

# GENERAL CHARACTERISTICS OF THE GLACIAL GEOMORPHOLOGY OF THE SERRA DA ESTRELA

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## 1. INTRODUCTION

Glacial studies in Portugal started in the 19th Century and were first marked by controversial observations. During that period *raa* deposits (Pliocene debris-flow deposits) were frequently and erroneously interpreted as of glacial origin by authors like RIBEIRO (1866-67), CABRAL (1881) and DELGADO (1895-98). These interpretations suggested a very wide glaciation especially in the North of Portugal, which according to CABRAL (1881) had reached the coast near Oporto. From these authors, CABRAL gave especially important contributions, once he was the first to suggest with conclusive observations the Serra da Estrela glaciation in 1884. It was also in that same year that PENCK, according to OBERMAIER (1884 in LAUTENSACH, 1929, 1932), suggested a glaciation for the Serra da Estrela and Sierra de Guadarrama (Spain).

Modern studies on the Serra da Estrela glaciation can be attributed to the current century. FLEURY (1914) has described the general features of the glaciation, but it was with LAUTENSACH, who visited the area for three months in 1927 and 1928 (papers published in 1929 and 1932) that the glacial geomorphology of the Serra da Estrela became more accurately interpreted and defined (figure 1). However, Lautensach's research was based in a poor topographic map at a scale 1:100,000 which made it difficult to map the glacial features.

Forty years later, DAVEAU (1971) publishes 'La glaciation de la Serra da Estrela' and with new field observations, a 1:25,000 topographical map and aerial photographs, she presents a more accurate study and overview of the glaciation of the Serra da Estrela. A map of the glaciation at an approximate scale of 1:90,000 was published and still constitutes the best synthesis of the

Serra da Estrela glaciation (fig. 2). According to DAVEAU (1971: 6), Lautensach's general ideas remain valid, especially the fact that only remains of one glaciation are observed in the mountain, and also the idea that the glacial morphology is to a large part controlled by the pre-glacial morphology and weathering conditions. DAVEAU interpretation points towards a somewhat smaller extent of the main glaciers than previously presented by LAUTENSACH.

Since 1995 the glacial and periglacial geomorphology of the Serra da Estrela are being studied by VIEIRA and FERREIRA following the main methodological framework of the studies by VIDAL-ROMANI *et al.* (1990) and FERREIRA *et al.* (1992) in the Serra do Gers (NW Portugal). Research is based in a detailed geomorphological mapping, aerial photo-interpretation, location and recognition of the main deposits, laboratory analysis of the sediments and data integration, handling and analysis using a geographical information system and database management system.

The present paper synthesises the present-day knowledge on the Serra da Estrela glaciation. The main features of the glaciation are mainly based in the results of DAVEAU (1971). The research of the authors conducted up to now focus in the NE sector of the Serra da Estrela and especially in the Zzere valley. The new observations correspond still to poorly studied evidence and a more accurate sedimentological description and laboratory analysis, in order to interpret their geomorphological significance is going on. Therefore, many of the new observations presented here, correspond to yet unsolved problems and most of the interpretation is preliminary.

