
Oblique rainfall and contemporary geomorphological dynamics (Serra da Estrela, Portugal)

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Abstract:

Coarse sand accumulations are polygenic microforms that attain a width of several metres, a height up to 30–40 cm, a gradient of 8–12° and a slope length up to 1 m. These accumulations are frequent in the grass-covered plateaus of the granite mountains of central and northern Portugal, but they have been described in other mountain areas (i.e. Cairngorms, Scotland). Though these microforms are frequent features, studies on them are rare. They have been attributed to complex genesis controlled primarily by aeolian processes, but also by wash and cryogenic dynamics. Results presented here add new insights into the origin of the sand accumulations and emphasize the importance of rainsplash-saltation induced by oblique rainfall as the main transportation mechanism. The study was conducted in the Serra da Estrela, a granite mountain in central Portugal (1993 m above sea level) and is supported by a detailed mapping of the orientation of the accumulations, monitoring of the surface material and analysis of meteorological data. The results are particularly significant since they indicate that the coarse sand accumulations are very active features that show a clear climatic and ecological signal. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS coarse sand accumulations; rainsplash-saltation; Mediterranean mountains

INTRODUCTION

Coarse sand accumulations are polygenic microforms that attain a width of several metres, a height up to 30–40 cm, a gradient of 8–12° and a slope length up to about 1 m. Vieira (1999) identified three main types of feature in the mountains of northern and central Portugal: (1) incipient coarse sand accumulations; (2) climbing tongues; and (3) climbing tongues with blow-out (Figure 1). All these types can be included in the wider definition of sand ripples suggested by King (1971) for the encroachments of feldspathic sand from denuded surfaces onto the surrounding vegetation described in the Cairngorms, Scotland. In Portugal, the encroachments were also found on rock outcrops, and a fourth type (closer to the ripple definition) constituted by parallel sets of microdunes has recently been identified (Figure 1). We prefer the term coarse sand accumulations, because their genesis is controlled by a larger set of geomorphological processes than the purely hydraulic and aeolian sand ripples.

Coarse sand accumulations are frequent features in the bare summit surfaces of the granitic mountains in central and northern Portugal (Vieira, 1999) also observed these in the Catalan Pyrenees, Japanese Alps and on Livingston Island (South Shetlands, Antarctic). Ballantyne and Harris (1994) mention that these accumulations appear in the Highlands of Scotland. Although these deposits are apparently widespread worldwide, references to them in the literature are sparse.

Vieira (1999) studied the sedimentology of coarse sand accumulations from two Portuguese mountain ranges approximately 150 km apart and showed that in both areas the accumulations were very similar. A coarse surface layer (polygenic lag-surface) about 1 cm thick covers the finer subsurface material. The grain-size

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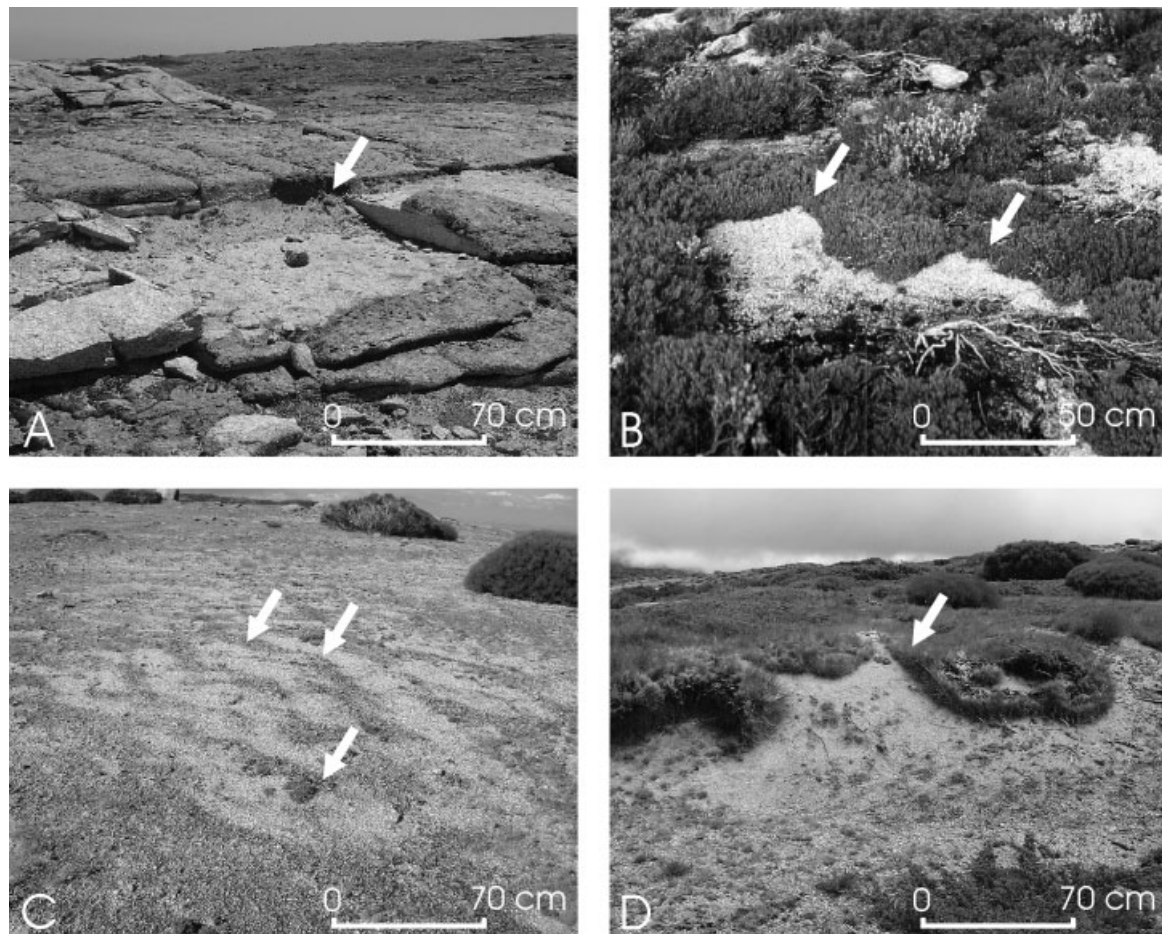


Figure 1. Types of coarse sand accumulation found in Serra da Estrela. (A) Incipient accumulation deposited against a rock outcrop; (B) climbing tongues deposited against *Calluna vulgaris*; (C) sets of microdunes in a flat surface; (D) coarse sand accumulation with blow-out. Note the higher slope angle when compared with the other types of accumulation

distribution of the surface layer is unimodal, with a diameter mode of 2.8 or 4.0 mm and graphic means (Folk and Ward, 1957; Friedman and Sanders, 1978) between 2.2 and 3.5 mm. The samples are generally moderately sorted. The subsurface layer is diverse, with different polymodal curves, poor sorting measures and graphic means between 0.5 and 1.8 mm (Figure 2). A very interesting observation was the constant orientation of the accumulations (south-southwest to west) within each mountain. Vieira (1999) proposed a polygenic evolution for the coarse sand accumulations that included an initial stage of growth of the main body of the accumulation controlled by aeolian transport and a second stage of development of the lag-surface, with deflation and wash that contributed to the coarse character and enrichment of fines of the subsurface material. The accumulation would then be formed and evolve with further episodes of aeolian deposition, deflation and wash. Cryogenic mechanisms were also mentioned as formative processes involved in the surface sorting.

