Landform Analysis, Vol. 4: 99–107 (2003)

Sedimentological analysis of sandy-gravel accumulations, Serra da Estrela plateaux (Portugal)

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Landform Analysis
2003

Abstract: Sandy-gravel accumulations are frequent features on the plateaux of the Serra da Estrela and other granitic mountains in Portugal. Their genesis has been attributed to both eolian and water processes and a detailed sedimentological study is needed to better understand the mechanisms involved. The present paper provides results obtained from the heavy mineral analysis and optical and scanning electron microscope study of samples from two sandy-gravel accumulations from the Serra da Estrela. The results indicate that the finer fractions of the original sediment have been illuviated. A well-sorted surface layer and poorly sorted subsurface of the accumulation have resulted from this process. A very short duration of eolian processes is evident from the analysis. Although wind seems to have been the responsible for the morphology of the accumulation, its action was not enough to produce significant abrasion in the surface of quartz grains.

Key words: wind erosion, water erosion, Scanning Electron Microscopy, Central Cordillera, Portugal

Introduction

The Serra da Estrela is the highest mountain in Portugal (Fig. 1) and reaches 1,993 m ASL in the Torre plateau. The central massif where this study was conducted is granitic and metasediments crop out peripherally.

The mountain's plateaux form steps above 1,400 m ASL (Fig. 2) and most of these were glaciated during the Last Glacial Maximum (LGM). This episode greatly influenced the landscape landforms of glacial erosion and accumulation are prominent. Bare-rock outcrops dominate in the glaciated area, while, beyond, a typical tor and bornhardt morphology prevails.

Post-glacial weathering has disaggregated the exposed rock surfaces and has produced a thin cover of granite gruss which is mobilised easily by the present-day geomorphological dynamics. Despite being coarse sand and fine gravel, it is actively transported by wind and water processes, and gives rise to small accumulations deposited against obstacles (Vieira, 1999). These are very frequent in the plateaux of the Serra da Estrela (Fig. 3 and 4).

Similar deposits have been studied in the Serra do Gerês, NW Portugal (Vieira, 1997, 1999). The accumulations have slope angles of 10 to 20° and are usually 20–50 cm long with a 100 cm maximum and can be several metres wide. Three types of sandy-gravel accumulation have been identified: incipient accumulations; climbing tongues; and climbing tongues with blowout. The granulometry of these deposits is of fundamental importance. The superficial part of the accumulations is a well-sorted layer, *ca.* 1 cm thick, with the mode in the –1.5 to –2.0 phi class. Below it, the material is finer and very poorly sorted. Comparison between samples from the Serra da Estrela and Serra do Gerês, located about 150 km apart, shows that the grain-size characteristics of the surface layer of the accumulations

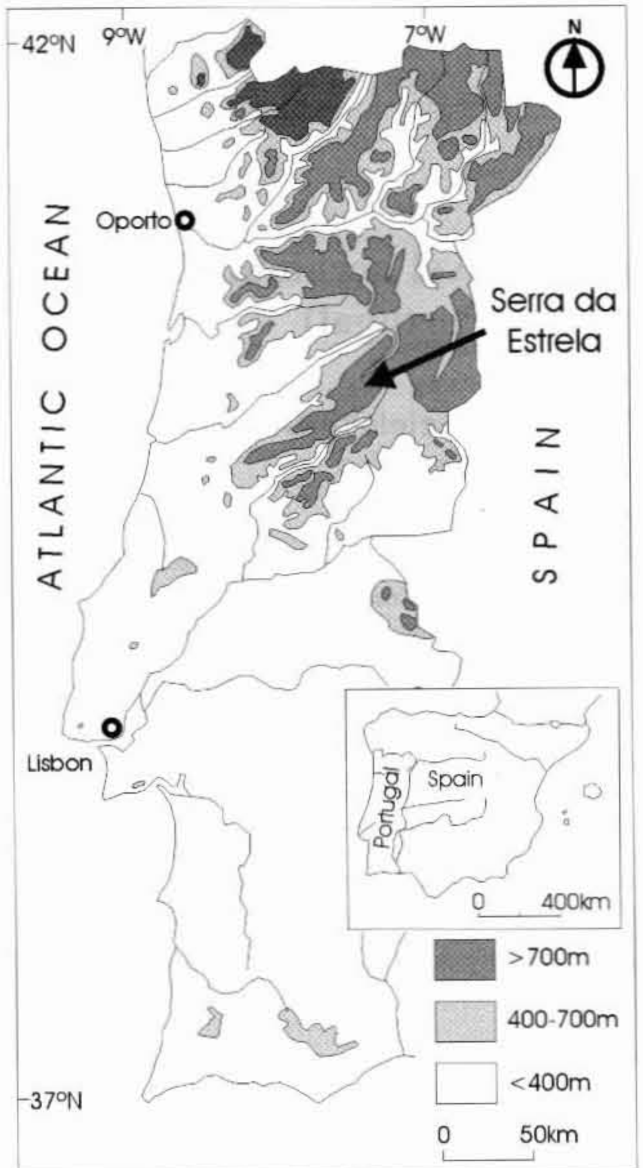

Fig. 1. Location of the Serra da Estrela

are very similar from site to site. By contrast, subsurface material is very variable.

