating that this strongly intensified during a large part of the Quaternary, cumulating since the Early/Middle Holocene.

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Tables

Table 1. Sediment volumes stored in different areas (in m^3) in Femés.

Vega bottom (V_{vega})		**Remaining catchment area ($V_{catchment}$)**	
V_2	1 185 890	V_1	696 120
V_3	7 843 660	V_6	6 151 370
V_4	6 819 200	V_7	2 218 780
V_5	3 637 560	V_8	502 740
		V_9	258 390
		V_{10}	511 960
		alluvial fans (V_{af})	1 602 180
		Slopes (V_s)	2 509 120
Sum	**19 486 310**		**14 450 660**
% of total volume	**57.4**		**42.6**

Figures

Figure 1. Horizontally stratified layers in the bottom of the vega of Teguise. Darker layers indicate layers derived from palaeosol material, lighter layers consist of slightly weathered loess-like sediments.

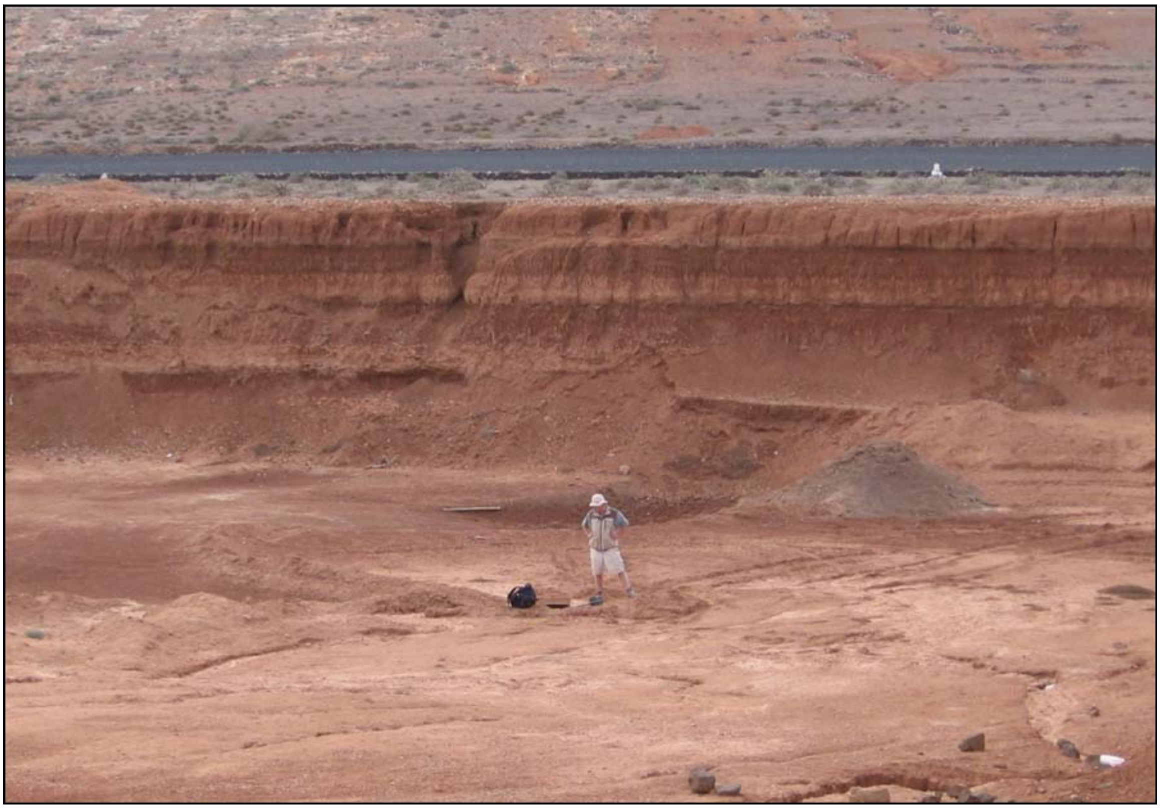

Figure 2. Eroded slope with calcrete in the vega of Femés.