However, the coarse grain size of the surface material of the sand accumulations is a problem when considering the aeolian genesis. The wind-exposed sites where the accumulations were found could justify such a coarse character; recently, however, coarse sand accumulations were found in sheltered areas between scrub vegetation. Could wind alone cause significant grain movement in these conditions? This was the main evidence to support the hypothesis that oblique rainfall and rainsplash-saltation were primary formation

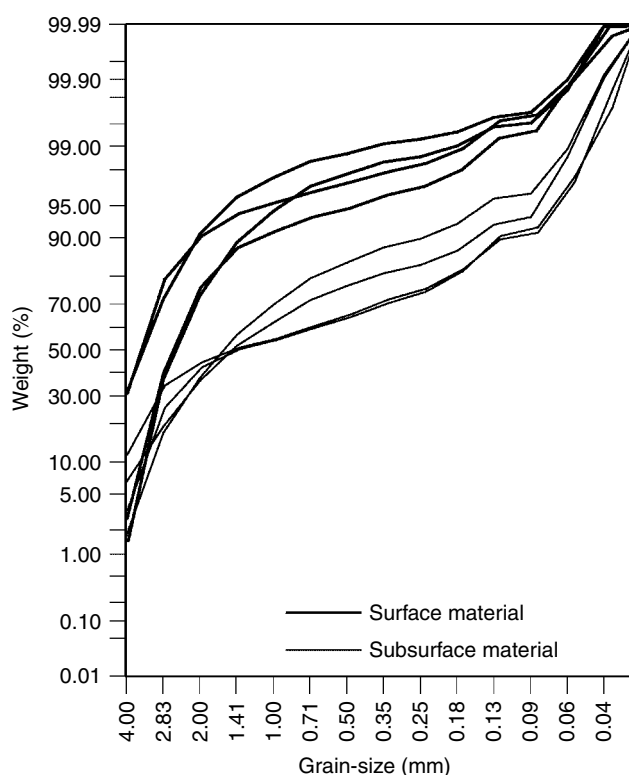


Figure 2. Typical grain-size curves of coarse sand accumulations of Serra da Estrela

processes. Subsequent visits to the Serra da Estrela after heavy rainfall events further supported this hypothesis, since the accumulations showed fresh signs of activity. Contrary to what had been observed during dry periods, the lag-surfaces below the accumulations were free of coarse sediments. These had been transported to the accumulations.

In this paper, the influence of oblique rainfall on the genesis of the coarse sand accumulations is studied. A map with their setting and orientation in the Serra da Estrela plateaux was prepared with the aim of characterizing the spatial distribution of the sand accumulations. In order to evaluate the surficial movement of the particles in the accumulations and to assess the processes involved, several of these features were monitored mainly by means of painted lines. Wind and rainfall data from a meteorological station located in the study area were used for comparison with the monitoring results from some sites, and also to evaluate directions of potential movement induced by oblique rainfall, as well as their relationship with the orientation of the accumulations.

THE STUDY AREA

The Serra da Estrela ($40^{\circ}20'N$, $7^{\circ}35'W$) is the highest mountain in Portugal and reaches 1993 m above sea level (ASL) in the Torre plateau (Figure 3). The central massif where this study focuses is granitic and the peripheral areas are metamorphic. The mountain is comprised of plateaux forming steps between 1400 m ASL and the summit. Most of the high plateau area was glaciated during the last glacial maximum (LGM; Lautensach, 1929, 1932; Daveau, 1971; Daveau *et al.*, 1997; Vieira *et al.*, 2001) and is dominated by glacial erosion forms. Bare-rock outcrops and moraines dominate the glaciated area; outside, typical tor and

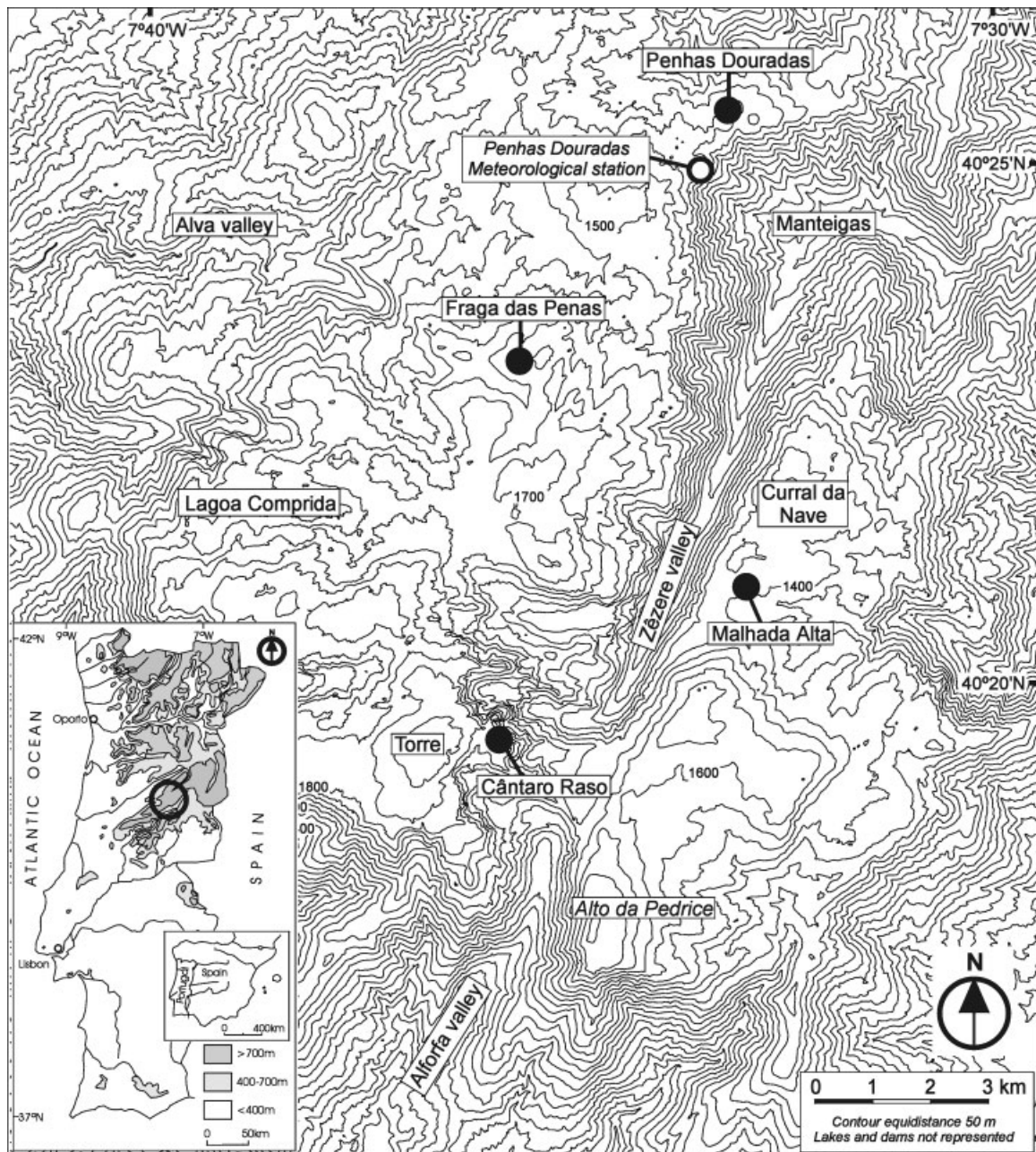


Figure 3. Location of the Serra da Estrela range and of the study sites

bornhardt morphology with regolith prevails. Post-glacial weathering on the granite outcrops produces grass that is easily mobilized by the present-day dynamics. It is within these mobile coarse sands and gravel that the accumulations form.

The climate is Mediterranean, with dry and warm summers and a wet season from October to May. Mean annual precipitation is about 2500 mm in the higher parts of the mountain (Daveau *et al.*, 1977). In most

of the plateau area, mean annual air temperatures are below 7°C and in the Torre area they are about 4°C (Vieira and Mora, 1998). Available data on snow is of very poor quality and cannot be analysed quantitatively. Andrade *et al.* (1992) indicate a median of 40 to 50 days with snowfall at 1400–1600 m ASL. A significant interannual variability occurs, and snow cover rarely lasts more than a few consecutive weeks per year below 1700–1800 m ASL. Wind regimes in the Serra da Estrela are complex with large spatial variations. Maximum wind speeds occur mainly from November to March (average 27 km h⁻¹). The stronger winds are from northwest to southwest and the annual wind frequency is composite, bimodal, or even polymodal, depending on the site (Vieira and Mora, 1998). In general, the more frequent wind directions are west and northwest.