Detailed geomorphological mapping, comparison with wind deformation of shrubs, and grain-size analysis were the basis for the proposal of a genetic model for the sandy-gravel accumulations (Vieira, 1997). The new results focus on the significance of their genetic processes and are based on a substantially more detailed sedimentological analysis, involving optical and scanning electron microscopy of the quartz grains and a study of the heavy minerals.

The climate of the Serra da Estrela is Mediterranean with dry and warm summers and a wet season from October to May. Mean annual precipitation is more than 2,000 mm in the higher parts of the mountain and plateau (Daveau *et al.*, 1977). Most of the plateaux have mean annual temperatures below 7°C. The Torre is the coldest area with an estimated mean annual temperature of *ca.* 4°C (Vieira & Mora, 1998). Snow data are scarce and of poor quality. The median number of days with snowfall at 1,400–1,600 m ASL is 40 to 50 but there is a significant interannual variability. This number increases with altitude (Andrade *et al.*, 1992). Wind regimes are complex and there are large variations depending on site. Maximum speeds occur in Autumn and Winter, especially from November to March, when monthly speeds average 27 km/h. The stronger winds are from Northwest to Southwest and the wind frequency is bimodal or even polymodal, again depending on the site (Vieira & Mora, 1998). In general, the dominant directions are West and Northwest.

The Study sites

Fraga das Penas

The Fraga das Penas site is located in the northern part of the Central Massif of the Estrela (Fig. 2) at the transition between the LGM glaciated area and the unglaciated sector. It is a smooth, E-W-trending ridge, with tors, bornhardts and castle-koppjes. The bedrock is Seia granite, a coarse-grained porphyritic two-mica granite with a relict Tertiary weathering mantle a few centimetres to a few decimetres thick. The surface comprises gruss which is primarily mobilised by wash, rainsplash, wind and needle ice. Vegetation is dominated by ericaceous and dwarf juniper shrubs but vegetation free patches are prominent, especially on the ridges where geomorphological processes are more active. The sandy-gravel accumulations are mainly in wind exposed areas on ridges, where sandy-gravel source material is readily available.

The sediment sampled was deposited by winds from WSW and is similar to the type shown in Fig. 5. It is 33 cm long and several metres wide and has a slope gradient of *ca.* 10°. The surface layer is *ca.* 0.5 cm thick.

Torre

The sample site is located in the northern part of the Torre plateau at 1,920 m ASL. (Fig. 2). It is a gently-sloping site covered by a herbaceous vegetation mat with bedrock outcrops in the convex sectors. The lithology is the Estrela granite, a medium-to coarse-grained muscovite granite. In this site gruss appears in small vegetation free patches and coarse sand accumulations are scarce. Owing to the vegetation cover little gruss