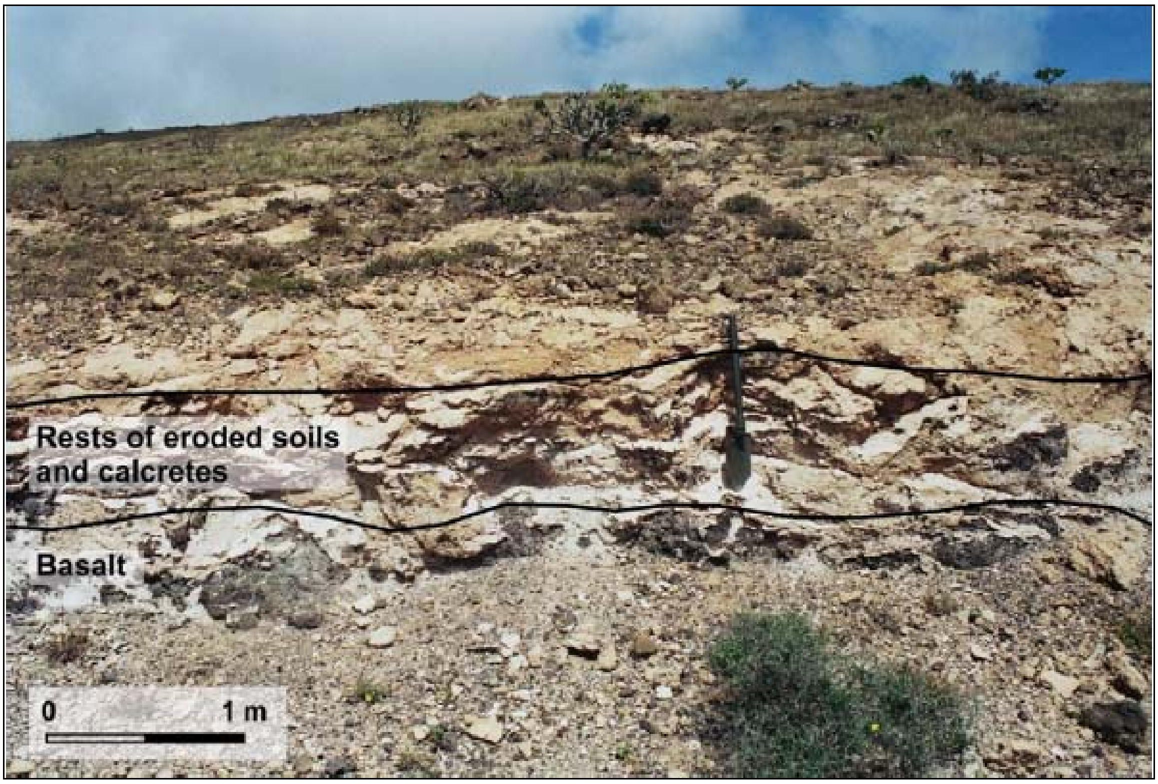

Figure 3. Geographic position of the Canary Islands (inset) and investigated sediment traps on Lanzarote (stars). On the right and lower margins elevation models of the sediment traps with locations of the investigated profiles (stars). Hatched areas indicate the valley bottoms and the dashed lines the catchment areas.