The research focused in the areas of Cântaro Raso, Fraga das Penas, Penhas Douradas and Malhada Alta (Figure 3). The Cântaro Raso is a flat summit at the eastern limit of the Torre plateau at 1916 m ASL. The gentle surface is formed by medium-grained two-mica granite (Covilhã granite). It outcrops extensively, but many areas are covered by centimetrical to decimetrical grass, where coarse sand accumulations develop preferentially. Vegetation is sparse, with scattered shrubs and widespread denuded surfaces. The Fraga das Penas site (1640 m ASL) is in a gently sloping interfluvium with steps where the coarse sand accumulations form. The bedrock is porphyritic coarse-grained, two-mica granite (Seia granite) and preserves a decimetrical mantle of coarse weathered material. It is located outside the glaciated area. Scrub vegetation covers some 50% of the area, but wide denuded areas are frequent. The Penhas Douradas site (1360 m ASL) is located in a smooth interfluvium in the Seia granite. Conditions are similar to those in Fraga das Penas, but altitude limits the cryogenic dynamics and favours the development of scrub vegetation. Finally, the Malhada Alta site (1430 m ASL) is located in the eastern plateau of the Estrela massif, also in the Seia granite. Dense scrub vegetation alternates with wide sectors of herbaceous vegetation and poorly vegetated weathered granite areas.

OBLIQUE RAINFALL AND EROSION: SOME CONSIDERATIONS

Several authors have studied the influence of wind on rainsplash-saltation (e.g. Moeyersons, 1983; Poesen, 1985, 1986; Pedersen and Hasholt, 1995). However, little research has been conducted on the microtopographical features produced by oblique rainfall.

Wind during rainfall episodes increases the raindrop kinetic energy (Evans, 1980; Pedersen and Hasholt, 1995) and, therefore, the efficiency of the rainsplash-saltation mechanisms. It also influences clod and ped detachability, related to the increase of wind shear (Lyles *et al.*, 1969; Disrud and Krauss, 1971). If the wind direction is stable during a rainfall event, then the net transport of material is highly influenced by the wind direction and by the angle at which raindrops strike the surface (Moeyersons, 1983; Poesen, 1986). In those conditions, a net upwind migration of mobile material occurs. Moeyersons (1983) also showed that, on inclined surfaces, if the angle between raindrops and the vertical is larger than a slope angle of $\pm 2^\circ$ then a net upslope transport was likely to occur. The role of wind and raindrops on rainsplash-saltation is complex and cannot be easily distinguished in nature; Moeyersons (1983) considered rainsplash-saltation to be a pluvio-aeolian process.

Based on these assumptions, and considering that the plateau surfaces where coarse sand accumulations occur are generally flat, a large rainfall obliquity is not necessary for the upwind movement of granules. The low slope angle (8–12°) of the surface of most accumulations is in agreement with this observation and does not constitute a significant obstacle for granules transported by rainsplash-saltation.

METHODS

Mapping

Rudberg (1968) used joint observations from aeolian morphology, anemomorphic deformations and vegetation scars to determine erosive wind directions in Sweden. Vieira (1999) characterized the stable

character of the coarse sand accumulations by detailed mapping in an interfluvial area in Serra do Gerês (northwest Portugal). King (1971) had previously mapped the accumulations of an area in the Cairngorms, but found a more irregular orientation. The survey that we present here was made on a 1 : 25 000 topographic map and is shown in reduced size for publication purposes. The map includes the location of the coarse sand accumulations in the Serra da Estrela and their orientation.

Monitoring

Monitoring of the dynamics of the surface of coarse sand accumulations in the Serra da Estrela began in 1997 with the objective of assessing their activity and evaluating the processes responsible for the movement. Different methods were used. Painted ground material for monitoring present-day dynamics has been widely used, particularly in periglacial environments (e.g. Pissart, 1964, 1973; Pérez, 1987, 1988; Matsuoka, 1998). In this study, accumulations were spray painted along lines in the four study sites. These lines were 3 to 5 cm wide and 30 to 130 cm long and were perpendicular to the slope of the accumulations in order to measure the upslope or downslope movement of granules. The sites were visited several times during the period 1997–2000. Vertical photographs were made for visual qualitative comparison. In some visits to Fraga das Penas and Cântaro Raso the surficial movement was also recorded; the position of the painted granules was drawn on transparent plastic sheets. These drawings were scanned, digitized and integrated in a geographical information system (GIS). A georeference was introduced in the images and it was possible to quantify the rates of movement in upslope and downslope directions.

The main advantages of the painted lines are the simplicity of the painting procedure and data collection (with photographs or using transparent sheets). Limitations of this methodology include:

1. Only one side of the granules is painted; therefore, if there is a rotation of the granule then the paint may become hidden and the movement subsequently not identifiable. The random nature of the rotation should not influence the results significantly.
2. Since all the granules are painted the same colour, it is not possible to follow the movement of single elements.
3. The movement measured is the shortest distance to the origin; this means that the minimum movement is used and it is not possible to identify accurate vectors of movement.

Digital photographs were used for visual comparison of the evolution of selected sites. This is a cruder method, but very useful for long-term comparisons.

Another experiment with painted granules, taking account of grain size, was conducted in the winter of 2000–01. A sample of granitic sand was sieved and separated into four classes: 1.4–2.0, 2.0–2.8, 2.8–4.0, and >4.0 mm. Each size class was painted with a different colour. The grains were painted on all sides. A sample of 80 g (20 g from each class) was mixed and placed along a line on the bare sandy-gravelly ground of the Cântaro Raso site on 13 December 2000. On 15 April 2001, the site was visited and vertical photographs were taken. These were later scanned, georeferenced, and the movement according to grain-size class studied in GIS software.

Climate data analysis

The only long-term climate data available for Serra da Estrela is measured at Penhas Douradas (PD: Figure 3), a regular station of the National Institute of Meteorology (IM). The station is located on the top of a valley slope near the plateau. Because of the topographical position and low altitude (1360 m), this station is not very favourable for characterizing the climate of the mountain. However, a preliminary comparison with data from a meteorological station installed at the summit shows that the data from PD may be used with caution.

As noted earlier, recent field observations suggest that the movement of coarse sand and granules that form the surface of the accumulations originates mostly by the action of rainsplash during oblique rainfall events. Therefore, to clarify the genesis of the accumulations, precipitation and wind data (speed and direction) were analysed. Wind and precipitation data were derived from the Daily Meteorological Bulletin (IM); observations are published for 00, 06, 12 and 18 GMT. The period 1989–99 was analysed but data were often missing. This problem was especially significant in the years 1989–94, when data were available only for 12 and 18 GMT. Two measurements per day were, therefore, lost during that period and daily totals could not be calculated. Thus, the data we used here were the existing records at 6 h intervals. The absence of snowfall records does not permit its separation from rainfall. Because snowfall amounts are relatively low at Penhas Douradas this is not considered a significant problem.

The 6 h rainfall data for the period 1989–99 was classified into different events: <5, 5–10, 10–15, 15–20, 20–30 and >30 mm. Wind speed and direction for each event were also recorded. It was possible, therefore, to study wind direction and speed according to rainfall class and to evaluate the relationship with the direction of the sand accumulations. The missing rainfall and precipitation data in the series made the interannual comparison of the sand accumulation dynamics impossible.

In November 1997, painted lines were set up on accumulations at Penhas Douradas and Malhada Alta and photographed 1 month later for monitoring purposes. Climate data from the Penhas Douradas meteorological station were available for that period and were used to study the origin of the movement.

RESULTS AND DISCUSSION

Orientation of the coarse sand accumulations in the Serra da Estrela

The systematic survey of the orientations of the coarse sand accumulations in the plateaus of the Estrela range enabled the identification of a very stable orientation from southwest to west in all the mountain (Figure 4); only minor variations were identified. This stable character was also found by Vieira (1995) in northwest Portugal (Serra do Gerês), where strong winds were suggested as the formative process. But, as noted earlier, the wind hypothesis cannot explain the formation of accumulations in sheltered sites. The map (Figure 4) indicates that the process that initiates the accumulations is unidirectional and is stable at a regional level.