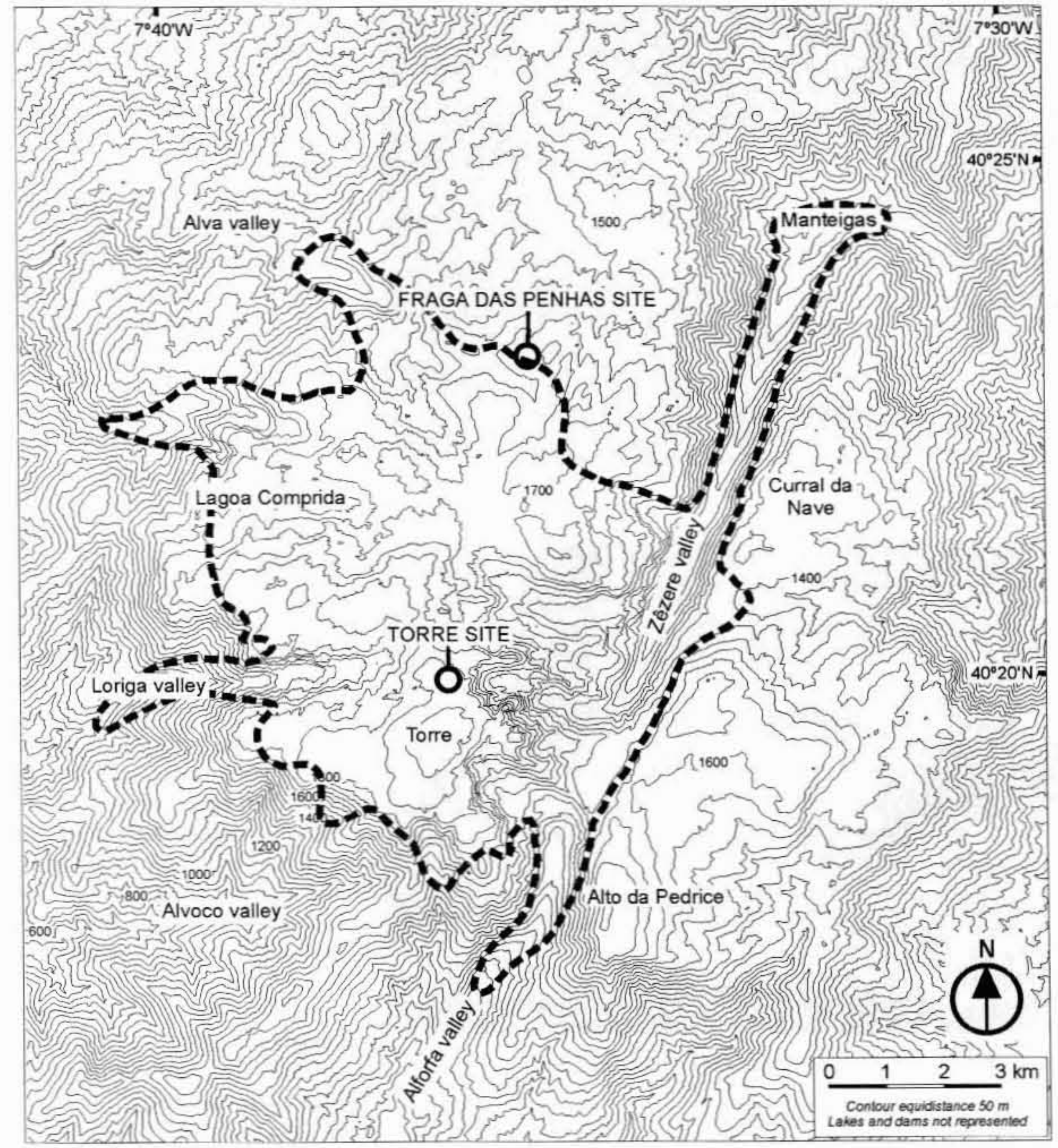

Fig. 2. Location of the Fraga das Penas and Torre study sites in the Serra da Estrela (maximum extent of the LGM glaciers indicated by a dashed line, following Daveau, 1971)

is available for transport and the accumulations are generally small. The high elevation of the plateau and exposure to the western side of the Serra da Estrela make it an area where wind speed is high, an important fact that much influence in the vegetation development.

The accumulation studied is a climbing tongue (Fig. 4) banked in the herbaceous vegetation. It is *ca.* 45 cm long and 100 cm wide. The slope gradient is close to 16° and the direction indicates a wind blowing from SSW. The lower part of the tongue contacts directly with a flat surface with granite cobbles and thin gruss, which corresponds to a wash sector. The superficial layer is *ca.* 0.5 cm thick in the upper sector of the accumulation and 0.5 to 1 cm thick in the lower sector.

Methodology

Samples were taken from the two study sites (Fig. 2). The upper and lower sector and both the surface and subsurface materials were sampled (Fig. 5).

Grain-size analysis of the coarse fraction was performed by sieving. Graphic representations and measuring indexes were used for the characterisation of the samples (Folk & Ward, 1967).

Fig. 3. The studied sandy-gravel accumulation of the Fraga das Penas site

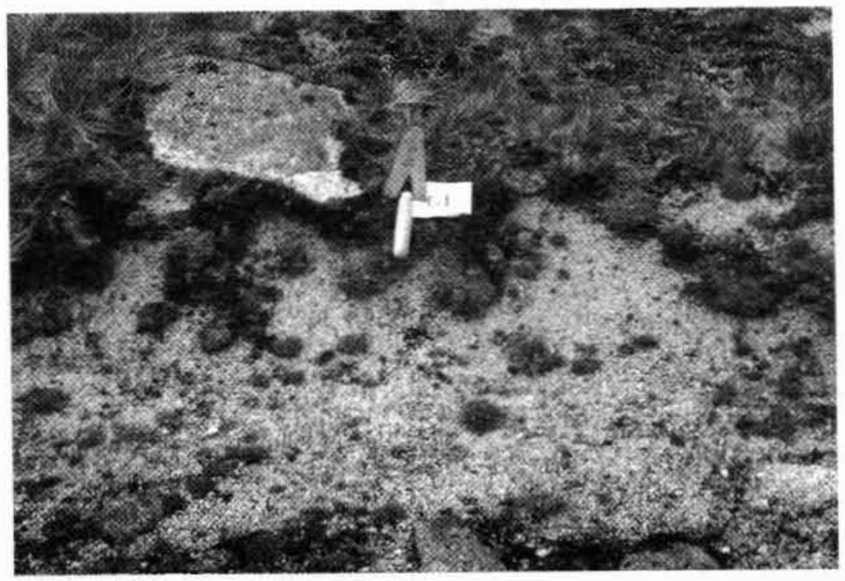

Fig. 4. The studied sandy-gravel accumulation of the Torre site

The heavy mineral distribution within the deposit can be significant for the reconstruction of the morphodynamic processes. This was determined for the 0.1–0.2 mm fraction.

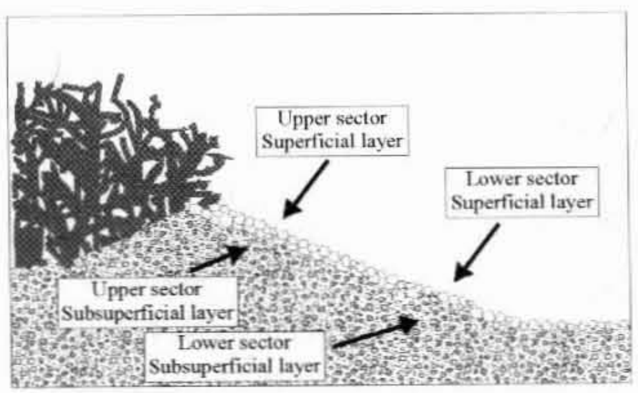

Fig. 5. Position of the samples in the sandy-gravel accumulation

For the determination of rounding and frosting of quartz grain surface under the light microscope, groups of 100 grains were selected from the size fractions 0.7–1.0 mm (referred onward as the fine fraction) and 1.0–1.4 mm (coarse fraction). At the Fraga das Penas site grain sizes over 1.4 mm were also studied. The method of Cailleux (1942, 1961) modified by Mycielska-Dowgiałło & Woronko (1998) was followed. Both surface and subsurface grains of the upper sectors and subsurface grains of the lower sectors of the accumulations were studied. At the Torre site, the surface layer of the lower sector was also analysed (Table 2).