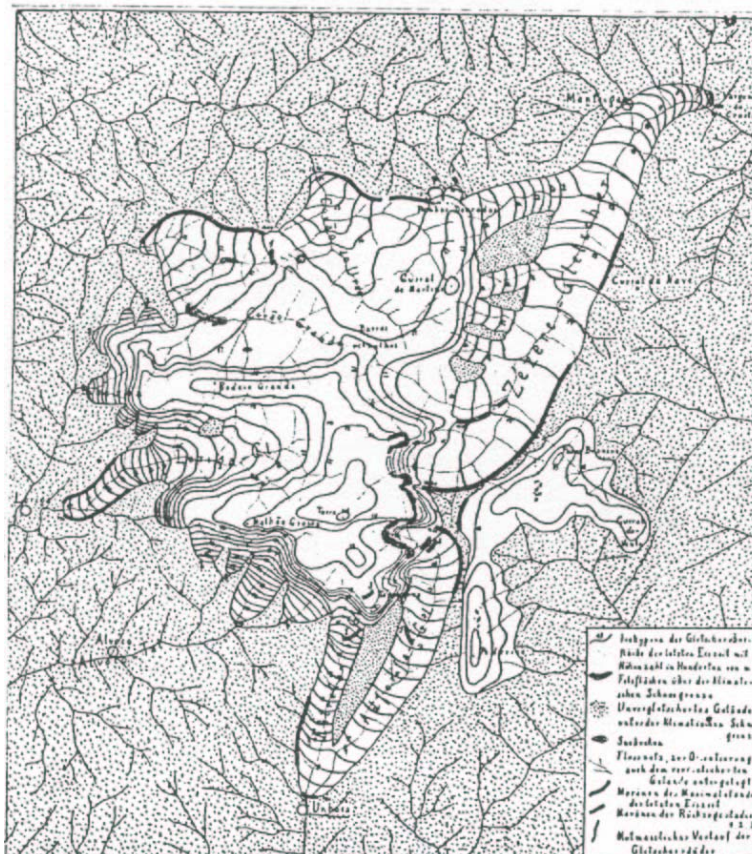


Figure 1 - The Serra da Estrela glaciation according to Hermann Lautensach (1929, 1932). Legend following the order in the figure: 1. Contours of the glacier surface; 2. nunataks; 3. lakes; 4. Post-glacial drainage; 5. Glacial maximum moraines; 6. Moraine of the retreat stages 1, 2 and 3; 7. probable glacier limit.

## 2. OVERVIEW OF THE SERRA DA ESTRELA GLACIATION

### 2.1 The glaciers

The Serra da Estrela glaciation is attributed to the Last Glacial Maximum, but absolute datings does not exist. This interpretation is supported in the good conservation of the moraine deposits and in the correlation with the western European glacial episodes.

The pre-existent morphology of the mountain largely controlled the glacier development (LAUTENSACH, 1932; DAVEAU, 1971). An ice-cap formed in the upper plateaus to the west of the Zêzere-Alforfa valleys between 1,993 and ca. 1,700 m asl and from it several valley glaciers diverged towards the lower parts of the Serra da Estrela (fig. 2). DAVEAU (1971) estimated a glaciated area of ca. 70 km<sup>2</sup> and 80 m thickness of ice in the Torre plateau. Lautensach and Daveau suggest that the Poios Brancos - Alto da Pedrice area, despite of its

high elevation (ca. 1,700-1750 m asl), did not present active glaciers, but a relatively thin and static snow (or ice) cover. This is supported by the conservation of tors, weathering mantle and absence of glacial deposits.

Daveau (1971) identified three types of valley glaciers:

- South and Southeast facing glaciers, which include the Estrela and Alvoco glaciers. These were small glaciers with 2.5 and 2 km length which stood hanging from the ice-cap in the southern part of the plateau at about 1,300 m asl;
- North and Northwest facing glaciers, including the Covão do Urso and Covão Grande glaciers, both ca. 6.5 km long, finishing at 1,050 and 970 m asl;
- the glaciers of the Zêzere, Alforfa and Loriga, with respectively, 13 km, 5.5 km and 7 km length, that terminated at much lower altitudes, between 680 m and 850 m asl, a fact mostly related to their lee position, which allowed a significant accumulation of snow.