General movement observed from 1997 to 2000

Several painted lines were set up in November and December of 1997 and 1998 in coarse sand accumulations lying against vegetation or rock outcrops (Figure 5). Visual inspection of the lines (in the field and *a posteriori* by photographs), made at least once a year until 2000, showed that there is a general trend of net retreat or stability in the Fraga das Penas site, whereas advances were identified more often in the Cântaro Raso (Table I). Only the general behaviour of the painted lines is considered, since there is always material that advances and material that retreats in relation to the original painted line. The winter of 1998–99 was characterized by a general retreat or stability of the accumulations at both sites.

Two assumptions can be drawn from these inspections: a spatial one, in which the Cântaro Raso site is characterized by a clearer advance of the material in the accumulations, whereas in the Fraga das Penas the material tends to retreat; and a temporal one, showing that, from year to year, significant differences in movement occur. The absence of detailed climate data limits the use of a climatic explanation. Field-based knowledge and preliminary data from monitoring of ground temperature regimes suggest that the Fraga das Penas site is more exposed to rainfall and wind during the winter months, because snow cover lasts longer in the higher sites, like Cântaro Raso. Shallow ground freeze–thaw cycles and needle-ice are more frequent in the Fraga das Penas. These cryogenic processes are responsible for the downslope movement of the granules on the surface of the sand accumulations. However, the factor that probably controls much of the dynamics

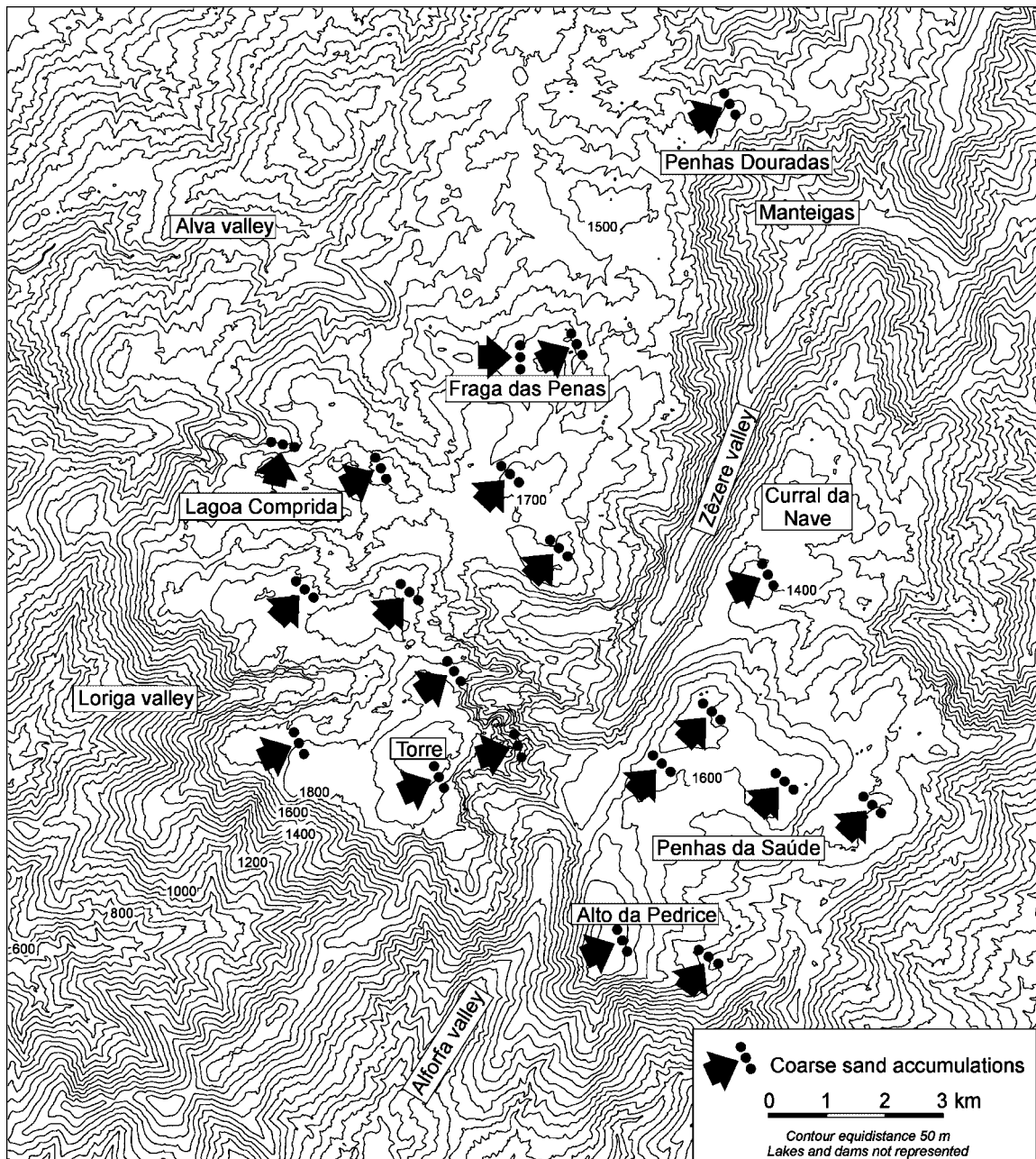


Figure 4. Distribution and orientation of the coarse sand accumulations in Serra da Estrela plateaux

of the granules is their grain size. In the net retreating Fraga das Penas sites, the granules are larger than at Cântaro Raso. In the former, the bedrock is coarse-grained porphyritic granite with centimetrical feldspar and large quartz minerals, which produce a much coarser gruss than at Cântaro Raso, where medium-grained porphyritic granite bedrock dominates. Though there is a trend for a net retreat of the granules, the coarse sands tend to advance. Furthermore, the obstacles against which the material is lying at Cântaro Raso are

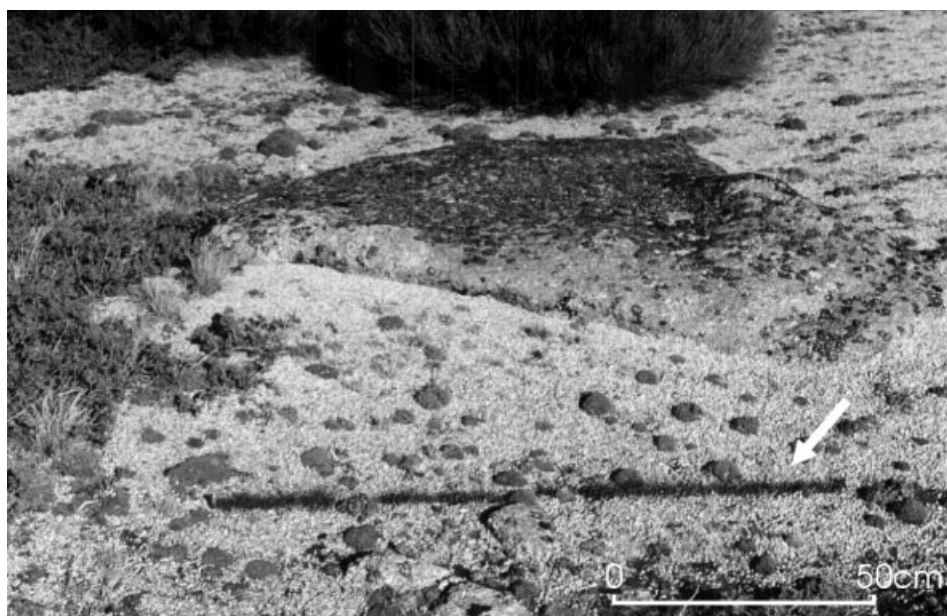


Figure 5. Painted line after installation at the site Cântaro Raso 2 (22 November 1998)

Table I. General characteristics of the movement of the granules on the surfaces of coarse sand accumulations in the Serra da Estrela^a

Location	Start date	Granule movement								
		28.12.97	07.04.98	11.07.98	17.08.98	23.11.98	30.07.99	30.11.99	04.11.00	13.12.00
Fraga Penas 1	23.11.98	—	—	—	—	—	Retreat	Stable	Retreat	—
Fraga Penas 2	29.12.97	—	—	—	Retreat	Retreat	Retreat	—	—	—
Cântaro Raso 1	30.11.97	—	Advance	Advance	RP	—	Stable	Advance	—	Advance
Cântaro Raso 2	22.11.98	—	—	—	—	—	Retreat	—	—	Advance
Penhas Douradas	30.11.97	Advance	—	—	—	—	—	—	—	—
Malhada Alta	30.11.97	Advance	—	—	—	—	—	—	—	—

^a RP: repainting of the line.

not so significant as those in Fraga das Penas; this is especially so in the site Cântaro Raso 1, where the accumulation lies only against exposed roots of *Juniperus nana* shrubs.