For the analysis of the micromorphology of the surface of quartz grains in the scanning electron microscope (SEM) groups of 6 typical grains were selected from each sample using the light microscope. The surface layer of the upper sector and subsurface layer of the lower sector of the accumulations were studied. From the Fraga das Penas site grains were chosen from the 1.0–1.4 mm class and from the Torre site the class 0.7–1.0 mm was also studied.

Results

Grain-size analysis

The accumulations studied show the typical grain-size characteristics of the sandy-gravel accumulations described by Vieira (1999) (Fig. 6).

In the Fraga das Penas accumulation the surface layer in the upper sector has a graphic mean of –1.3 phi and is moderately sorted, positively skewed and leptokurtic. In the lower sector it becomes coarser (graphic mean –1.7 phi), well sorted, very positively skewed and mesokurtic. The subsurface material is very distinct. In the upper sector, the graphic mean is –0.4 phi and it is very poorly sorted, very positively skewed and leptokurtic. In the lower part, the graphic mean is –0.1 phi and the material is poorly sorted, very positively skewed and mesokurtic. The subsurface grain-size distribution is very similar. The differences in kurtosis appear to be explained by the sediment distribution in the extreme classes.

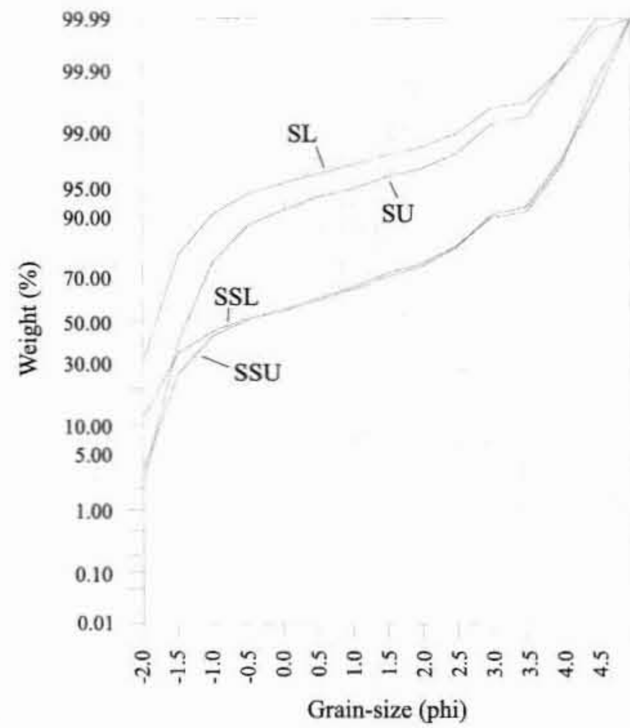

Fig. 6. Grain-size distribution in the Fraga das Penas sandy-gravel accumulation
SU – surface layer upper sector; SSU – subsurface material upper sector; SL – surface layer lower sector; SSL – subsurface material lower sector

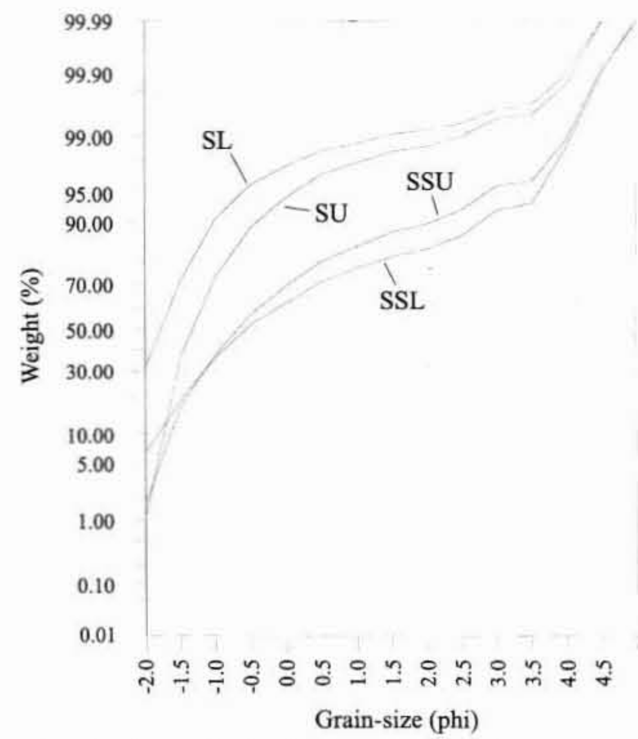

Fig. 7. Grain-size distribution in the Torre sandy-gravel accumulation
SU – surface layer upper sector; SSU – subsurface material upper sector; SL – surface layer lower sector; SSL – subsurface material lower sector

The surface samples from the Torre site have similar grain-size distribution curves to those at the Fraga das Penas (Fig. 7). The upper sector has a graphic mean of –1.3 phi, it is moderately sorted, very positively skewed and very leptokurtic. In the lower sector the sediment is coarser (graphic mean –1.7 phi), well-sorted, very positively skewed and very leptokurtic. The subsurface material is different from that at the Fraga das Penas. This difference is very common in the coarse sand accumulations studied in the Serra da Estrela and Serra do Gerês (Vieira, 1999). In the upper sector, the graphic mean is 0.1 phi and in the lower sector is 0.0 phi. As in the subsurface samples from the Fraga das Penas site, the sediment in the lower sector of the accumulation is slightly more mesokurtic than in the upper sector. There is an increase in sediment coarser than –2 phi and also finer than 3.5 phi.