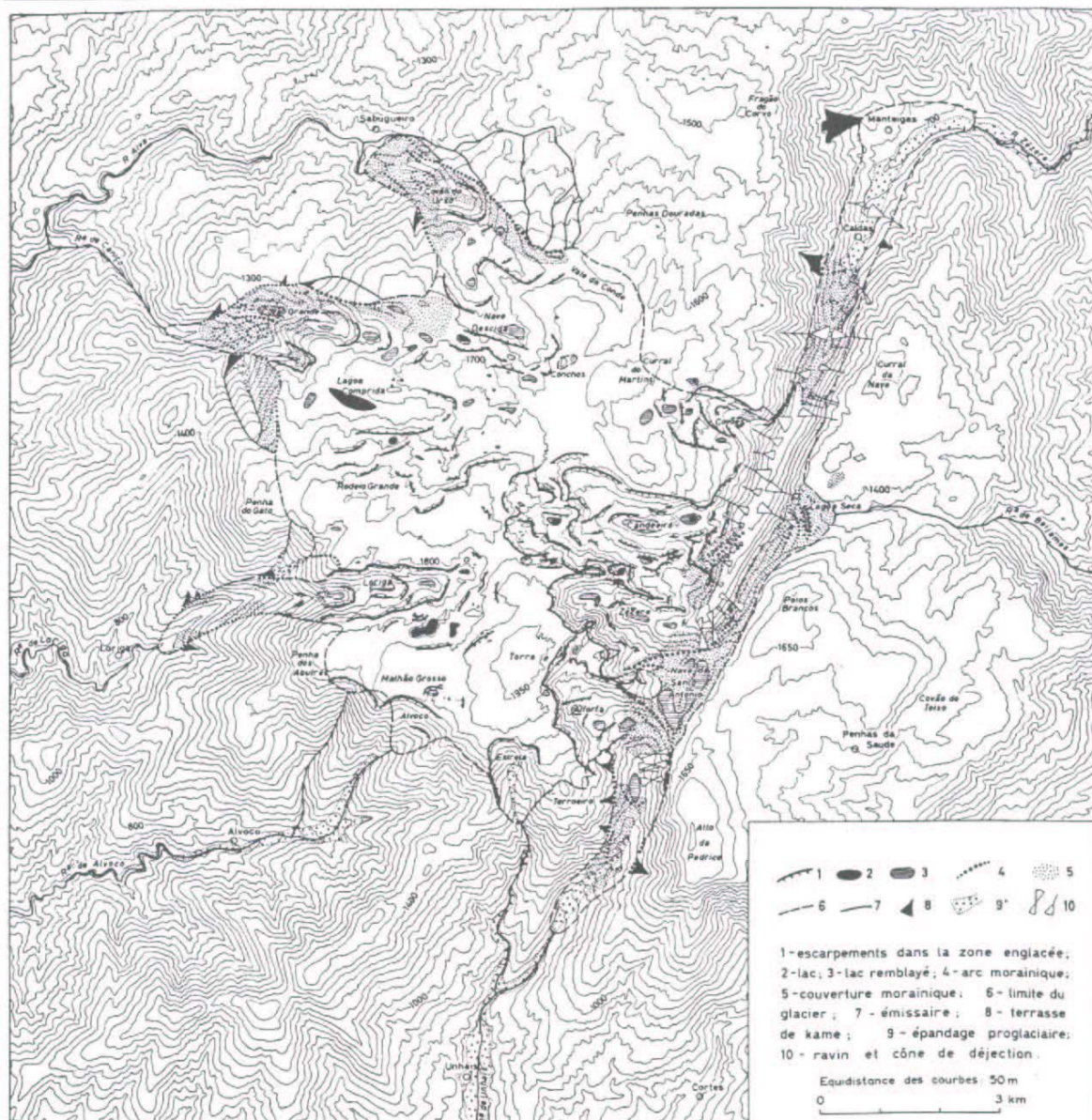


Figure 2 - The Serra da Estrela glaciation according to DAVEAU (1971). 1. Scarps in the glaciated area; 2. lake; 3. infilled lake; 4. moraine ridge; 5. moraine debris; 6. glacier boundary; 7. proglacial river; 8. kame terrace; 9. proglacial deposit; 10. creek and cone.

The west-east asymmetry that characterise the Serra da Estrela glaciation was attributed by LAUTENSACH (1932) to west wind action that caused snowdrift towards the Zêzere and Alforfa glaciers. DAVEAU (1971) supports this idea but also emphasises a north-south asymmetry related to the more important snowmelt in the southern slopes that must have occurred during Summer. Daveau also suggests that this asymmetry

reflects important Summer insolation, may be related to a Mediterranean climatic regime. During Winter the role of wind would be prevailing.

The low altitudes attained by the Zêzere, Alforfa and Loriga glaciers seems mostly related to the pre-glacial morphology that conduced a rapid glacier flow from the ice-cap towards lower areas.





Figure 3 - The 'U-shaped' sector of the Zêzere valley.

## 2.2 The erosion landscape

The distinction between glacial and non-glacial landscape is relatively easy in the Serra da Estrela. The areas affected by the glaciers are mostly characterised by bare-rock outcrops or only by a veneer of recently weathered granite. The area outside the glacier limits usually show a granite weathering mantle inherited from pre-Quaternary morphoclimatic conditions and a typical tor and Bornhardt granite morphology. This very obvious difference was used by Lautensach and Daveau for the definition of the maximum extent of the glaciers and has proved to be a very valuable method in the area, once the obtained results are usually confirmed by the more recently studied sedimentological evidence (DAVEAU *et al.*, 1997).

