1 2 9 0 UNIVERSIDADE DE COIMBRA

Photo by Sérgio Brito

10th IAG INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY

COIMBRA - PORTUGAL

« GEOMORPHOLOGY AND GLOBAL CHANGE »

FIELDTRIP GUIDEBOOK

The Estrela UNESCO Global Geopark: from planation surfaces to glaciations

17-19 September 2022

Gonçalo Vieira
Emanuel de Castro
Fábio Loureiro

Coimbra, 2022

Gonçalo Vieira
Emanuel de Castro
Fábio Loureiro

10th International Conference on Geomorphology Fieldtrip Guidebook – The Estrela UNESCO Global Geopark: from planation surfaces to glaciations

17-19 September 2022

Coimbra, 2022

Edition notice:

Title: *10th International Conference on Geomorphology. Fieldtrip Guidebook – The Estrela UNESCO Global Geopark: from planation surfaces to glaciations*

Authors: *Gonçalo Vieira (University of Lisbon), Emanuel de Castro (Estrela Geopark) and Fábio Loureiro (Estrela Geopark)*

Fieldtrip guided by: *Gonçalo Vieira (University of Lisbon), Emanuel de Castro (Estrela Geopark) and Fábio Loureiro (Estrela Geopark)*

Edition: *Universidade de Coimbra, Faculdade de Letras*

Fieldtrip and Guidebook Coordination: *António Vieira (University of Minho)*

Cover: *Zêzere glacial valley (photograph by António Vieira)*

ISBN: *978-972-95222-9-1*

Introductory Note

The 10th International Conference on Geomorphology will take place in Coimbra (Portugal) from 12th to 16th September 2022, under the theme "Geomorphology and Global Change" and it is organized by the International Association of Geomorphologists (IAG) and the Portuguese Association of Geomorphologists (APGeom).

As in previous international conferences on Geomorphology, and as is the tradition in many geomorphological events organized around the world, the organizing committee of the 10th International Conference on Geomorphology proposed several fieldtrips to the participants, occurring before, during and after the main event.

These fieldtrips intend, above all, to show to geomorphologists from all over the world the diversity and richness of the geomorphological elements of the Portuguese territory (and also from Cape Verde) and to allow an exchange of experiences between the specialists that investigate these territories and the visitors, contributing for mutual scientific enrichment and for the valorization of this international conference.

The pre-conference fieldtrip is dedicated to the islands of Santiago and Fogo, in the Archipelago of Cape Verde. It will take place from 6th to 9th September and will be led by colleagues from the University of Cape Verde (Vera Alfama, Sónia Victória, Sílvia Monteiro, José Maria Semedo and Romualdo Correia). The volcanic geomorphology will dominate the visit (including well conserved structural volcanic forms such as cones, domes, craters and calderas), especially in the island of Fogo where recent volcanic activity has been registered.

The one-day mid-conference fieldtrips will take the visitors around the Portuguese mainland territory, the 14th September, allowing the visit of four different geomorphological realities.

In the Arouca UNESCO Global Geopark, internationally recognized territory since 2009, participants will be able to visit unique geological and geomorphological features (such as planation surfaces, bowl-shaped valleys and narrow river valleys) and witness the remarkable effort of protection and promotion of natural (abiotic and biotic) and cultural (tangible and intangible) heritage. The visit to the “516 Arouca” suspension bridge will be an excellent opportunity to observe the magnificent landscapes of this mountainous territory. This fieldtrip will be led by Artur A. Sá, António Vieira and Daniela Rocha.

The field trip to coastal areas of central Portugal will be led by Pedro Dinis and António Campar Almeida. Their proposal is to observe the different morphotectonic units of central west Portugal, namely the Coastal Mountain of Serra da Boa Viagem (revealing karstification features), the littoral plain (with aeolian dunes associated with some reliefs with higher elevation), the Cértima subsiding area (structurally-controlled morphology), and the Buçaco region (with the Syncline of Buçaco).

The visit to the Schist Mountains of Central Portugal will be centered in the mountains of Lousã and Açor, and will be conducted by Luciano Lourenço and Bruno Martins. It is proposed the observation of the main contrasts of the landscape, especially in terms of its physical geography, translated into geological, hypsometric, geomorphological, and hydrographic differentiation, or the land use and occupation and evolution of vegetation cover, namely following the recurrent large forest fires and the subsequent erosive processes they caused.

The fourth one-day fieldtrip will be oriented to the Estrela UNESCO Global Geopark, and led by Gonçalo Vieira, Emanuel Castro and Fábio Loureiro. The main geoheritage significance of the Estrela UGGp is the extent and richness of the Late Pleistocene glaciation(s) landforms and deposits (with spectacular morphological features such as the Zêzere glacial valley or the glacial cirques, moraine boulders, erratics or *roches moutounnées*) as well as the peculiar long-term geological evolution (revealing a significant diversity of granite types and landforms).

The three post-conference fieldtrips include a visit to the Lisbon Region, Serra da Estrela and, finally, Minho and Galicia (Spain), and will take place from 17th to 19th September.

The fieldtrip to the Lisbon Region will be guided by José Luís Zêzere, César Andrade, Sérgio Oliveira, Jorge Trindade and Ricardo Garcia, and will cover topics related with slope instability and landslides that affect the region of Lisbon, the floods occurring in the area north of Lisbon, and the coastal dynamics, morphology, cliff instability and beach erosion at north and south of Lisbon.

The three days field trip to the Serra da Estrela is led by Gonçalo Vieira, Emanuel Castro and Fábio Loureiro. Participants will be taken to visit some of the Geopark's most inaccessible geosites and observe breathtaking landscapes during two hikes: one in the Zêzere valley and the other between Penhas Douradas and Lagoa Comprida. The different geosites to visit include features of glacial, periglacial, granite weathering, fluvial, hydrogeological, petrological and tectonic themes, and aspects related with the management of a UNESCO Global Geopark will be discussed.