Heavy mineral analysis

The heavy minerals of the Fraga das Penas accumulation reflect the mineral composition of the bedrock. Dominating are biotite and opaque minerals (Table 1). In the lower sector a distinct impoverishment in lamellar minerals of the mica group (biotite, chlorite, glauconite, muscovite) is ob-

Table 1. Content of heavy minerals in the studied samples (grain-size 0.1–0.2 mm)

Samples	FRAGA DAS PENAS				TORRE			
	SU	SSU	SL	SSL	SU	SSU	SL	SSL
Amphibole	–	–	–	0.2	2.4	3.2	1.9	4.3
Biotite	81.3	74.7	71.2	68.0	4.8	7.8	6.5	19.0
Chlorite	0.4	0.1	–	0.5	–	0.9	–	1.1
Zircon	–	0.1	–	–	–	–	–	–
Kyanite	–	0.1	–	–	–	–	–	–
Epidote	–	–	1.2	0.1	0.8	0.4	–	1.1
Glauconite	–	–	–	–	–	0.9	–	–
Muscovite	2.3	1.0	–	1.3	76.3	79.6	77.5	61.6
Piroxene	–	–	–	–	–	0.2	–	–
Rutile	–	–	–	–	0.8	–	1.0	–
Sphene	–	–	–	–	0.8	–	–	–
Staurolite	0.8	–	0.6	–	0.8	0.4	–	0.5
Tourmaline	–	–	–	0.1	3.8	2.0	4.7	4.3
Carbonate	–	–	–	–	4.0	–	–	0.5
Opaque	15.2	24.0	27.0	29.8	5.5	4.6	8.4	7.6
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

SU – surface upper sector; SSU – subsurface upper sector; SL – surface lower sector; SSL – subsurface lower sector served, whereas, in the upper sector, there is an enrichment in these minerals. In the surface layer, the total content of mica group minerals amounts to 71.2% in the lower sector and to 84.0% in the upper sector. A similar situation is observed in the subsurface material (69.8% in the lower sector and 75.8% in the upper).

In the lower sector of the accumulation a pronounced enrichment in opaque minerals may be observed in comparison with the upper sector. This applies to both the surface and subsurface materials (Table 1).

The accumulation from the Torre site shows a richer heavy mineral spectrum, but, nevertheless, these are still strictly related to the bedrock mineral composition (Table 1). Muscovite dominates but there is a considerable content of biotite. Amphiboles occur in the group of minerals which are little-resistant to weathering and mechanical abrasion. Considering the spatial distribution of the total content of minerals of higher specific gravity (opaque minerals plus tourmaline), a distinct enrichment is notable in the lower sector of the accumulation in both the surface and subsurface materials. The enrichment of minerals of lamellar structure of the mica group is visible in the upper sector of the subsurface material. In the surface layer, the distribution is the converse of this and the total content of the mica group minerals is slightly higher in the lower sector of the deposit.

Optical microscopy

The Fraga das Penas samples show that irrespective of grain size and sample sector, cracked, poorly rounded grains with partial or total frosting of the surface are dominant (50–72.7%) (Table 2). Frosted, poorly rounded grains without cracks (EM) comprise the second most important group (21.8–46.7%). They are characterised by a low rounding degree (0.3–0.5 after the scale of Krumbein, 1941). Angular and completely non-abraded grains (NU) comprise 2 to 5% of the sample. Their share is higher in the finer fraction (0.7–1.0 mm – 12.0%).

With respect to the Torre site, the counts showed that, irrespective of localisation within the deposit, among coarse fraction quartz grains, those with weak rounding and partial or total surface frosting (EM) prevail (46.0–61.9%). The content of weathered grains in the fine fraction (0.71–1.0 mm) is much lower (18%). In both size fractions the share of cracked grains (EM/C) is much lower than in the samples from Fraga das Penas. This share is from 12.7 to 22.5%, whereas that of angular entirely fresh quartz grains (NU) is considerably higher (17.2–36.7% in the coarse fraction and up to 66% in the fine).

Scanning Electron Microscopy

SEM analysis of the Fraga das Penas samples showed that none of the examined grains exhibited effects of eolian processes, especially on edges and corners, which are particularly susceptible to eolian abrasion (Fig. 8). On the other hand, on the majority of the examined grain surfaces the effects of intensive physical (Fig. 8-A and E) and chemical weathering (Fig. 8-B, C, D and F) are pronounced. The chemical etching becomes apparent due to the presence of oriented structures (Figs. 8-B and F) and crystallisation of secondary minerals. Records of weathering are visible in all depressions and on cracked surfaces.