LAUTENSACH (1929, 1932) presented an interesting simplification of the Serra da Estrela landscape, which is influenced by this overall symmetry. Roughly four concentric areas with characteristic morphology were to be found:

- first, the 'roche moutonnées and erratics area' in the upper part of the mountain;
- second, the thin belt of lateral and end-moraines;

- third, the belt of 'bell-shape rocks and the boulder and pebble fields', described as equivalent to the transitional fluvio-glacial fans;
- fourth, the domain of the tors and castle-koppjes and 'weathered slopes'.

The glacial erosion forms appear especially above 1,300 m asl. Although, most of the glacial landscape results in fact from the glacial erosion on the existing pre-glacial relief, which still prevails. This is especially true in what respects to the plateaus that are pre-Quaternary, where the glaciers only caused minor erosion. In the plateaus, where slope is higher and the glaciers were more active, a knob and basin morphology appears. Small lakes and peat-bogs develop and in some areas a 'roche-moutonnée' morphology also appear (e.g. the Lagoa Comprida area).

It was along the valleys and steeper slopes that glacier flow was more active. Good examples of typical 'U-shaped' valleys exist along parts of the Alforfa, Loriga, Alva and Ribeira da Caniça valleys. The Zêzere valley has an almost perfect 'U-shape' and is considered an excellent example of a glacially sculpted valley (fig. 3). Its perfect form is due to an active and thick (more than 300 m) glacier, but moreover,

to a fragile and tectonised substratum related to the major Unhais da Serra - Bragança fault.

The typical glacial treads and risers are especially present in the upper parts of the valleys, with the best examples in the 'Covões' of the Loriga valley in the western slope of the Serra da Estrela, where a succession of glacial steps exist (fig. 2). Many of the treads are over-excavated and constitute basins occupied by lakes, especially where a well-developed riegel appears.. In the Serra da Estrela these basins are in many cases buried by the Holocene sediment deposition. Many of these sites were used for the construction of hydro-electrical dams (e.g. Covão do Ferro, Lagoa Comprida and Covão da Nave).

Cirques appear around the plateau and can be divided in two main types. The Zêzere valley head cirque, named locally Covão Cimeiro, is the best example of a simple cirque with a 850 m wide amphitheatre form and very steep and long walls (*ca.* 300 m). The Covão do Ferro cirque is also of this type, the same happening with other smaller cirques. The other type of cirques are more complex features. They are usually wider, not so steep and their complexity is related to the existence of smaller cirques, steps, knobs and basins in the interior of amphitheatres up to 2,300 metres wide. These cirques are generally in a transition position between the plateau and the valleys. Good examples of complex cirques appear in the Candieira, Covão do Boieiro and Covões.

In what concerns to small-scale features, they appear all over the erosion areas. Very nice examples of asymmetrical roches moutonnées appear in the Lagoa Comprida area. Nye-channels were found in the Covões cirque. Friction cracks, striations, glacial polished quartz veins and rock surfaces can be found especially in the treads and rieglers in the Covão do Boieiro, Covão do Meio, Covões and Candieira areas.

### 2.3 The accumulation features

The accumulation forms of glacial origin, especially the moraines are well-developed features in the Serra da Estrela. Daveau (1971) considers that their development is large when compared to the extent and probable duration of the glaciation. This is attributed to the significance of pre-glacial weathering, which

prepared the bedrock for glacial erosion and explains the importance of the morainic accumulations.

The moraines appear in distinct locations in the Serra da Estrela, but concentrate in the areas away from the dispersion centre in the Torre plateau. The maximum altitude of the lateral moraines was used by Lautensach (1929, 1932) and Daveau (1971) as an indicator of the snow-line during the glacial maximum, which was set to *ca.* 1,650 m asl.

The main moraine ridges are lateral moraines and they are still present in all the main glaciated valleys. The Covão do Urso lateral moraine with *ca.* 4,500 m length is the longest moraine in the Serra da Estrela and marks the northern limit of the ice-cap. Similar, but smaller is the Covão Grande moraine, with *ca.* 2,500 m. In the Lagoa Seca several moraine arcs (fig. 4) show that this col was a diffuence site of the Zêzere glacier and that the glacier had at least 300 metres thickness in this section of the valley. But the more impressive site in what respects to the morainic accumulations is the Nave de Santo António (fig. 5), a col where the Zêzere and Alforfa glaciers probably joined during the glacial maximum. There, it is possible to identify two moraine ridges from both glaciers and a complex boulder field, which still raises many unsolved problems.