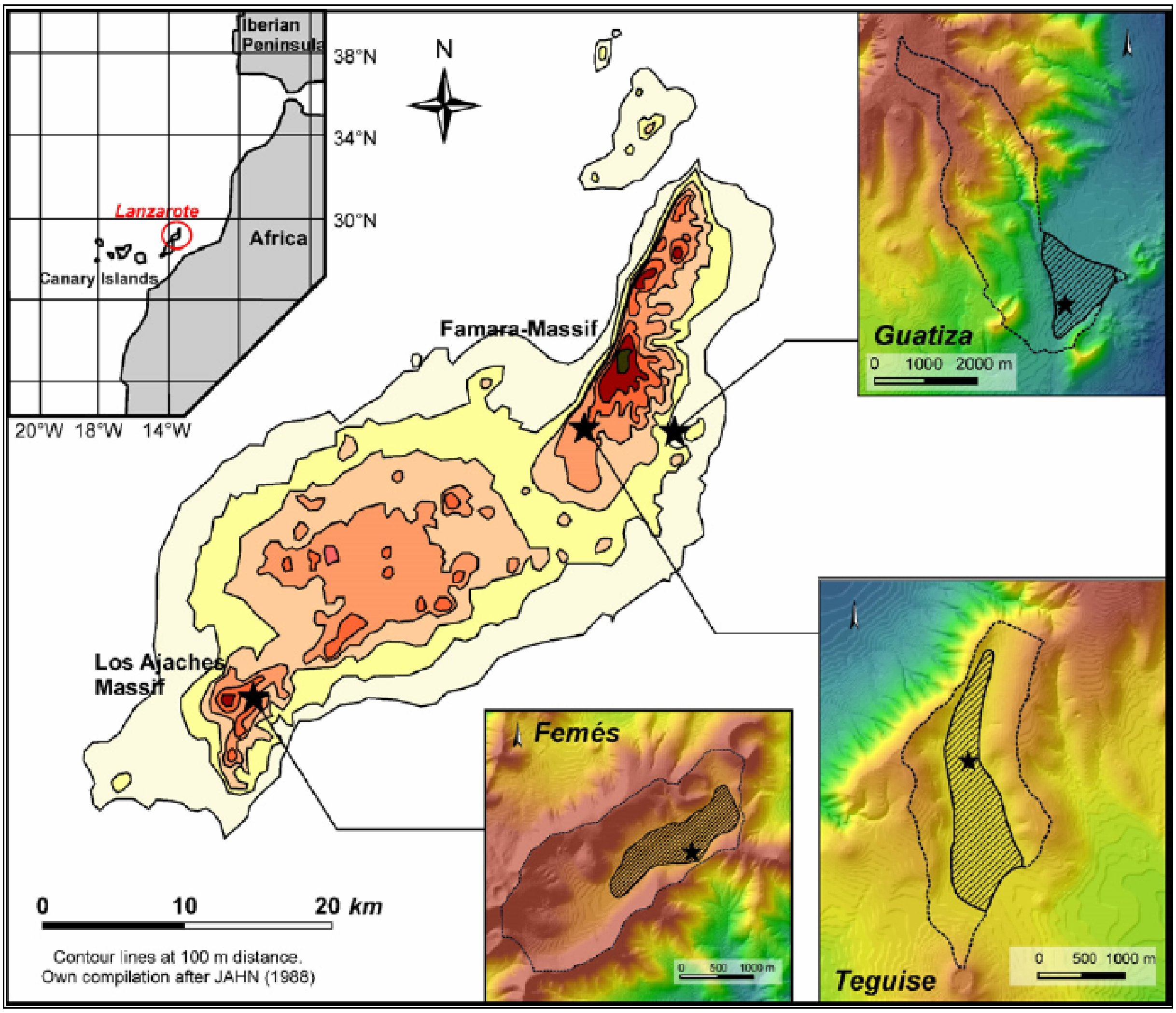

Figure 4. Vega transects, surface of sediment bodies and alluvial fans used for the calculation of stored sediment in Femés.