The third three-days fieldtrip is destined to the northwestern part of Portugal and the Spanish region of Galicia. Guided by Alberto Gomes and Antonio Perez Alberti, will be mainly devoted to the coastal area and to the observation and discussion of issues related to coastal dynamics, marine terrace staircases, differential uplift of coastal blocks, coastal geoheritage, coastal geoarchaeology, coastal erosion and coastal land planning.

It is our expectation that these visits will please all participants and promote the scientific enrichment of all involved, allowing a better understanding of the topics covered in each one.

We also hope that this set of fieldtrip guidebooks can help in the understanding of the themes discussed and that they can be a testimony of the commitment and dedication shown by all the scientific responsible for the several visits, to whom the organizing committee of the International Conference on Geomorphology expresses its greatest recognition and gratitude.

have a good fieldtrip!

Lúcio José Sobral da Cunha
António Vieira

on behalf of the ICG2022 Organizing Committee

ITINERARY AND SCHEDULE

Itinerary

Day 1

08:00 Departure from Coimbra (Largo D. Dinis) (Fig.1)

Stop 1 – Folgosinho

Stop 2 – Linhares da Beira

Stop 3 – - Videmonte

Stop 4 – Quinta da Taberna

Overnight in Manteigas

Day 2

Stop 1 – Hike from Penhas Douradas to Lagoa Comprida (all day)

Stop 2 – Sabugueiro

Overnight in Manteigas

Day 3

Stop 1 – Barroca d'Água – Zêzere valley (easy hike - 2h30)

Stop 2 – Covão da Ametade

Stop 3 – Piornos

Stop 4 – Covão do Boi

Stop 5 – Alto da Torre

Stop 6 – Salgadeiras

18:00 - Return to Coimbra

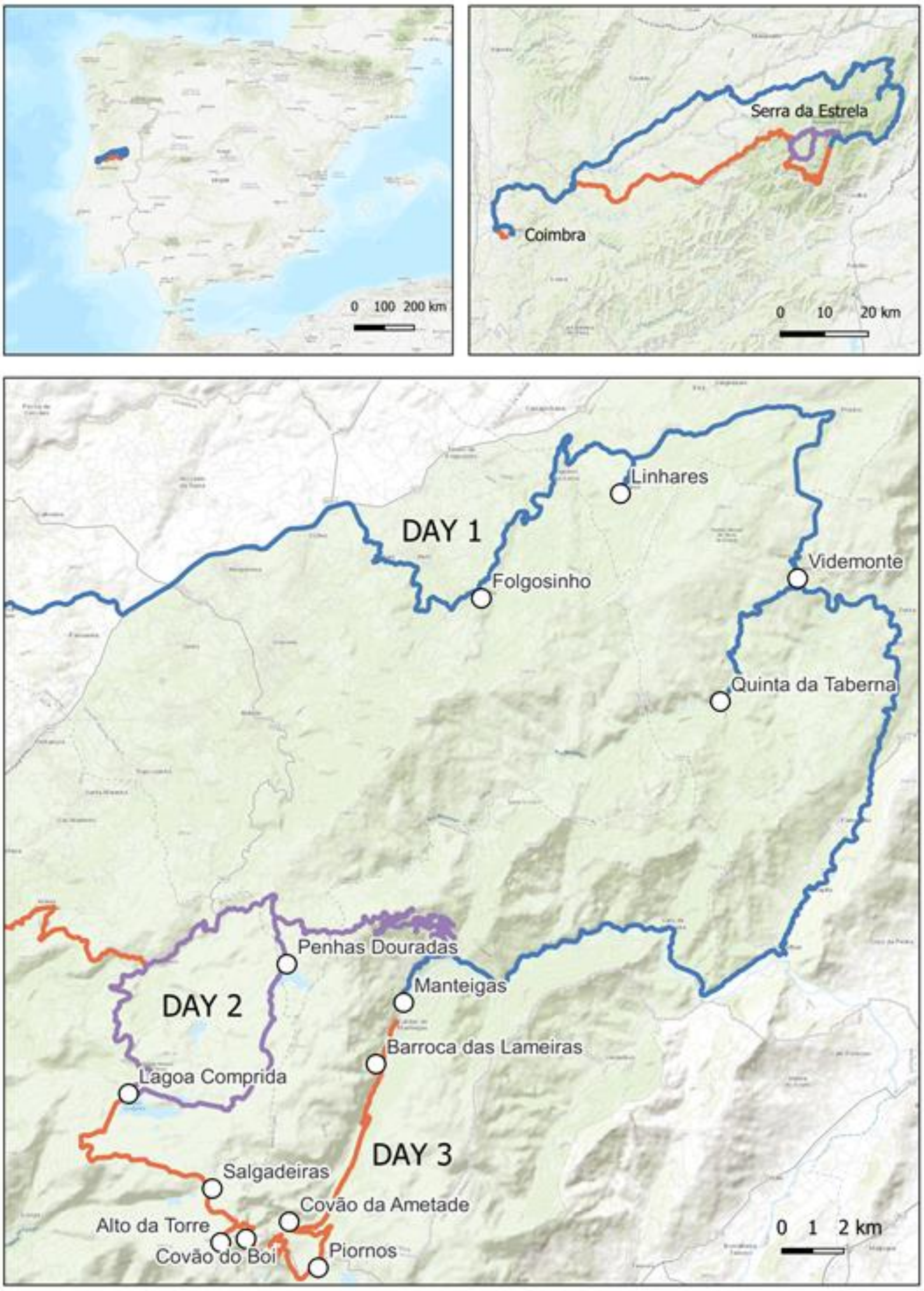


Figure 1. Itinerary of the field trip to the Serra da Estrela.