DAVEAU (1971) was the first to identify the existence of kame terraces along the main valleys. These consist of hanging accumulations of non-sorted debris-flow deposits that accumulated against the main valley glaciers. Their hanging position and size make them easily observed both in the 1:25,000 topographical maps and aerial photos and allow, in the absence of lateral moraines, to identify the position of the valley glaciers. Very good examples of kame terraces are to be found in the Zêzere (fig. 6 and 7) and Alforfa valleys.

According to DAVEAU (1971), proglacial accumulations appear in the Zêzere, Alforfa and Alvoco valleys. They consist of accumulations of poorly sorted, boulders, cobbles and pebbles of rounded granite and are related with the melting of the glaciers. The best example are the Unhais da Serra terraces which following the author has deposits from the glacial maximum and from a later recession stage. The Zêzere valley near Manteigas also presents significant proglacial accumulations (fig. 8 and 7). Daveau



Figure 4 - The Lagoa Seca col with moraine accumulations that resulted from the Zêzere glacier diffluence. It is possible to see a small moraine-dammed lake, now almost completely infilled by post-glacial sediments.



Figure 5 - The Nave de Santo António col with the Poio do Judeu moraine and a complex boulder accumulation.





Figure 6 - The Covais kame terrace, first identified by DAVEAU (1971). The material accumulated against the Zêzere valley glacier and now is hanging in the slope above the valley floor.

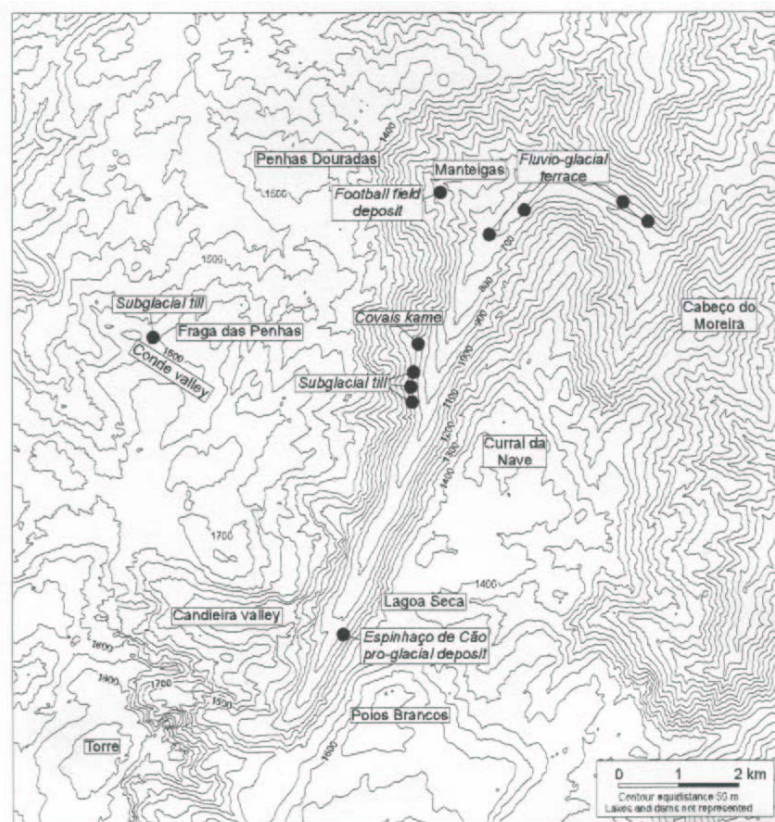


Figure 7 - Location of the main deposits mentioned in the text (Zêzere valley).



Figure 8 - Glaciofluvial terrace of the Zêzere glacier in Manteigas.

suggests that these are not related to the maximum of the Zêzere glacier, but to a stage when the glacier was stable near Caldas de Manteigas at an altitude of 850 m.

### 3. NEW OBSERVATIONS ON THE SERRA DA ESTRELA GLACIATION

Research that is being conducted in the Serra da Estrela since 1995 is in an early stage and several steps are still needed, especially in what concerns to the conclusion of the systematic geomorphological mapping and laboratory analysis of the sediments. Several new findings are worth mentioning.