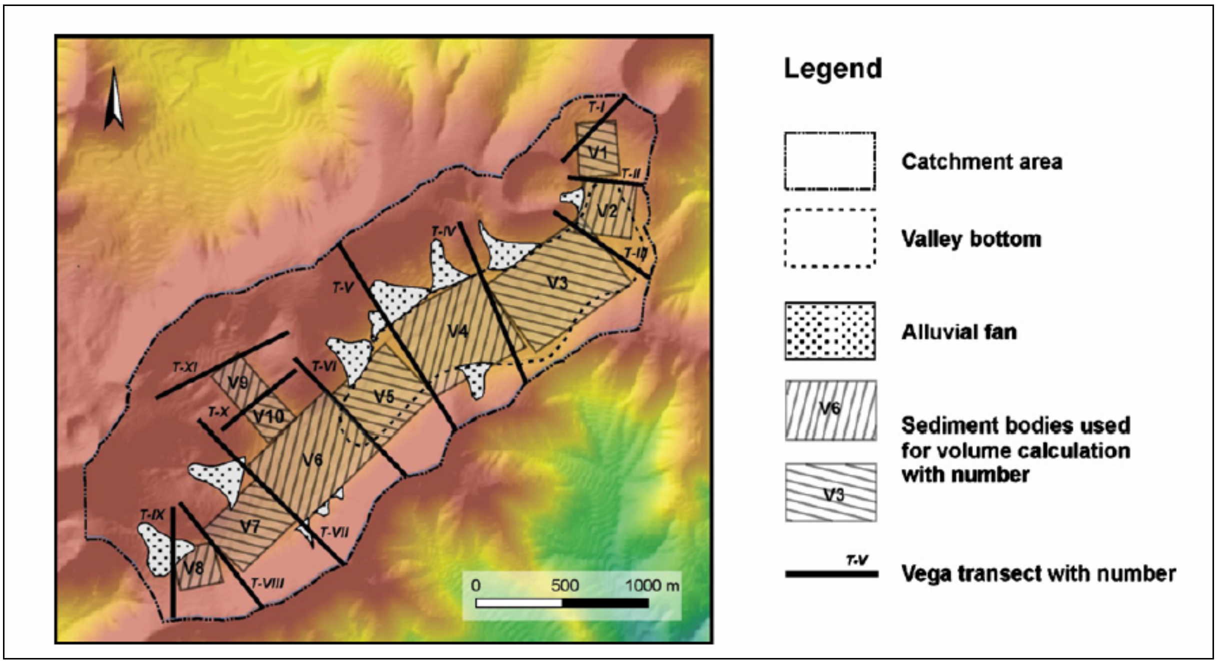

Figure 5. Vega transects in Femés (left side: N/W-slope, right side: S/E-slope). Dashed lines show extrapolated slopes.

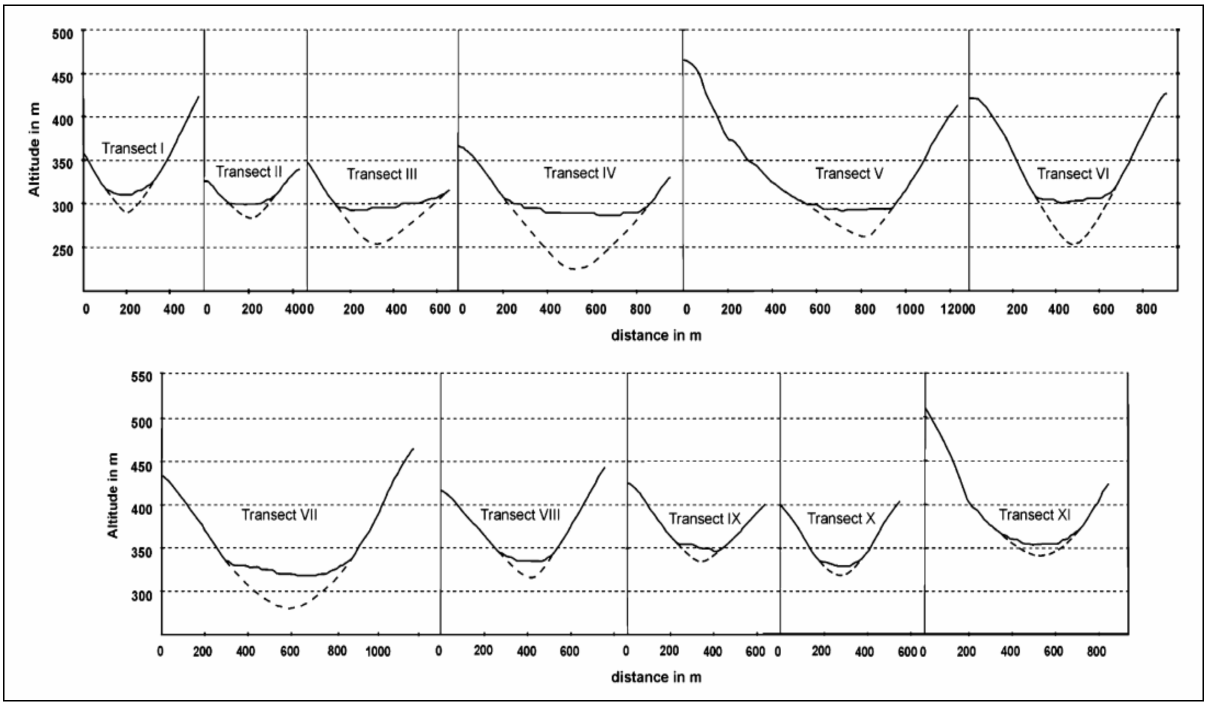

Figure 6. Model of a horizontal cut through a sediment body along a vega transect.