Monitoring of the movement in the Fraga das Penas and Cântaro Raso

The digitizing and GIS analysis of the painted lines permitted the characterization of the movement of the surface of the accumulations in the Fraga das Penas and Cântaro Raso sites (see an example of the movement recorded in Figure 6 and the synthesis of the monitoring in Figure 7):

1. Independent of the advancing or retreating trend of the majority of the granules, the movement of advancing granules is greater than that of the retreating granules whenever the obstacle located upslope is small. This is significant, since the advancing granules move in an upslope direction.
2. The movement is not uniform along the entire painted line. There are very dynamic sectors, whereas others are more stable.

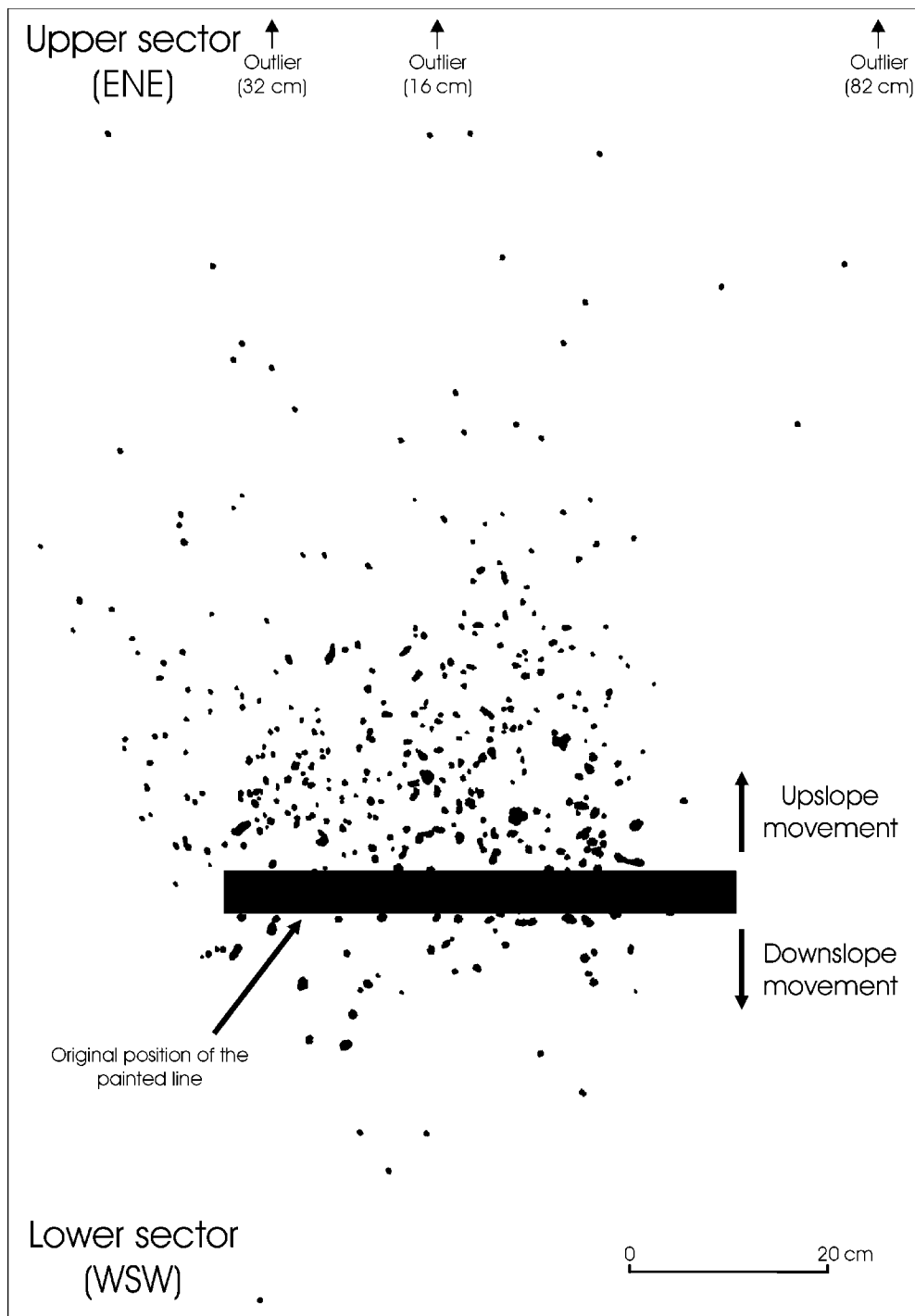


Figure 6. Movement of the painted granules recorded with a transparent plastic sheet in the coarse sand accumulation, Cântaro Raso 1, on 5 November 1999

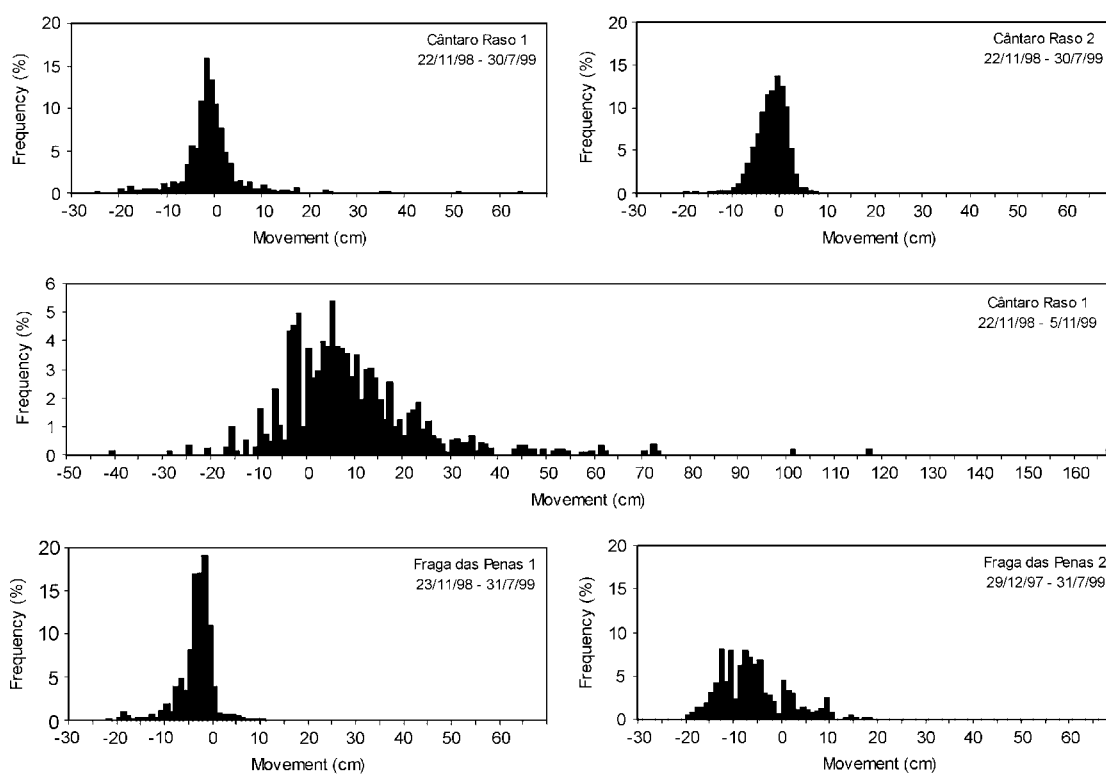


Figure 7. Movement of the painted granules recorded at the Fraga das Penas and Cântaro Raso sites. Negative values refer to movement downslope and positive values to movement in the upslope direction

3. The comparison of the dynamics of the accumulations of Fraga das Penas 1 and Cântaro Raso 1 and 2, for the period of 22–23 November 1998 to 30–31 July 1999, shows a unimodal distribution of granule movement. The mode was close to zero, meaning that there was no movement or that the granule returned to the original line. The general movement is also close to zero on the three sites. This suggests that there was a similar control on granule movement at all locations, probably related to regional climatic conditions.
4. When longer time spans are analysed, the dispersion of the movement increases considerably. The advance of the granules in Cântaro Raso 1 is particularly significant, with individual elements moving more than 1 m upslope.