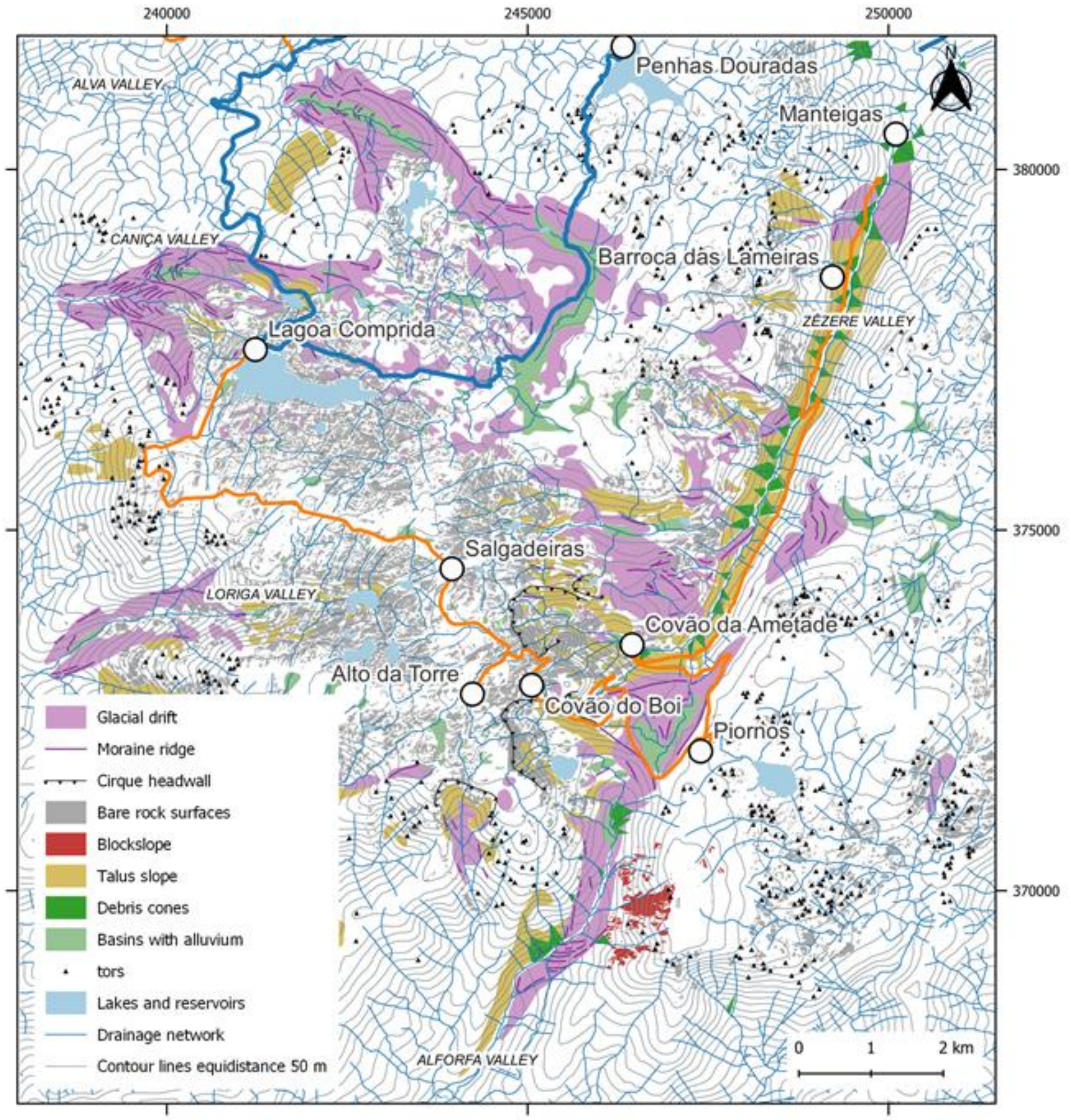


Figure 2. Glacial geomorphology of the Central area of the Serra da Estrela and itineraries in days 2 and 3.

1. The geology and geomorphology of the Serra da Estrela

1.1. Introduction

The Estrela UNESCO Global Geopark (Estrela UGGp) is located in Central Portugal and is part of the Iberian Central System, a mountain range that extends from Guadarrama, north of Madrid, to Montejunto, northeast of Lisbon. The Serra da Estrela is the highest mountain in mainland Portugal, rising to 1993 m a.s.l. at Alto da Torre, but the Estrela UGGp is a larger and encompassing area. Its boundaries include the major elements of the geology that contributed to the present-day landforms, but also to reflect how geology shaped the human nature of the Estrela inhabitants and the regional socio-economy (Fig. 3). The Estrela UGGp integrates the Estrela mountain range from its SW limits at the border with the Açor mountain, to the NE contact with the Meseta surface, as well as the piedmont regions that bound the Estrela to the NW and SE and where, for millennia humans lived in an intimate relationship with the mountain and with what it had to offer (Fig. 4).