As with the observations in the light microscope, the SEM samples from the Torre site revealed an almost complete lack of traces of eolian mechanical abrasion on edges and corners (Fig. 9). On the other hand, as with the Fraga das Penas samples the majority of grains bear a history of chemical and physical weathering.

Table 2. Rounding and frosting analysis of quartz grains (%) using the criteria of Cailleux (1942) modified by Mycielska-Dowgiałło & Woronko (1998)

Samples		NU Entirely fresh	EM/RM Poor rounding and total frosting	EM Poor rounding and total or partial frosting	EM/C Poor rounding and total or partial frosting with cracks
FRAGA DAS PENAS	SU (>1.4 mm)	5.0	1.0	21.8	72.7
	SSU (>1.4 mm)	3.9	0.0	27.4	68.8
	SSL (>1.4 mm)	4.0	0.0	44.0	52.0
	SU (1.0–1.4 mm)	3.3	0.0	46.7	50.0
	SSL (1.0–1.4 mm)	2.0	0.0	45.1	52.9
	SSU (0.71–1.0 mm)	12.0	0.0	26.0	62.0
TORRE	SU (1.0–1.4 mm)	36.7	4.7	46.0	12.7
	SSU (1.0–1.4 mm)	32.7	0.0	54.0	13.3
	SL (1.0–1.4 mm)	18.5	0.0	58.6	22.5
	SSL (1.0–1.4 mm)	17.2	0.0	61.9	20.8
	SU (0.71–1.0 mm)	66.0	0.0	18.0	16.0

SU – surface upper sector, SSU – subsurface upper sector, SL – surface lower sector, SSL – subsurface lower sector

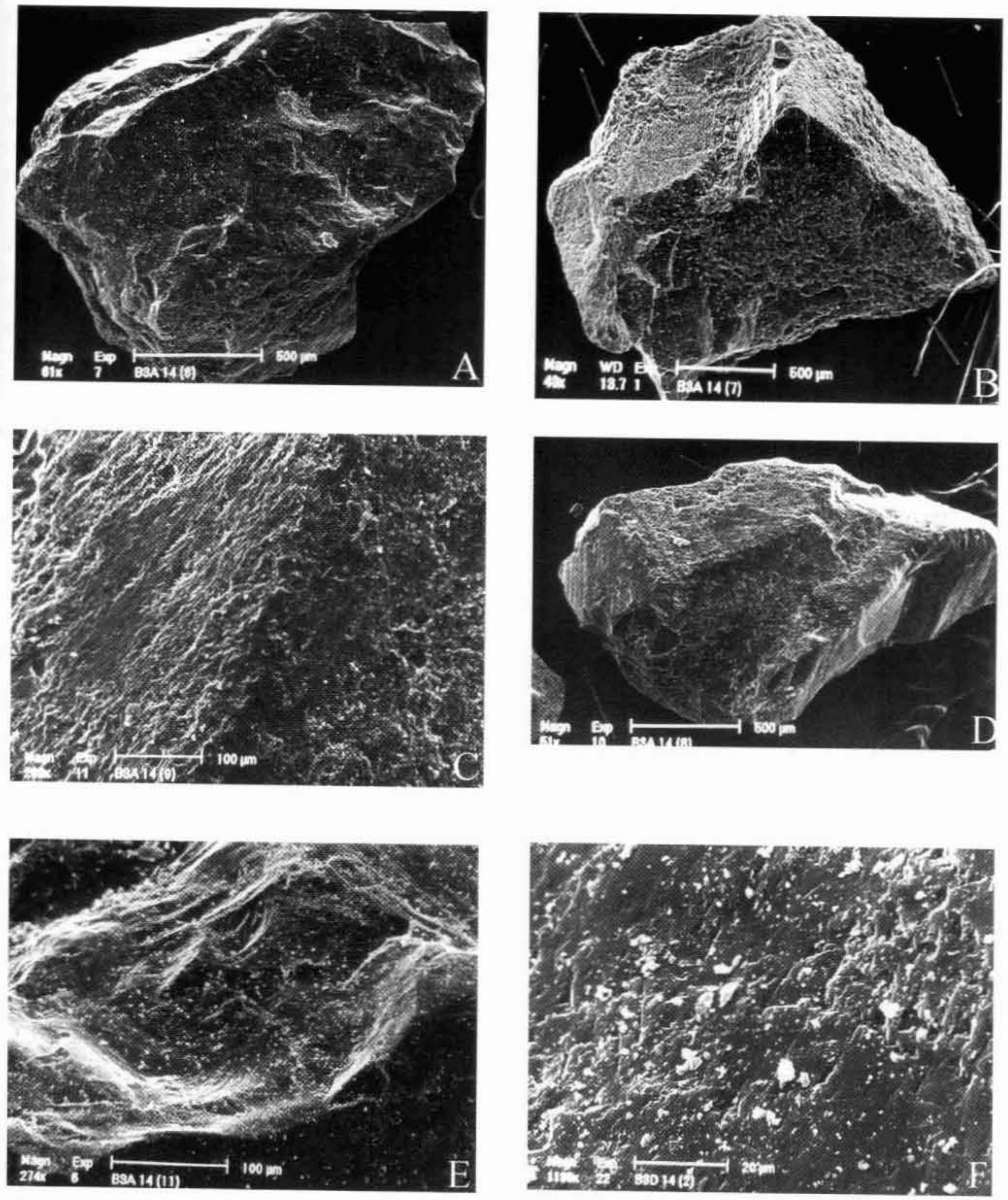

Fig. 8. Scanning Electron Microscope photographs of quartz grains from the Fraga das Penas sandy-gravel accumulation
A – Non-abraded quartz grain with sharp edges and corners; B – quartz grain altered by chemical weathering process. Oriented structures are visible; C – fragment of quartz grain surface altered by chemical weathering with oriented structures; D – quartz grain altered by chemical weathering with fresh crack; E – fragment of quartz grain with various fresh breakages due to physical weathering; F – oriented structures visible on the quartz grain surface