Grain size and movement

The field experiment for monitoring the effect of grain size on movement of the grains was installed in Cântaro Raso on 13 December 2000 and photographed on 15 April 2001. Only the granules that moved from the 5 cm wide original line were used in these analyses. The results show a relatively small movement during the study period (Figure 8), especially if compared with other particularly dynamic situations (i.e. November–December 1997), but they confirm the general direction of the movement towards east-northeast. The distribution of grain sizes according to the distance upslope or downslope (Table II) indicates that coarser granules were less affected by the movement than finer granules (Figure 9). It is clear that, for the finer material, the movement was greater. This is identifiable both when analysing the graphs of the average grain size for each class of distance (Figure 10) and graphs of the average movement of each grain-size class (Figure 11). Both have very strong linear correlation coefficients ($R^2 > 0.87$).

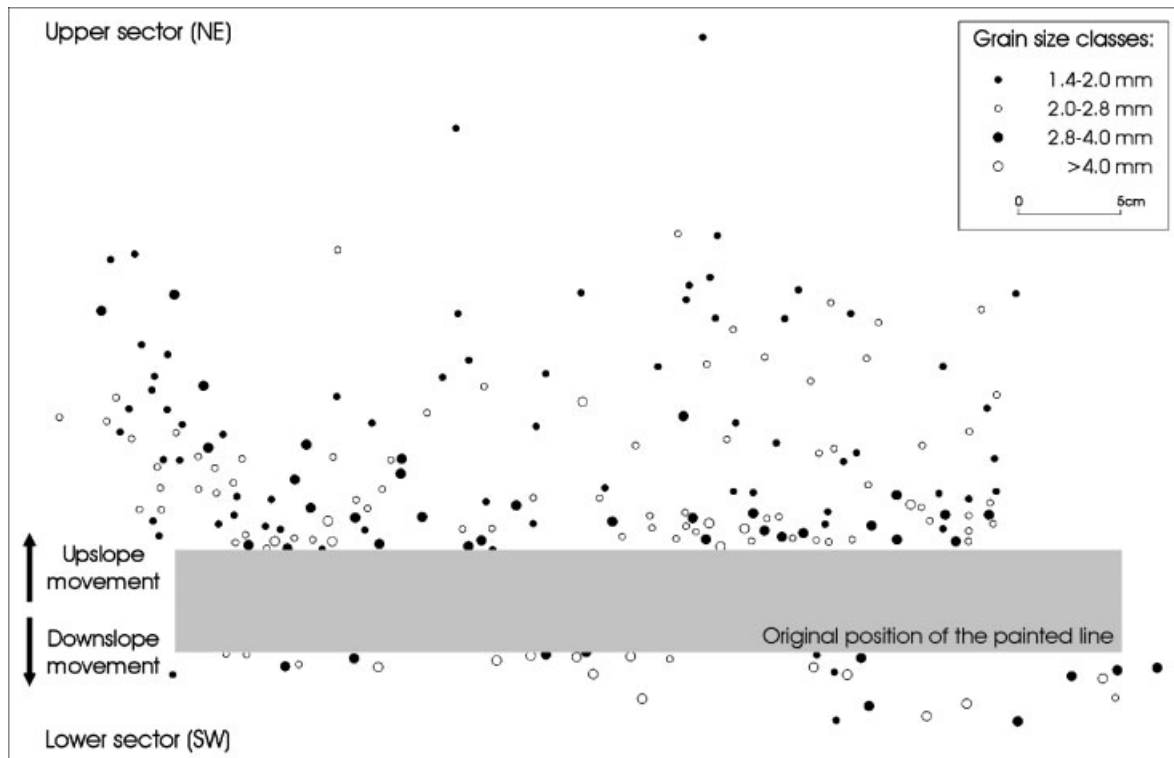


Figure 8. Position of the granules with different sizes on 15 April 2001 in an experiment installed at the Cântaro Raso on 13 December 2000

Only the coarser granules (>4 mm) were more static and exhibited a net (but short) downslope displacement (Figure 9). All the other finer classes had a net upslope movement. This confirms the unidirectional control on the movement of material finer than approximately 3–8 mm on the plateaux (Figure 11). These high areas are, therefore, experiencing a depletion of, at least, the sand fraction, which is being transported towards the east-northeast and forming widespread lag-surfaces.

A larger dispersion of sediment movement was found for the finer grain sizes (Figure 9). This dispersion may be related to the lower energy needed for movement to occur and the greater influence of the horizontal component of movement produced by wind on the finer material when saltating. The results of this experiment agree with the earlier findings by Vieira (1999), which showed that the upper part of the accumulations is finer than the lower part.

Climatic control on the orientation of the coarse sand accumulations

To evaluate whether oblique rainfall and rainsplash-saltation are mechanisms for producing the coarse sand accumulations, wind speed and direction during rainfall events in the Penhas Douradas (at 6 h intervals) were analysed from 1989 to 1999 (Figure 12). Wind direction was bimodal for rainfall events of <30 mm with maximum frequencies around N290° (west-northwest) and N130° (southeast). For heavier rainfall (>30 mm) the wind direction mode was around N270° (west); however, these events rarely occurred. These observations do not directly reflect the southwesterly to westerly orientation of the accumulations as mapped in the field. However, the orientation of the accumulations does not result from a single event, but from a cumulative granule movement in different directions during distinct events. The sum of wind directions (Figure 12) shows that the resulting vector is approximately west-southwest for all rainfall classes, except the heavier episodes (northwest). This indicates that the coarse sands and granules may move in different directions, but agrees

Table II. Transport according to grain size (number of granules) from 13 December 2000 to 15 April 2001 in relation to a painted line in the Cântaro Raso (~1900 m ASL). Negative values indicate downslope movement (retreat) and positive values upslope movement (advance)

Transport (mm)	Grains transported			
	1.41–2.0 mm	2.0–2.8 mm	2.8–4.0 mm	>4 mm
-55	1	0	2	1
-45	0	1	0	2
-35	2	1	4	5
-25	1	3	4	4
25	2	11	8	3
35	9	11	8	3
45	6	12	5	1
55	5	6	2	0
65	4	7	2	0
75	3	5	2	0
85	5	5	1	0
95	4	2	0	1
105	4	2	1	0
115	4	3	0	0
125	1	1	0	0
135	4	2	1	0
145	5	1	1	0
155	1	0	0	0
165	2	1	0	0
175	1	1	0	0
185	2	0	0	0