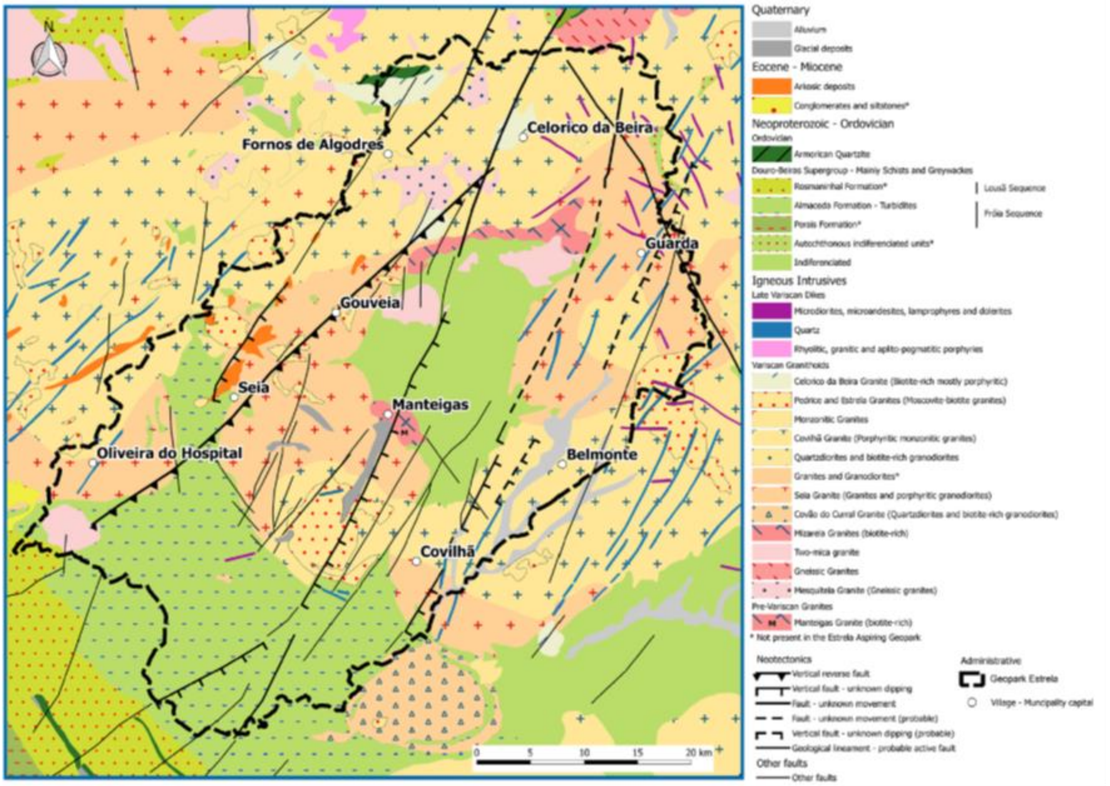


Figure 3. Geology of the Estrela UNESCO Global Geopark (based on Geological Map of Portugal 1:500.000).

The main geological originality of the Estrela UGGp is the breadth and richness of the Late Pleistocene glaciation(s) landforms and deposits, of high pedagogical and scenic values and with a remarkable scientific value, when considering the geographical position at the SW limit of Europe. However, the glaciation and geodiversity of the Estrela UGGp would not have been possible without the peculiar long-term geological evolution from the distant past to the recent landscape evolution (Table I).

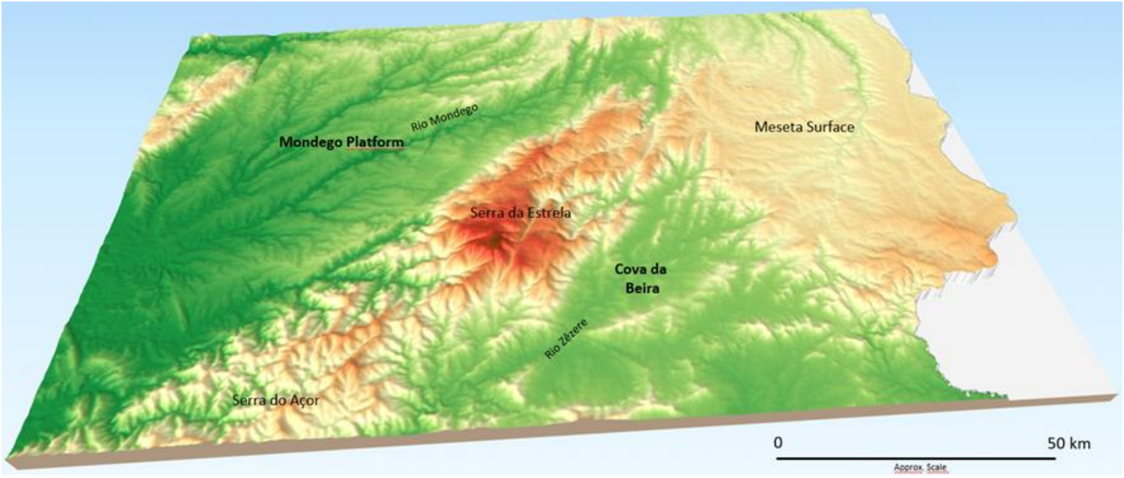


Figure 4. Overview of the Serra da Estrela topography from south to north. The Estrela rises to almost 2000 m asl and the Mondego platform averages 400-500 m asl.