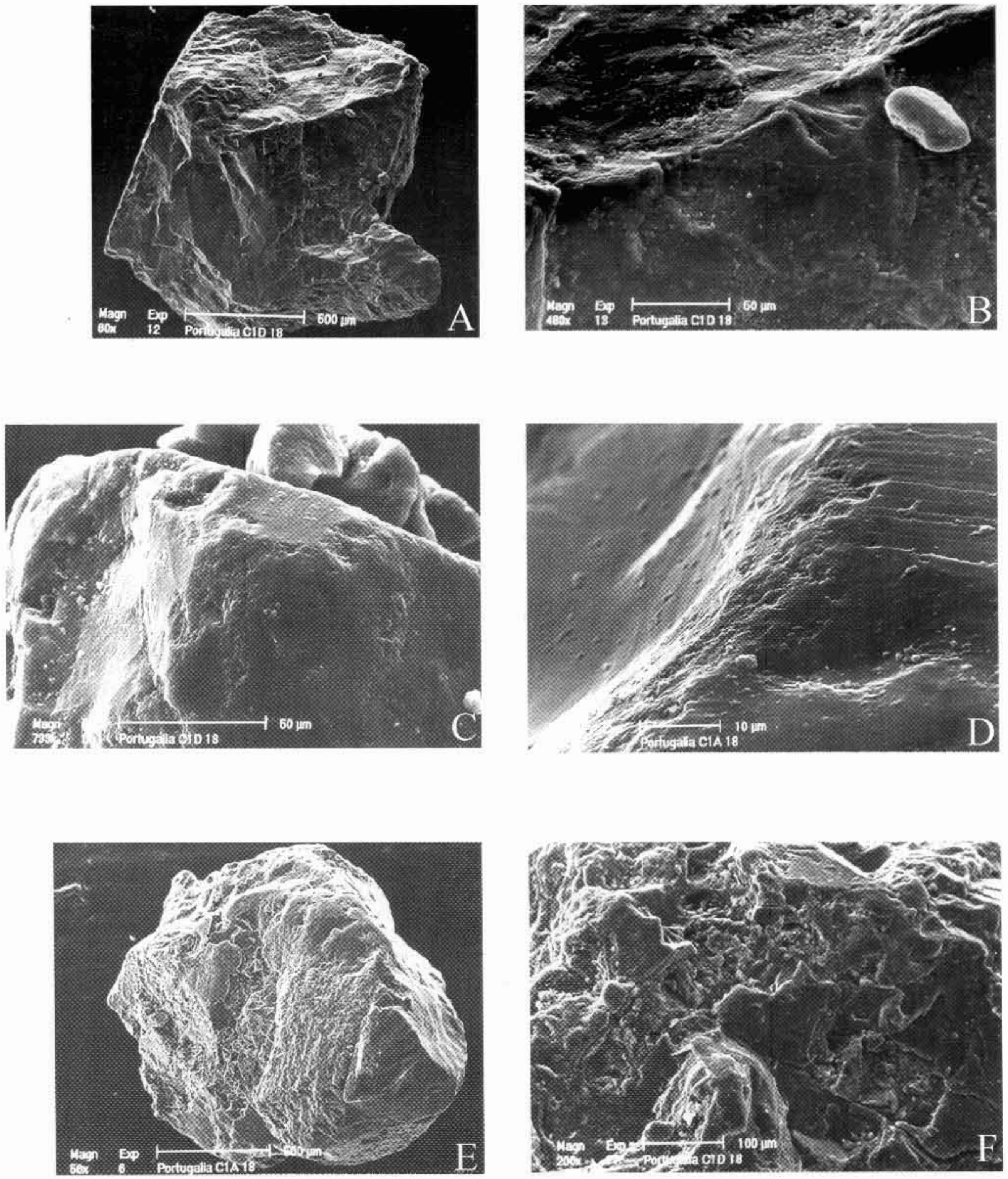

Fig. 9. Scanning Electron Microscope photographs of quartz grains from the Torre sandy-gravel accumulation
A – angular quartz grain; B – fragment of the edge of quartz grain presented on A; C – quartz grain with minor changes on the edge due to aeolian abrasion; D – fragment of quartz grain with oriented structures and the edge with some changes due to aeolian abrasion; E – quartz grain with the surface significantly altered by chemical weathering; F – fragment of quartz grain significantly altered by chemical weathering

Discussion

Grain size

The surface layers of the two accumulations show similar grain-size characteristics. They form a lag surface of well-sorted sandy-gravel. The coarsening of the lag in the lower sector indicates an increase in wash and probably an eolian sorting (coarser grains are more difficult to move upwards in the accumulation slope). The subsurface material is poorly sorted and grain-size differences occur between the deposits. These differences were found in accumulations studied at other mountain sites and were interpreted as relating to the different parent materials and differences in the downwash of fines (Vieira, 1997).