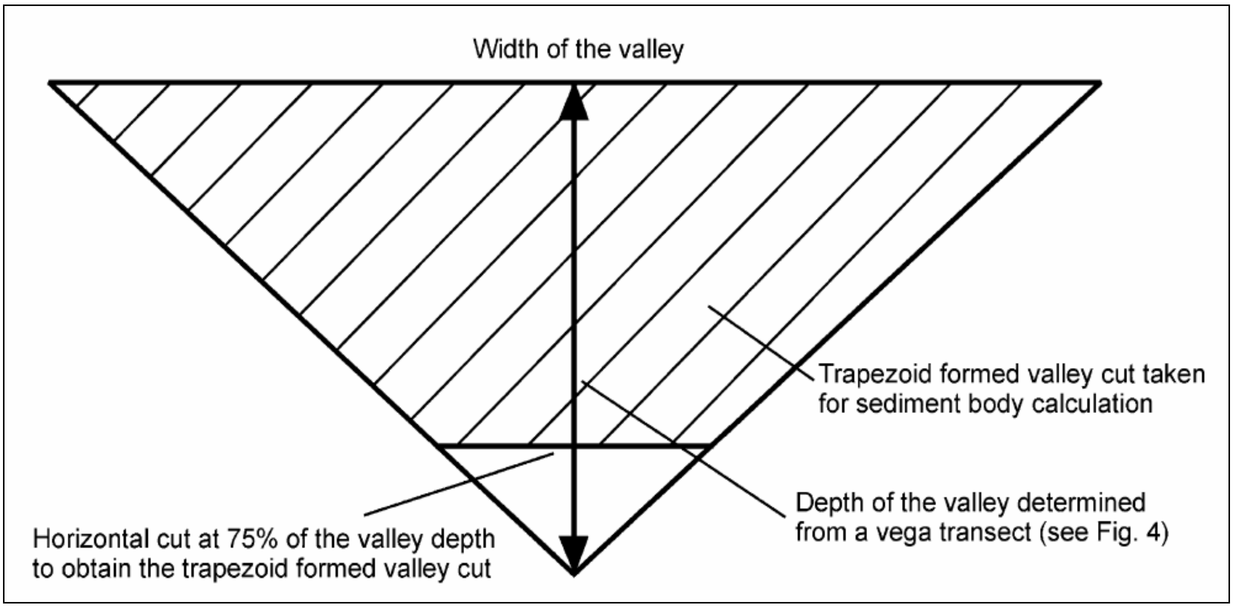

Figure 7. Thin section of a carbonatic horizon from Femés showing a large ped fragment (arrow) within the fine silty matrix. Analysis by Peter Kühn.