1.2. The Variscan orogen heritage: a precursor of the present-day dynamics

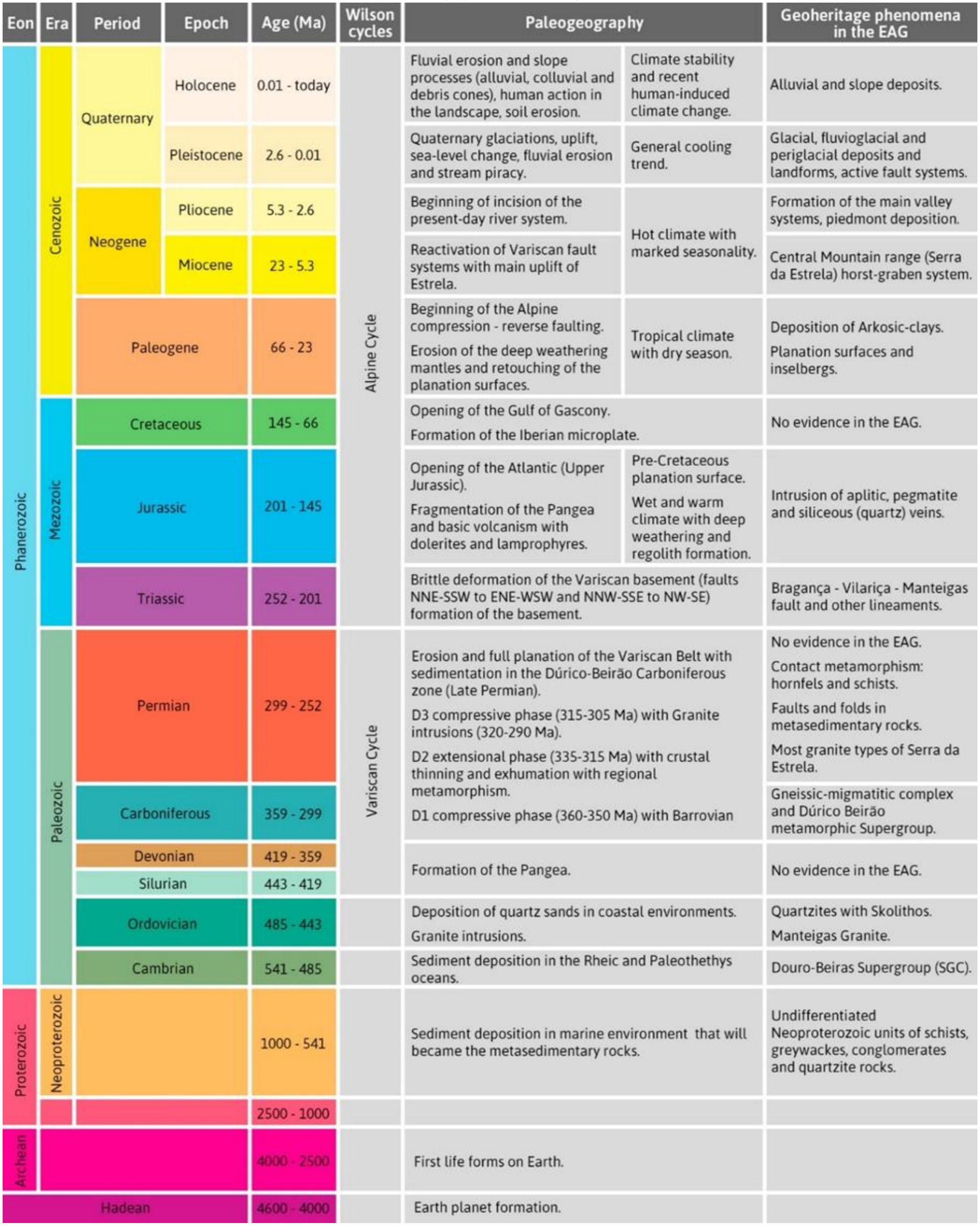
After over 270 million years, the Variscan orogeny still shows a significant imprint in the geology of Western Iberia and jointly with the effects of Paleogene planation and Alpine tectonics, is responsible for the major features of the large-scale morphostructures and hence, for the major patterns of ecosystems, history and cultural heritage in Central Portugal.

The Estrela UGGp is located in the Central Iberian Zone (CIZ), which represents in the tectonic and paleogeographic zoning of the Iberian Peninsula, the axial zone of the Variscan orogen. This large scale orogen resulted from continental collision after the opening and subsequent closing of the Rheic and Paleothethys oceans (Ribeiro, 2013), within the context of a passage from an active continental margin (Late Precambrian) to a continental collision (Martínez-Catalán *et al*., 2009). The resulting amalgamation of the continental masses of Laurentia, Baltica and Gondwana gave origin to the Pangea supercontinent.

In Iberia, the Variscan basement is named Iberian or Hesperian Massif and due to its paleogeographic setting is a key sector in the definition of the Palaeozoic peri-Atlantic orogens (Ribeiro, 2013). At the end of the Palaeozoic, Iberia occupied a position at the junction of the Appalachians (to the SW), the Caledonides (to the NW) and the Variscan (to the NE) (Martínez-Catalán *et al*., 2009). Today, the Iberian Massif is present in most of the Western part of the Iberian Peninsula, with the tectono-stratigraphic model of Jullivert *et al*. (1974)(Fig. 5) dividing it into five broadly parallel zones following the Variscan structures:

- The Cantabrian and the South Portuguese zones are the external zones of the Iberian Variscan belt, with well-developed upper Palaeozoic sedimentary sequences, low-grade metamorphic and scarce sin-orogenic granite intrusions. The former is a Gondwanan overthrust foreland belt, while the later initially developed as a foredeep basin and later as an accretionary complex (Martínez-Catalán *et al.*, 2009).

Table I. Synthesis of the geological history of the Estrela UNESCO Global Geopark (EAG in the table) (AGE, 2017).