#### 3.1. The Zêzere valley

The Zêzere valley is the best example of the effects of glacial morphogenesis in the Serra da Estrela. It had the longest valley glacier with *ca.* 13 km length, down to the Manteigas area (fig. 2). The preliminary field survey, followed by the aerial photo interpretation, systematic detailed geomorphological mapping at a scale 1:10,000 and study of the deposits, is allowing the

identification of new evidence concerning the glacial history of the valley.

The problem of the maximum extent of the Zêzere glacier, which has been a subject of debate for a long time is still unsolved. The high gradient of the slopes in the Manteigas area and the importance of fluvial erosion in the valley make the moraine and sediment conservation very difficult. The scarcity of geomorphological elements is in fact the main reason for the debate that is going on for several decades.

##### 3.1.1. *The Manteigas football field deposit*

Hermann Lautensach (1932) defined the maximum glacier extent to be located near São Gabriel, 2 km downvalley from Manteigas at an altitude of 650 m. This was also what Cabral (1884) had thought, based on deposits he interpreted as a subglacial moraine. DAVEAU (1971, 1973) has shown that those deposits were periglacial and indicated the glacier limit some 1 km upvalley at 680 m asl. This assumption was based on the existence of a coarse and poorly-sorted deposit (fig. 9 and 7) probably related to debris-flow phenomena in the left slope of the valley, near the Manteigas football field, at an altitude of 900 m (fig. 9). The slope position of





Figure 9 - Manteigas football field deposit (Zêzere valley).

the deposit, hanging over the valley bottom, led Daveau to interpret it as a kame terrace of genesis similar to others that appear upvalley.

DAVEAU *et al.* (1997) rise some questions concerning this interpretation. Without a detailed sedimentological study and geomorphological mapping, it is difficult to accurately define the existence or not of a relationship between the 'football field deposit' and the glacier itself. Field observations suggest that the deposit is part of a more complex fan, probably of debris-flow origin. The accumulation of the material in a slope position may be possible without a glacier blocking the sediment transport, once in this part of the slope there exists an erosion level, which may have favoured the accumulation.

### 3.1.2. The subglacial tills of the Zêzere valley

Recent investigations have also stressed on the existence of several diamicton outcrops with a facies very similar to the ones of the Serra da Gerês, for which a glacial origin has been proved through laboratory analysis (VIDAL ROMANI *et al.*, 1990). These diamictons are granitic origin

deposits, non-sorted, silty-sandy, with gravel and very compacted. They are probably sub-glacial lodgement tills (DAVEAU *et al.*, 1997). Several diamicts of this kind were found in exposures all over the Zêzere valley upvalley from Manteigas in variable slope positions and altitudes (fig. 7). The exposures found between Lameiro do Grilo and Caldas de Manteigas between 1,050 and 1,085 m asl indicate that the glacier in the Lameiras area was at least 200 m thick (DAVEAU *et al.*, 1997). Furthermore, these deposits support the interpretation proposed by DAVEAU (1971) for the Covais accumulation - a kame terrace.

### 3.1.3 The lateral moraine of the Zêzere glacier in Fonte Santa

Another very recent finding in the Zêzere valley that is important for the definition of the end of the Zêzere glacier, is a well-preserved lateral moraine up-slope of Fonte Santa, *ca.* 1 km upvalley from Manteigas. The moraine has an height of 3-5 m where it is better preserved at appears inside a small forest area in the right slope of the valley. Its location inside the forest

area may be the cause for the lateness of its finding. Its existence was suggested by the 1:15,000 stereoscopic aerial photo interpretation and later confirmed in the field. It appears in the upvalley continuation of a small kame-terrace indicated by DAVEAU (1971) and therefore also confirms its genesis.

The finding of the moraine is important because it is located in a low slope position, indicating that the Zêzere glacier reached a location about 1 km upvalley from Manteigas. Furthermore, the moraine geometry seems to be in relation with the location of the Covais kame terrace, indicating a stability position of the glacier front. The presence of slope tors in the right slope downvalley from this site makes it difficult to point for a longer glacier. Yet another possibility is that a weathering mantle could have been preserved subglacially from glacier erosion and that the slope tors are post-glacial forms.

#### *3.1.4. The glaciofluvial deposit of Manteigas (Zêzere valley)*

An important type of glacial deposit found in the Serra da Estrela are the proglacial complexes - figure 8 (DAVEAU, 1971). During fieldwork in the area of Manteigas several exposures of the Zêzere proglacial complex of glaciofluvial origin were found (fig. 7). These exposures evidence a coarse deposit of rounded cobbles and boulders with a coarse sandy matrix, with imbrication fabric and a typical glacio-fluvial structure. The complex appears in several sites, in erosive terraces about 2 meters higher than the present valley floor (this corresponding to a minimum of the post-glacial fluvial erosion in the site).