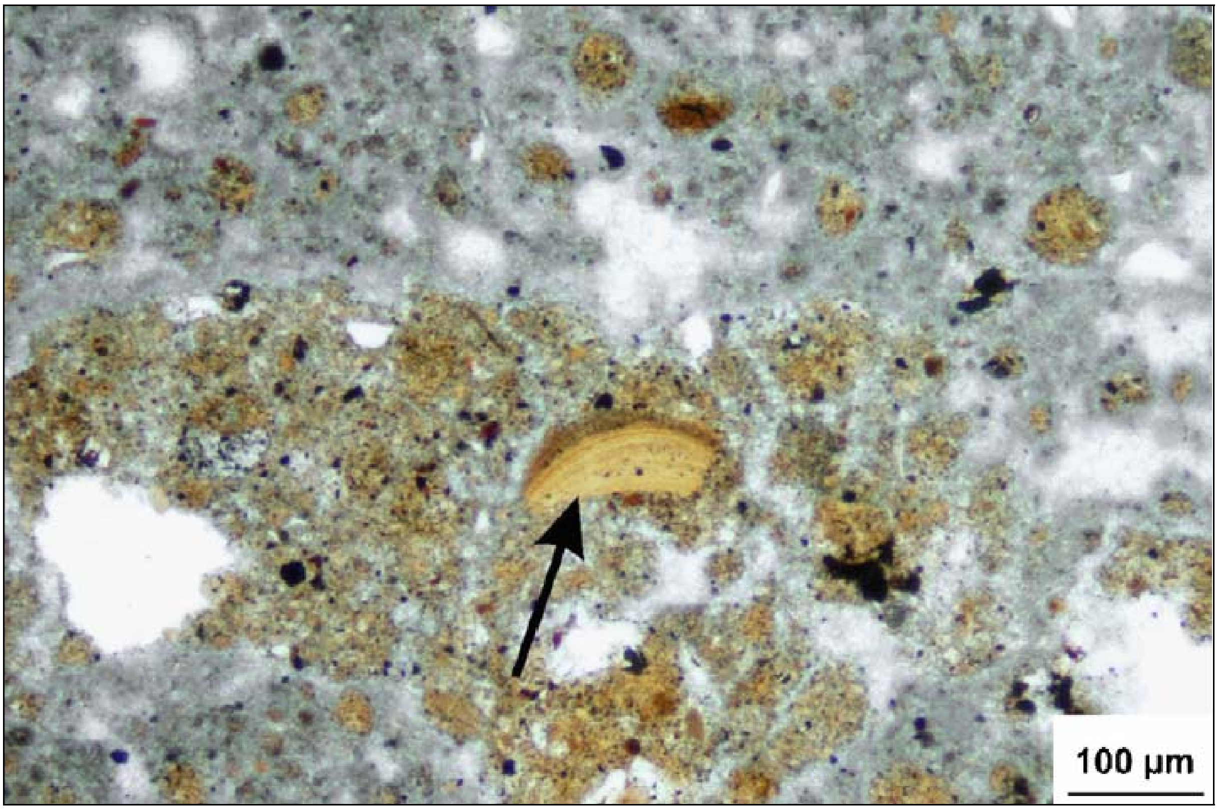

Figure 8. Quartz contents and grain size fractions from a profile in the center of the vega of Femés (in %). Error bars (2σ) are given in the lower right parts of the graphs. Increasing influence of coarse volcanic fallout on the fine sand fraction is indicated with arrows.