Eon	Era	Period	Epoch	Age (Ma)	Wilson cycles	Paleogeography		Geoheritage phenomena in the EAG
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01 - today	Alpine Cycle	Fluvial erosion and slope processes (alluvial, colluvial and debris cones), human action in the landscape, soil erosion.	Climate stability and recent human-induced climate change.	Alluvial and slope deposits.
			Pleistocene	2.6 - 0.01		Quaternary glaciations, uplift, sea-level change, fluvial erosion and stream piracy.	General cooling trend.	Glacial, fluvioglacial and periglacial deposits and landforms, active fault systems.
		Neogene	Pliocene	5.3 - 2.6		Beginning of incision of the present-day river system.	Hot climate with marked seasonality.	Formation of the main valley systems, piedmont deposition.
			Miocene	23 - 5.3		Reactivation of Variscan fault systems with main uplift of Estrela.		Central Mountain range (Serra da Estrela) horst-graben system.
		Paleogene		66 - 23		Beginning of the Alpine compression - reverse faulting. Erosion of the deep weathering mantles and retouching of the planation surfaces.	Tropical climate with dry season.	Deposition of Arkosic-clays. Planation surfaces and inselbergs.
	Mezozoic	Cretaceous		145 - 66		Opening of the Gulf of Gascony. Formation of the Iberian microplate.		No evidence in the EAG.
		Jurassic		201 - 145		Opening of the Atlantic (Upper Jurassic). Fragmentation of the Pangea and basic volcanism with dolerites and lamprophyres.	Pre-Cretaceous planation surface. Wet and warm climate with deep weathering and regolith formation.	Intrusion of aplitic, pegmatite and siliceous (quartz) veins.
		Triassic		252 - 201		Brittle deformation of the Variscan basement (faults NNE-SSW to ENE-WSW and NNW-SSE to NW-SE) formation of the basement.		Bragança - Vilariça - Manteigas fault and other lineaments.
	Paleozoic	Permian		299 - 252	Variscan Cycle	Erosion and full planation of the Variscan Belt with sedimentation in the Dúrico-Beirão Carboniferous zone (Late Permian). D3 compressive phase (315-305 Ma) with Granite intrusions (320-290 Ma). D2 extensional phase (335-315 Ma) with crustal thinning and exhumation with regional metamorphism. D1 compressive phase (360-350 Ma) with Barrovian		No evidence in the EAG. Contact metamorphism: hornfels and schists. Faults and folds in metasedimentary rocks. Most granite types of Serra da Estrela.
		Carboniferous		359 - 299				Gneissic-migmatitic complex and Dúrico Beirão metamorphic Supergroup.
		Devonian		419 - 359		Formation of the Pangea.		No evidence in the EAG.
		Silurian		443 - 419				
		Ordovician		485 - 443		Deposition of quartz sands in coastal environments. Granite intrusions.		Quartzites with Skolithos. Manteigas Granite.
		Cambrian		541 - 485		Sediment deposition in the Rheic and Paleothethys oceans.		Douro-Beiras Supergroup (SGC).
Proterozoic	Neoproterozoic			1000 - 541		Sediment deposition in marine environment that will became the metasedimentary rocks.		Undifferentiated Neoproterozoic units of schists, greywackes, conglomerates and quartzite rocks.
				2500 - 1000				
Archean				4000 - 2500		First life forms on Earth.		
Hadean				4600 - 4000		Earth planet formation.		

- The West Asturian-Leonese, the Central Iberian and the Ossa-Morena zones, are the internal zones, with prevailing terrains of Pre-Cambrian and Lower Palaeozoic ages. In these zones, the Variscan deformation was stronger, while high-grade metamorphism is present and sin-orogenic granite plutons are frequent.

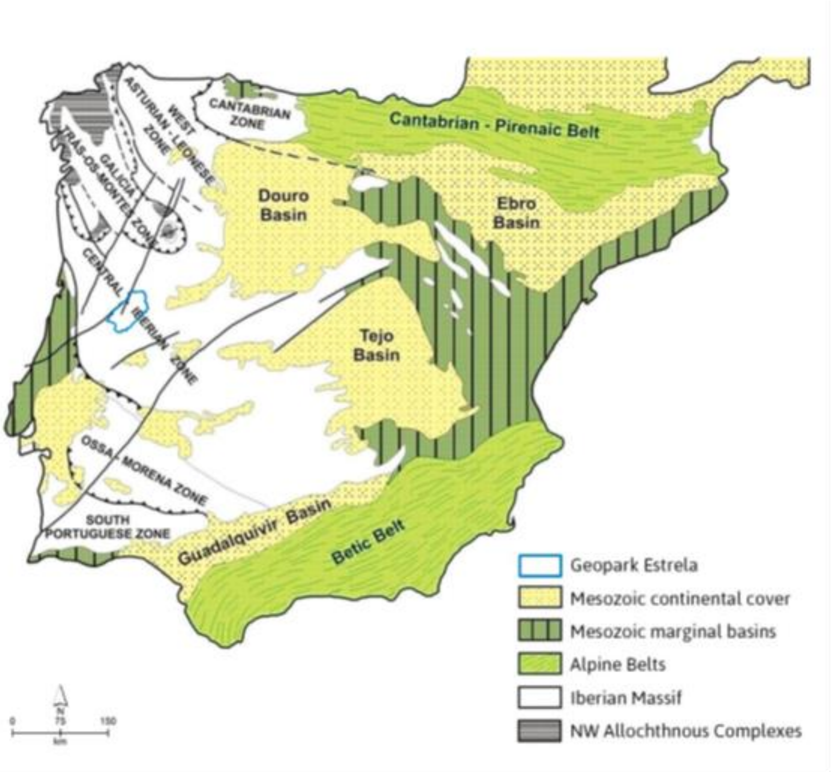


Figure 5. Tectonic and stratigraphic zoning of the Iberian Peninsula according to Julivert *et al.* 1974 (adapted from Santos and Tassinari, 2012).

1.3. The Pre-Ordovician autochthonous

The Central Iberian Zone, of special significance to the Estrela UGGp, extends from northwest to central Spain, covering most of the centre and north of Portugal and is ca. 400 km wide in the centre of the massif. Based in stratigraphic criteria and on the lithology of the autochthonous sequences underlying the Lower Ordovician quartzites, the CIZ is divided into (Martínez-Catalán *et al*., 2009):

- The Schist-Greywacke Complex Domain (Complexo Xisto-Grauváquico, Carrington da Costa, 1950; Teixeira, 1955), a thick terrigenous sequence, currently named in Portugal the Douro-Beiras Supergroup, Sousa e Sequeira, 1987; Oliveira et al., 1992). This sedimentary sequence from the Upper Precambrian to the Lower Cambrian is divided into the Douro (to the N) and the Beiras Groups (to the S), characterized as turbiditic lithofacies accumulated in two basins (Neiva et al., 2013). The former shows calciturbitic occurrences and is probably upper Neoproterozoic to lower (middle?) Cambrian, while the latter is traditionally considered as monotonous non-carbonated deeper facies sequence dating from the Neoproterozoic. Recent studies reported the existence of two distinct stratigraphic sequences bounded by a first rank unconformity (Meireles *et al.*, 2014), which is confirmed in the current 1:200.000 geological map of Portugal.