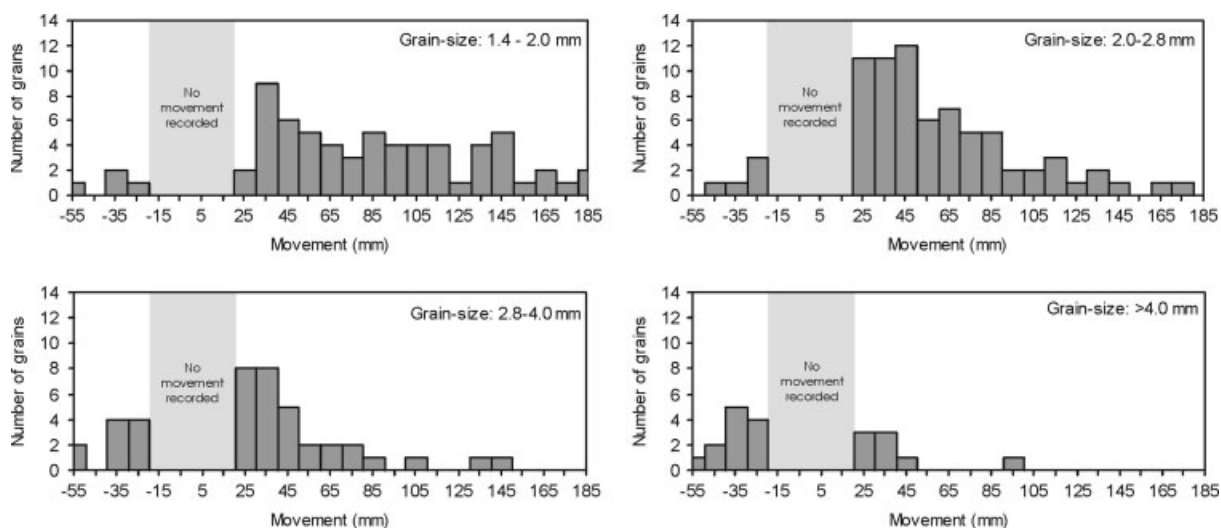


Figure 9. Movement according to grain-size class at the Cântaro Raso site (13 December 2000 to 15 April 2001). Negative values refer to movement downslope and positive values to movement in the upslope direction

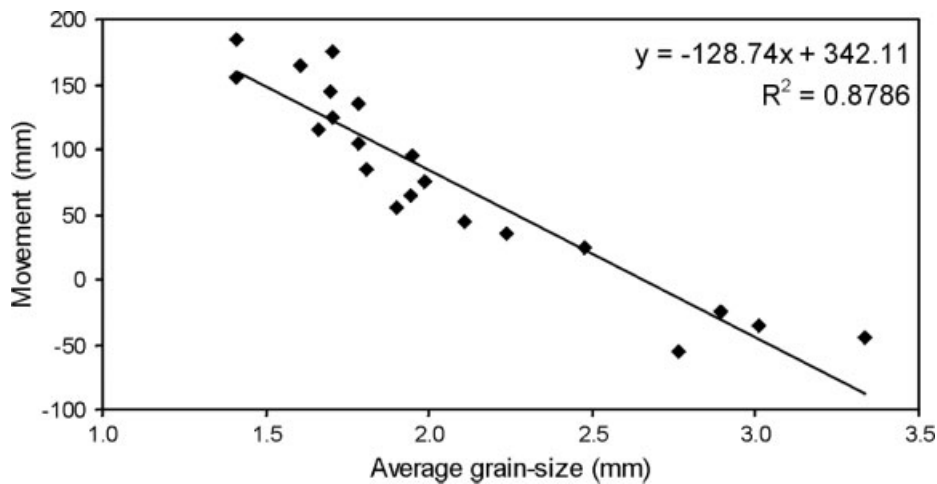


Figure 10. Average grain size per class of distance of transport at the Cântaro Raso site (13 December 2000 to 15 April 2001). Negative values refer to movement downslope and positive values to movement in the upslope direction

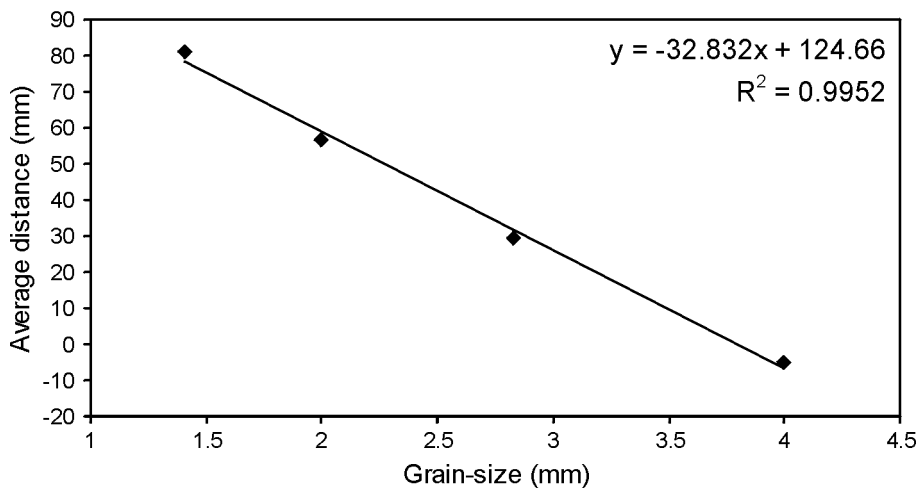


Figure 11. Average displacement distance per grain-size class at the Cântaro Raso site (13 December 2000 to 15 April 2001). Negative values refer to movement downslope and positive values to movement in the upslope direction

with the fact that their net movement is generally towards east-northeast. The limitations of this approach arise from considering the same raindrop kinetic energy for all the wind speeds and rainfall classes; however, since there are no data on rainfall intensity and wind speed during short intervals, this analysis is difficult to improve upon.

Climatic conditions and movement during December 1997

Two painted lines installed in Penhas Douradas and Malhada Alta on 30 November 1997 were photographed on 28 December 1997. The accumulations at both sites were oriented towards west-southwest. Both showed significant advances of the surficial granules, but movement was greater at Penhas Douradas (Figure 13). For the same period, climate data for the Penhas Douradas meteorological station was available (Figure 14).