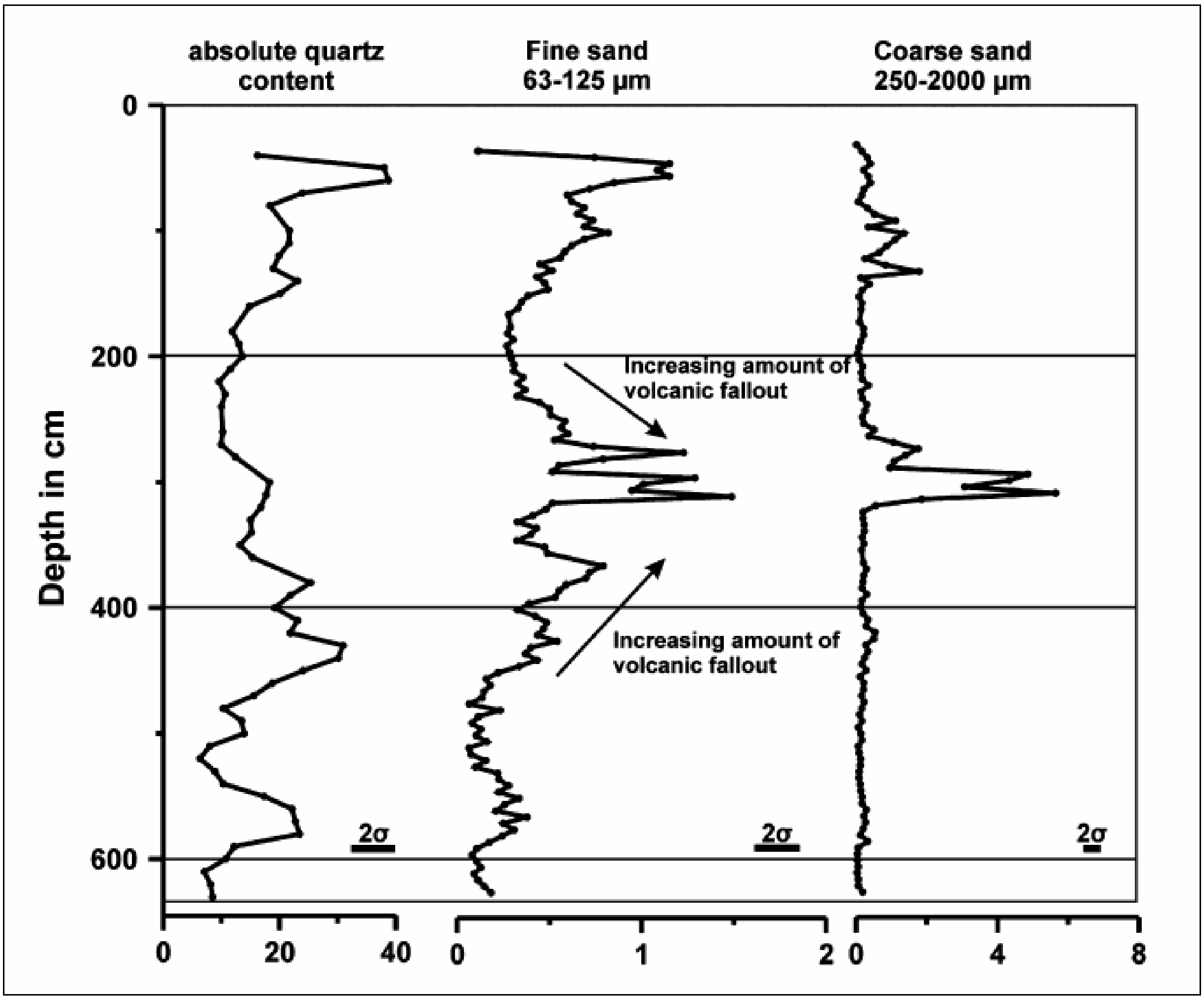

Figure 9. Sedimentation scenarios from Femés assuming a time span of 10 ka and a constant sedimentation rate of 3.5 cm/ka.

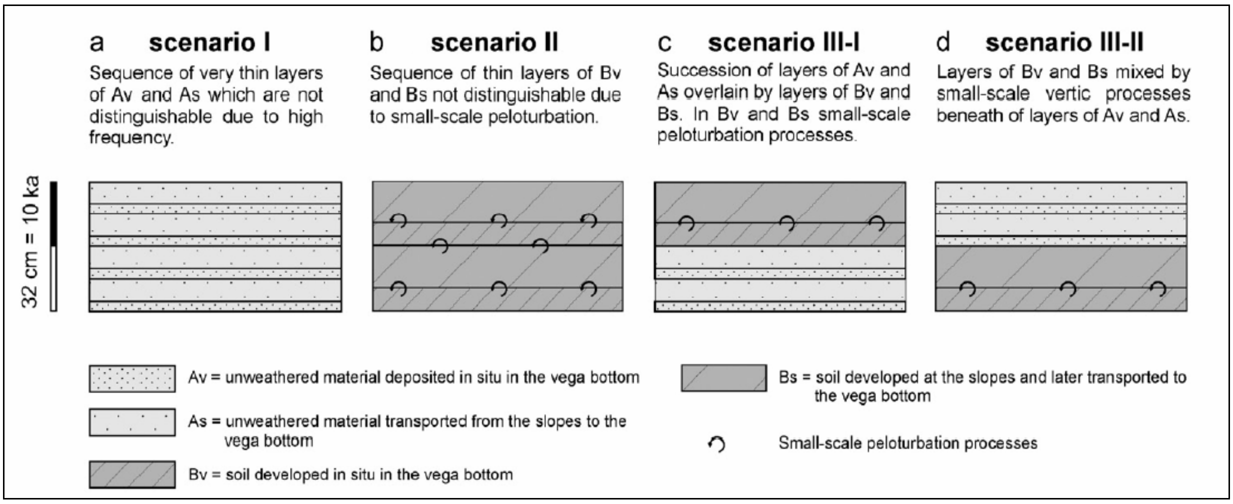

Figure 10. Sediment yield correlated with annual average precipitation and sedimentation scenarios (dashed rectangles). I = recent average precipitation in the vega catchment areas, II = eventual precipitation range during moister palaeoclimatic periods. After Langbein and Schumm (1958), modified.