- The Ollo de Sapo Domain, a volcano-sedimentary complex, located to the N and NE of the CIZ.
- The Meridional allochthonous unit, composed by Upper Neoproterozoic to Lower Cambrian rocks with close relation to the Ossa-Morena Zone.

1.4. A wealth of granite intrusions at the late stages of the orogeny

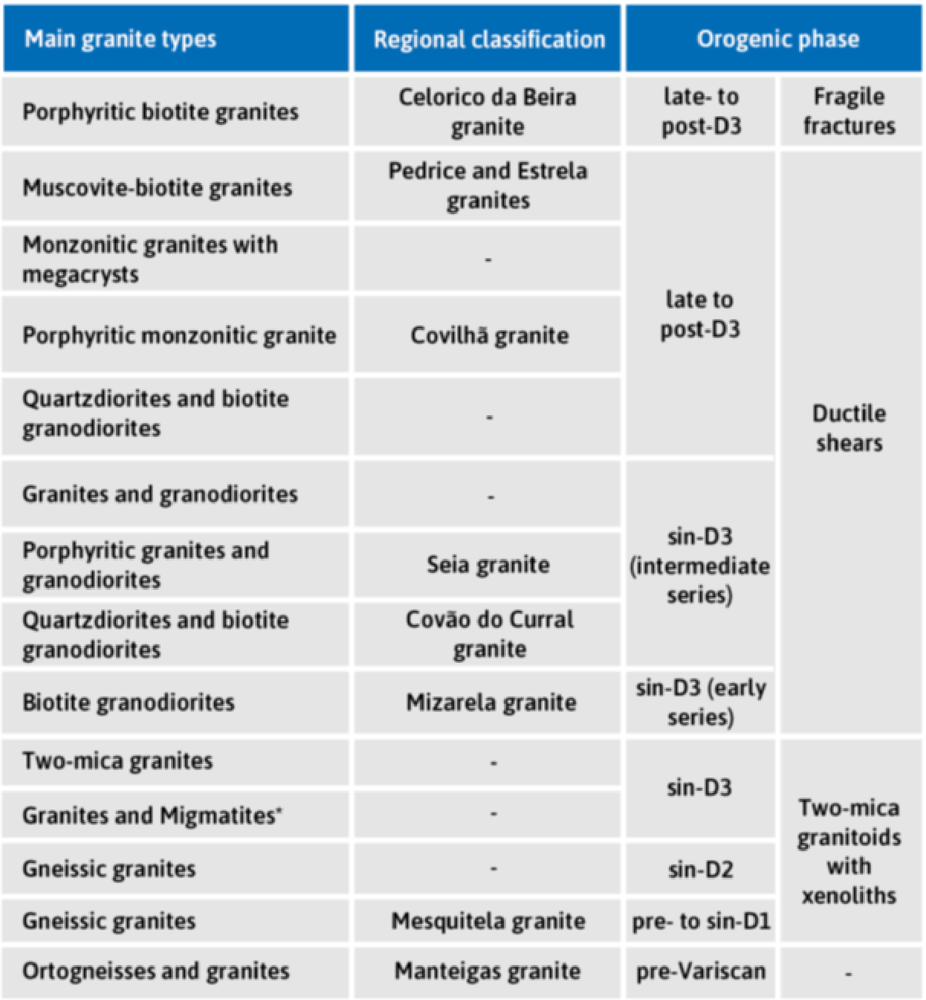
The Variscan orogen was active in Iberia from the lower Devonian to the end of the Carboniferous and showed three major phases of deformation (D1, D2 and D3). The crustal thickening generated metamorphism and synorogenic magmatism, resulting in extensive formation of granitic rocks. Late and post-tectonic magmatism was widespread from 310 to 290 Ma, with the CIZ being the section of the European Variscan chain where granitic rocks show a wider diversity and outcrop in larger areas (Azevedo and Aguado, 2006).

The classical petrographical and geochemical classification for the granitoids of northwest Iberia groups the Variscan granites in two large categories (Capdevila and Floor, 1970; Capdevila *et al.*, 1973):

- Two mica granitoids related with migmatites and high-grade metamorphic terrains.
- Granodiorites and biotitic calc-alkaline granites (sin- and late-post-kinematic), frequently associated to mafic and intermediate igneous rocks.

Recent studies showed that the Variscan plutonism is associated with the last ductile deformation stage (D3). Hence, the Variscan granites can be divided into four groups [32]: pre-D3, sin-D3, late-D3 and post-D3. As for the scarce intrusions dating from the upper Proterozoic to the lower Palaeozoic, they are broadly classified as pre-Variscan [29] (Table II). Pre-D3 granites show similar characteristics to sin-D3 but are almost lacking in Portugal. Most of the large batholiths of peraluminous two-mica granites and leucogranites, as well as some granodiorite and biotitic granite masses are sin-D3 (320-310 Ma). The late-post-D3 granites (310-290 Ma) frequently form composite zoned massifs with contact metamorphism zones and are mainly non-deformed granodiorites and biotitic granites. They are low to moderate peraluminous, showing frequent association with basic and intermediate composition rocks. Intrusions of biotite-muscovite granites and two-mica granites, which are late- to post-D3 are also included in this group (Azevedo and Aguado, 2006).

Table II. Granites of the Estrela UNESCO Global Geopark following (Oliveira *et al.*, 1992) (* Not mapped at 1:500000 Geological map of Portugal).



