

Combined numerical and geomorphological reconstruction of the Serra da Estrela plateau icefield, Portugal

Gonalo Vieira *

Centro de Estudos Geogrficos, Universidade de Lisboa, Faculdade de Letras, Alameda da Universidade, 1600-214 Lisboa, Portugal

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Abstract

The paper focuses on reconstructing a plateau icefield surface from field geomorphological data and a physical-based glacier model. The results allow the analysis of the patterns of glacial erosion and the estimation of the palaeo-Equilibrium Line Altitudes (ELA). The study area is the Serra da Estrela, a plateau in Central Portugal rising to ~2000 m ASL. The glaciated area during the Last Maximum of the Serra da Estrela Glaciation (LMGSE) was ~66 km². The reconstruction of the topography of the icefield and valley glaciers in the LMGSE is based on the Schilling and Hollin model. It iterates along the valley longitudinal profile and is based on the gradient, on valley-shape indices and on yield basal shear stresses. These variables influence ice thickness and therefore, also the slope of the ice surface allowing for its reconstruction. The key variable is basal yield shear stress and its value was included in the model manually starting from the points of maximum extent of the valley glaciers and following a range known to occur in contemporary conditions. The input values are validated by matching the resulting ice surface to geomorphological features. Where these are absent, a constant value of 100 kPa was used. The icefield was reconstructed from a radiating set of long-sections, along which ice thicknesses were calculated. A DEM of the ice surface was constructed, allowing the estimation of the hypsometric curves of the distinct glacier catchments and the calculation of the palaeo-ELAs. The results show a regional ELA at 1650 m ASL with spatial variations across the icefield reflecting mainly the effect of eastward snow drift. The LMGSE glaciers were very sensitive to minor climatic changes, especially due to the large area of the plateau icefield, and to the positioning of the ELAs, close to, or in the, flat part of the hypsometric curve. The model of the ice surface is of significant value for the analysis of the patterns of glacial erosion at the landscape level. In the Serra da Estrela most of the glacial erosion occurred near the plateau margins and in valley heads, where glacier surface slope was steeper allowing for a faster ice flow and where ice flow concentrated. Strong glacier erosion in the Z zere valley is linked to the tectonic setting, but also to the confluence of glaciers and to the overfeeding of snow from the plateau.

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1. Introduction

Equilibrium Line Altitudes (ELA) of glaciers are particularly sensitive to changes in summer temperature and winter precipitation (Ohmura et al., 1992; Paterson, 1994; Nesje and Dahl, 2000). The accurate estimation of the ELA is therefore of major importance for

* Tel.: +351 217940218, fax: +351 217938690.

E-mail address: gtvieira@ceg.ul.pt.

palaeoenvironmental reconstruction. Several empirical studies show a correlation between temperature and precipitation at the ELA in present-day glaciers and therefore knowing one of the variables it may be possible to estimate the other (Lowe and Walker, 1997).

Plateau icefields are glaciers showing topographic control on ice flow and develop on generally flat surfaces limited by steep slopes. If the former ice cover was cold-based the geomorphic signature of palaeo-icefields can be subtle or non-existent (Rea and Evans, 2005). The lack of glacial geomorphic evidence in plateau areas has led to misinterpretations of glacier extension in some regions and consequently to problems in the estimation of palaeo-ELAs (e.g. Sissons, 1980). Plateau icefields have been an issue of new interest in the geomorphological and glaciological literature and are treated in detail by Rea and Evans (2005). The development of physical models for ice surface reconstruction enables us to determine ice thicknesses in areas where geomorphological information is lacking. This allows analysis of the influence of glacier characteristics on erosional landforms, offering new insight into the issue of glacial landscape evolution.

Ice sheets and ice caps react slowly to climate change in comparison to small mountain glaciers that tend to react quickly, even to small oscillations. Small mountain glaciers located near the glaciation limits are therefore good indicators of regional climate change. In the case of plateau icefields with the ELA lying on the plateau, the climate sensitivity becomes even greater. This is due to the fact that small altitudinal changes in the ELA may result in a significant modification to the relative sizes of the accumulation and ablation areas. The consequences may result in rapid retreat or advance of valley glaciers fed by the icefield (Sugden and John, 1976). Therefore, it is important to accurately define the hypsometry of the plateau icefields and to distinguish them from simple valley glacier systems in order to model correctly the palaeo-ELAs and their climatic sensitivity (Rea and Evans, 2005).

Rivera and Casassa (1999) have studied the Pio XI glacier in the South Patagonian Icefield comparing the hypsometric curve of the glacier surface with the recent changes in the ELA. They showed that these changes occurred in the steepest part of the curve, but that in the next years the increase in the ELA will start to affect the plateau area of the glacier, with significant implications for the mass balance. This type of analysis can only be performed accurately when the glacier topography is known in detail. In the case of plateau icefields that lack geomorphic evidence for ice thickness, the application of physical-based models for glacier surface reconstruction is the best approach for ELA estimation.

In this paper, the plateau icefield of the Serra da Estrela is reconstructed using the 2D model developed by Schilling and Hollin (1981) and data from field geomorphological surveying. The application of the model along individual flow lines enabled the identification of multiple ice surface profiles that were interpolated according to topography and geomorphic evidence in the valleys. Similar approaches were conducted with success by Locke (1995) in the American Rockies, McDougall (1995) in Scotland and by Evans et al. (2002) in northern Norway. In this study a digital elevation model (DEM) of the glacier surface was obtained allowing for the estimation of the ELAs in the different catchments. Plotting the ELA over the hypsometric curve allowed the evaluation of the climatic sensitivity of the Estrela glaciers.

The modelling approach links geomorphological observations to physical-based models and is very robust since it enables result validation in the valley sections where palaeo-ice thicknesses are known. The model outputs arise from a linkage between geomorphological and glaciological techniques, with outcomes useful for both these disciplines, but also for palaeoclimatological purposes. It is worth noting that the ice surface reconstruction originates from a significant amount of data arising from geomorphological observations at the landscape level, but that it also provides new insight into the patterns of erosion inside the plateau icefield. This is not circular reasoning, since inputs are solely the external limits of the icefield, while the outputs are areal, enabling the spatial analysis of the distribution of landforms that were not inputs for the model (i.e. comparing the modelled ice thicknesses and basal shear stresses with the patterns of glacial erosion).

2. Regional setting

The Serra da Estrela is a granite mountain in Central Portugal showing a plateau that rises to 1993 m ASL (Fig. 1). The mountain range is part of the Iberian Central Cordillera and is limited by two steep fault scarps with a relative relief of over 1000 m. The Serra da Estrela is an important condensation barrier to the moist air masses from the Atlantic that enter the Iberian Peninsula from the west. The upper area shows two plateaus, divided by the NNE–SSW tectonic lineament of the Zêzere and Alforfa valleys. The western plateau is the highest at 1400–1993 m ASL, while on the eastern plateau altitudes stay below 1750 m.

The general geomorphological characteristics of the Weichselian glaciation of the Estrela are well-known but a glacial chronology is lacking. Cabral (1884) was the first to show the occurrence of glacial features in the

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