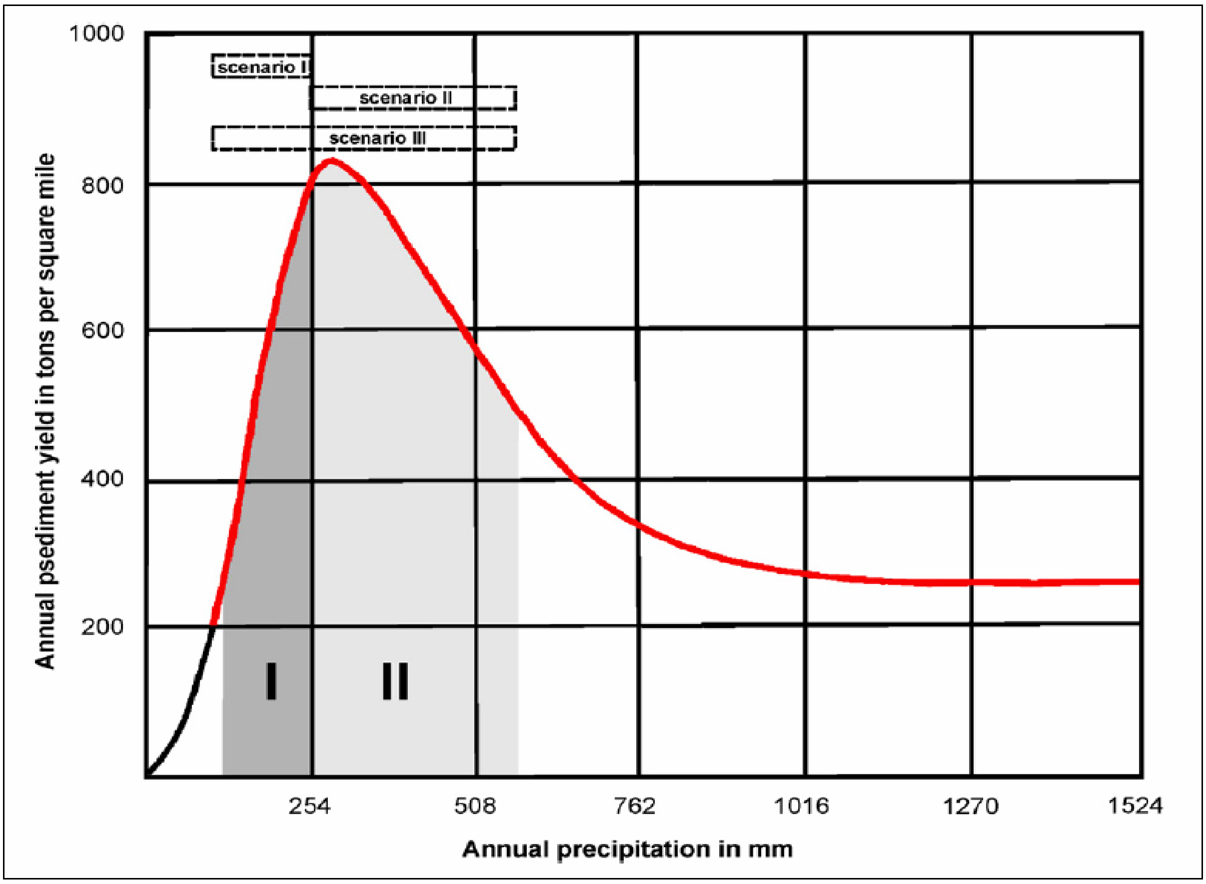

Figure 11. Middle Holocene Layer deposited 8 to 2.5 (or 5) ka (A) beneath a Young Holocene colluvium consisting of two layers (B_I and B_{II}).