Heavy minerals

The analysis of the heavy mineral spectrum produced interesting results. The high proportion of opaque minerals at Fraga das Penas may indicate that the Tertiary regolith is the source for the deposit studied. At the Torre site, the presence of amphiboles and a markedly lower content of opaque minerals suggests a lower contribution from the Tertiary regolith. This is explained by the location of the Torre site in the glaciated area where the Tertiary weathering mantle is absent. Data thus indicate a local origin for the sediment forming the accumulations.

The differences in the proportions of mica group minerals between the accumulation's lower and upper sectors at Fraga das Penas apparently reflect their sensitivity to eolian selection processes, in respect that this group is the first to be removed from the deposit (Mycielska-Dowgiałło, 1993). From this it is concluded that the differences result from their removal by wind action from the lower sector of the slope and accumulation in the upper sector, in front of a plant obstacle. At the Torre site, the participation of the eolian segregation process may be inferred only from the mineral composition of the subsurface material.

The opaque minerals comprise a group of high specific gravity (usually >4.6 g/cm^3). This group contains various iron oxides and sulphides as well as other minerals, which, in the weathering process, became coated with iron hydroxides and oxides. They are subject to a process converse to that of the mica group and their segregation, owing to their high specific gravity is particularly effective in the aqueous environment or in the presence of washing-out with water (Mycielska-Dowgiałło, 1995).

In the case of the Fraga das Penas deposit, the higher content of opaque minerals in the subsurface material and lower sector is most probably the effect of washing-out by the surface water flow. At the Torre site, the same effect is present, but the differences are only significant in respect of the higher content of opaque minerals and tourmaline (specific gravity >3.0 g/cm^3) in the lower sector.

At the Torre site, the slightly higher content of the amphibole group in the subsurface material seems to indicate a deeper weathering within the modern surface.

To recapitulate, the distribution of heavy minerals indicates that two processes were involved in the formation of the sandy-gravel accumulations: wind activity and surface water flow.

Optical and scanning electron microscopy

In the studied samples, the frosting type visible on most of the very poorly rounded grains already at low magnifications, indicates the action of intensive chemical and physical weathering in the formation of the surface relief. On cracked surfaces, traces of initial frosting due to weathering are visible.

Similarly to the results of the heavy mineral analysis, rounding and frosting of quartz grains in Fraga das Penas indicates that these chiefly originate from the Tertiary weathering mantle. This weathered material was probably subsequently transformed by frost shattering (a high proportion of broken grains). The rounding and frosting of quartz grains at the Torre site indicate a stronger impact of physical weathering with a higher proportion of entirely fresh grains. The proportion of grains transformed by chemical weathering (EM) (probably during the Tertiary), is similar at both sites.

Very few light traces of abrasive action of eolian processes on edges and convex surfaces were observed in the Torre samples and none in those from Fraga das Penas. This suggests a short duration of eolian processes within the transport history in both sites, but particularly at the Fraga das Penas. This conclusion is also supported by the low degree of rounding of feldspar grains. The proportion of these minerals is significant despite their low resistance to mechanical abrasion as compared to quartz.

The SEM observations support the results obtained with the light microscope. The grain surface analysis proved a very short duration of modern eolian processes; this is evident from the lack of a characteristic microrelief on quartz grain surfaces. On the other hand, the results of both chemical and physical weathering processes are clear, the latter being responsible for both the high share of cracked grains and the grain surface frosting.

Conclusions

Heavy mineral analysis and quartz grain surface texture studies using the optical and scanning electron microscopes provide new insights into the characteristics and genesis of the sandy-gravel accumulations at high elevations in Portugal. The results support the genetic model by Vieira (1997) and emphasise the significance of wash processes in the post-depositional evolution of the accumulations.

The analysis of the surface morphology of the quartz grains indicates intense chemical and physical weathering but almost no traces of eolian abrasion. These observations suggest that the action of the eolian processes in the genesis of the deposits was short, i.e. not longer than 100–200 years (Mycielska-Dowgiałło, 1993; Mycielska-Dowgiałło *et al.*, 1998). As follows from earlier investigations (Mycielska-Dowgiałło, 1993; Ovchinnikov, 1998), the first indication of eolian processes is the dune form, and only afterwards are the textural features of the sediments manifested.

Plainly, the evolution of the accumulations was controlled by a complex interaction of eolian processes and wash during rainfall or snowmelt. The first phase was eolian mobilisation by high winds to move materials finer than fine gravels and to deposit them in gently-sloping deposits about 50–150 cm wide, 20–50 cm long and 5–10 cm high. After deposition wash processes dominated thereby leaving a surface lag layer with some of the fines downwashed into the deposit. Thus, the deposit is poorly-sorted at depth in contrast to the well-sorted character of the surface layer.

Acknowledgements

Professor António de Brum Ferreira is thanked for the comments on the manuscript and suggestions on field research. Professor Peter Birkeland and Dr. Peter Walsh are thanked for the comments and suggestions, which very much contributed to enrich and clarify the article. The Natural Park of the Serra da Estrela (P.N.S.E.) gave logistical support during fieldwork. The Universities of Lisbon and Warsaw have funded this research.

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