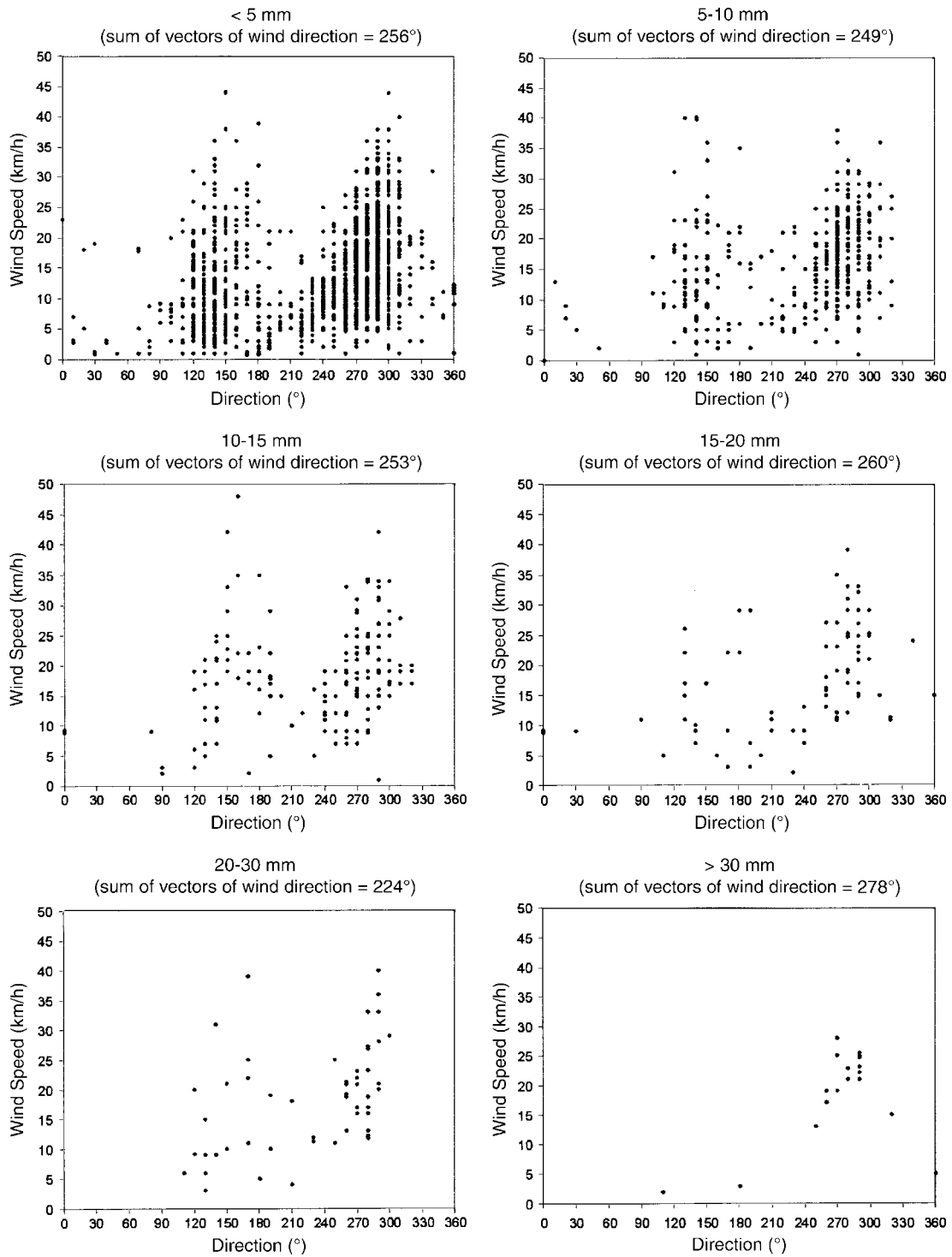


Figure 12. Wind speed and direction at Penhas Douradas meteorological station during rainfall events with different intensities (1989–99)

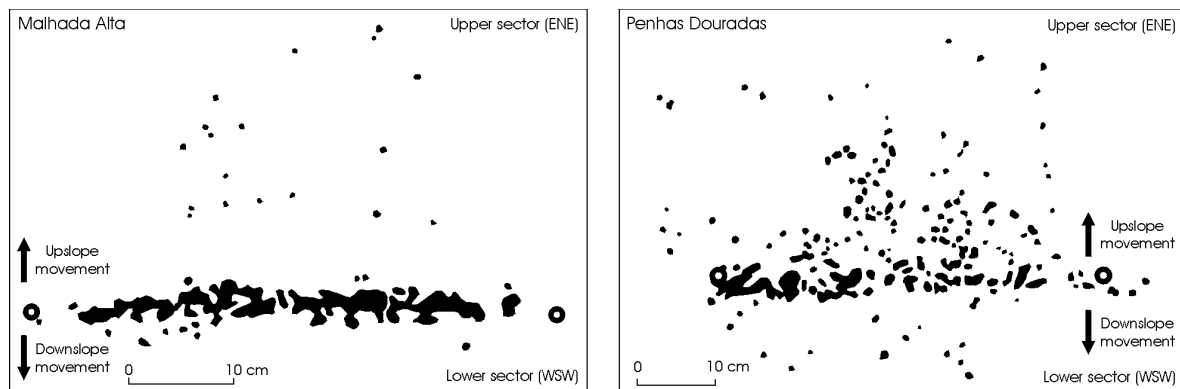


Figure 13. Movement of painted lines in coarse sand accumulations at Malhada Alta and Penhas Douradas from 30 November to 28 December 1997

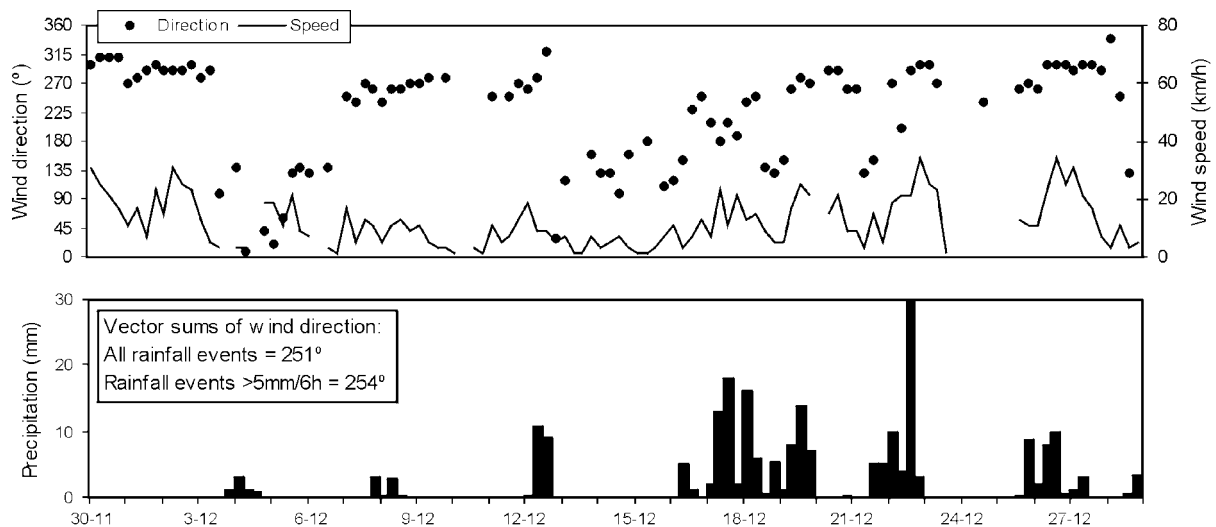


Figure 14. Precipitation, wind speed and direction measured at 6 h intervals at Penhas Douradas meteorological station from 30 November to 28 December 1997

Several rainfall events occurred. The vector sum of the wind directions during rainfall episodes yields an east-northeast net transport of the granules. The resulting vector for origin of movement is 251° if all the rainfall events are analysed, and 254° if only the episodes above 5 mm are used (Figure 14). This is in agreement with the movement on the accumulation surfaces and supports the inclusion of oblique rainfall as the main triggering mechanism of the movement.

CONCLUSIONS

The results obtained from field mapping and monitoring, together with the climate data analysis, indicate that rainsplash-saltation resulting from oblique rainfall events is the most active transportation process of the coarse sands and granules on the bare surfaces of the Estrela plateaux. Wind alone cannot explain the movement of granules in locations sheltered by vegetation. Therefore, the model proposed by Vieira (1999) needs to be modified. Wind speed during dry episodes may, however, play a minor role, as suggested by Vieira *et al.*

(2004), based on the heavy mineral spectrum and optical and scanning electron microscope analysis of quartz grains. The other processes that contribute to the differentiation of the surface and subsurface characteristics of the accumulation (deflation, wash, needle-ice and upfreezing) were not assessed here.

It is difficult, without continuous field monitoring of particle movement and climatic parameters, to identify thresholds for the initiation of movement of coarse sand and granules. Several factors influence the retreating or advancing character of the accumulations. Years with different meteorological conditions are responsible for different dynamics, and since the accumulations are very dynamic, monitoring may help in the assessment of environmental changes. Grain-size characteristics of the surface material also seem to be important, with larger granules tending to migrate more in the downslope direction and coarse sands tending to move upslope. Hence, coarser-grained grass accumulations (i.e. Fraga das Penas site) should take longer to form, but they should attain a more stable character earlier than the finer accumulations (i.e. Cântaro Raso site). Accumulations whose stability is not supported by an adjacent obstacle (i.e. Cântaro Raso 1) achieve a state of dynamic equilibrium, where an equal amount of material reaching the accumulation is offset by material leaving the accumulation. In such a case, the availability of material is of primary importance.

This study indicates that coarse sand accumulations are active features that show a clear climatic and ecological signal. They are related to upland environments with strong ecological constraints that limit the development of the vegetation. In the Estrela range, these constraints are especially related to aeolian and cryogenic processes, snow cover, and grazing. The occurrence of heavy rainfall, especially when associated with strong winds (which induce obliquity), produces directional movement in the exposed grass.

The eventual identification of coarse sand accumulations in the Quaternary record could then be considered an indicator of such environmental conditions, which, although relatively widespread (e.g. Portuguese mountains, Japanese Alps, Catalan Pyrenees and Scottish highlands), are representative of climates where stress on the vegetation is high and where, at least during a part of the year, there are intense oblique rainfall events forming unidirectional accumulations.

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