The deposit must have been continuous forming a valley train from the Santo André area (Manteigas) at least down to the Leandres valley. In the latter site a periglacial scree covers the glaciofluvial terrace. This and other recent observations may give us some information on the relationships between glacial and periglacial evolution.

#### *3.1.5 The Espinhaço de Cão complex (Zêzere valley)*

Apart from several recently discovered moraine ridges of small size, significant findings

took place near the Espinhaço do Cão moraine, just below the Candieira hanging valley (fig. 7). The Espinhaço do Cão is a very well preserved lateral moraine presumably of the Zêzere glacier and corresponding to a late glacial stabilisation phase.

The deposits that are worth mentioning appear in the opposite slope from the Espinhaço de Cão, some 10 m above the valley floor. It is a sedimentary complex probably related to a recessional stage of the Zêzere glacier after the Espinhaço de Cão stage. The deposits are characterized by horizontal or sub-horizontal layers of poorly sorted coarse sand and granules, intercalating with silty and sandy layers. These seem to correspond to a valley train environment marked by recessions and small advances of the glacier. The sediments are glacio-fluvial, with layers of flow-till and even compact sub-glacial till. But these observations are still preliminary and a systematic study of the complex is to be done. Furthermore, the presence of a peat layer in the lower part of the complex gives us some hope on obtaining absolute datings for the complex. It would be the first dating on the glaciation of the Portuguese mountains.

#### *3.2 The Cerro Rebolado - Fraga das Penhas area (Penhas Douradas plateau)*

The Cerro Rebolado - Fraga das Penhas area is very interesting in a geomorphological perspective. Besides its significance in what concerns to present-day processes it presents also important evidence on the Pleistocene glacial dynamics of the Serra da Estrela. The area marks a very clear geomorphological limit between the glaciated plateaus to the south and the glacier free areas, to the north. This difference is sharply defined in the landscape, with a typical granite morphology related to differential weathering with tors and castle-koppjes to the north, and a tor free area to the south. The limit of the plateau glacier is coincident with the Fraga das Penhas - Cerro Rebolado ridge, where a huge linear boulder field corresponding to a moraine exists. This moraine is in fact the eastern extension of the Covão do Urso lateral moraine (DAVEAU *et al.*, 1997) and marks the flow towards the west of the glacier that was channelled along the Conde valley.





Figure 10 - The Cerro Rebolado till.

However, the most striking geomorphological feature is an exposure *ca.* 150 m long showing a regressive sequence of the Conde valley glacier (fig. 10). The exposure appears in a south-north oriented artificial gully that transports the outflow water from a small dam in the Conde valley. It is the major and more complex till found up to date in the Serra da Estrela. The deposit presents roughly three sedimentary units.

The lower unit, visible in the northern part of the gully presents the characteristics of a subglacial lodgement till. It is a very compact diamict, in some places sandy-silty and in others more coarse-grained. In some sectors stratified sand lenses related to subglacial melting appear. In places, the sand lenses are deformed may be due to ice-margin glaciotectionic processes. Silt and clay injections in fractures in the granite substratum are present in parts of the gully.

The intermediate unit is a coarser and poorly consolidated diamict. It presents no organised structure and is constituted by cobbles and boulders with a sandy matrix. It is interpreted has a supra-glacial till deposited during glacier recession.

The upper unit present all over the exposure is a gyttja-type deposit, an organic rich sandy

accumulation, with some stratification. Its genesis is probably related to the snowmelt and runoff dynamics. It is a typical Holocene deposit in the Portuguese granitic mountains. Above this unit a humic soil develops, corresponding to a recent mountain ranker. Towards the south of the exposure, the upper horizon becomes more humic related to the low energy environment of the Conde valley where some peaty layers appear. The small plain of the Conde valley, with abundant herbaceous vegetation and seasonal flooding corresponds to a post-glacial sediment filling.

The discovery of the Cerro Rebolado complex is very recent and a detailed sedimentological study is to be carried in the near future. The main objectives are to fully map and describe the exposure, determine its implications in what concerns to the glacial history of this part of the mountain and to obtain absolute datings.

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