Main granite types	Regional classification	Orogenic phase	
Porphyritic biotite granites	Celorico da Beira granite	late- to post-D3	Fragile fractures
Muscovite-biotite granites	Pedrice and Estrela granites	late to post-D3	Ductile shears
Monzonitic granites with megacrysts	-		
Porphyritic monzonitic granite	Covilhã granite		
Quartzdiorites and biotite granodiorites	-		
Granites and granodiorites	-	sin-D3 (intermediate series)	
Porphyritic granites and granodiorites	Seia granite		
Quartzdiorites and biotite granodiorites	Covão do Curral granite		
Biotite granodiorites	Mizarela granite	sin-D3 (early series)	
Two-mica granites	-	sin-D3	Two-mica granitoids with xenoliths
Granites and Migmatites*	-		
Gneissic granites	-	sin-D2	
Gneissic granites	Mesquitela granite	pre- to sin-D1	
Ortogneisses and granites	Manteigas granite	pre-Variscan	-

A large area of the Estrela UGGp is in the granitic batholith of the Beiras that intrudes metasediments from the Upper Proterozoic/Lower Cambrian to the Upper Carboniferous, which were variously affected by the polyphasic Variscan deformation (D1, D2 and D3). The tectono-magmatic evolution of the Beiras Batholith during the Variscan Orogeny showed the following phases (Azevedo and Aguado, 2006):

- Deformation phase D1 (~360-335 Ma), with a compressive regime inducing crustal thickening and Barrovian type metamorphism of the pre-Carboniferous metasediments, with partial crustal melting.
- Extensional phase D2 (~335-315 Ma) marked by a large-scale gravitational collapse, generating crustal thinning, exhumation of the orogen, which was the climax of the regional metamorphism with intense migmatization.
- Compressive phase D3 (~315-305 Ma), marked by significant crustal melting, which allowed for separation from the solid residuum. At this stage, peraluminous granite magmas (type-S) rose, suffered differentiation and consolidated, forming large two-mica leucogranite batholiths. Simultaneously, the lithospheric mantle,

> separated from the crust inducing the ascension of basaltic magmas that intruded the interface crust-mantle in a process of underplating. This heat source induced the melting of the lower crust rocks and mixing and mingling of mantle and crustal magmas, generating I-S type magmas, forming calc-alkaline granodiorites and biotitic monzogranites (sin-D3). This pulse is present at the Estrela UGGp at the Maceira massif installed sin-cinematically at the Juzbado-Penalva do Castelo shear zone and is interpreted as evidence of the continuation of the tectonic exhumation. At the late D3 with the continuation of isostatic rebound and exhumation, the decompression of the asthenosphere generated basic magmas that hybridized with the molten felsic crust, forming calk-alkaline metalominous to slightly peraluminous magmas. Their ascension occurred post-D3 generating the late-post-kinematic composite hybrid biotitic granite massifs of the Beiras batholith at 306 Ma. A period of ca. 20 Ma dominated by hydrothermal activity followed the deformation acting mainly along the major Variscan fault zones (Sant'Ovaia *et al*., 2013).

Despite the Variscan age of most granitic rocks in the CIZ, the Manteigas granite, a medium to coarse-grained slightly porphyritic biotite granodiorite, outcropping in a small mass at the Estrela UGGp, is Ordovician (481.1 ± 5.9 Ma), hence completely unrelated with the Variscan Orogeny (Neiva *et al*., 2009). This granite and the Mizarela granite are considered the same unit in the geological map of Portugal (Oliveira *et al*., 1992), which was the base map for the Estrela UGGp. The current 1:200.000 map in the works, with the support of LNEG, will allow the differentiation of several of these lithologies.

1.5. The planation at the end of the Variscan cycle

The full cycle of the Variscan orogeny ended in the Late Permian with the planation of the mountain belt. This erosional phase is marked in continental sedimentation in intramontane basins such as the Dúrico-Beirão Carboniferous zone (Ferreira, 2005). This pre-Triassic planation surface is currently very deformed in Portugal, where it only occurs fossilized by Triassic sedimentation, while in Spain is still visible at the surface.

At the end of the orogenesis the Iberian Massif was affected by brittle tectonic deformation, giving origin to two main fault systems: an older set of NNE-SSW to ENE-WSW sinistral lateral strike-slip faults, and a younger set of NNW-SSE to NW-SE dextral lateral strike-slip faults. The former was much more significant for the subsequent geomorphological evolution in the Estrela UGGp (Ferreira, 2005), which reflects the changing tectonic and paleogeographical conditions following faulting at the end of the Variscan cycle.

In the Mesozoic, a new Wilson cycle started with rifting south and west of the present boundaries of the Iberian Massif initiating the breakup of Pangea. The stage lasted from the Triassic to the Middle Jurassic, while a second stage associated with the opening of the Atlantic, started at the Upper Jurassic. The continuous formation of oceanic lithosphere west of Iberia and the opening of the Gulf of Gascony induced the anticlockwise rotation of Iberia, forming the Iberian microplate in the Lower Cretaceous (Ribeiro, 2013).

The current relief of the Estrela UGGp is mainly a result of the evolution since the Paleogene and particularly of the interplay between climate and tectonics, controlled by the Variscan structures. During large part of the Jurassic, the western part of the Iberian Massif was subject to intense chemical and biochemical weathering in a warm and wet climate, generating thick regoliths and the deposition of carbonates in the continental margin (Ferreira, 2005). These conditions lasted until the end of the Mesozoic (Martin-Serrano, 1988), with the deep weathering probably being the cause for the pre-Cretaceous planation surface, as an etchsurface. Following tectonic activity and lasting until the Middle Tortonian (Pais *et al*., 2012), climate changed to a tropical climate with dry season, and an erosional regime installed, removing the weathering mantles (Ferreira, 2005).

The pre-Cretaceous surface was retouched during the Paleogene and gave origin to subsequent planation surfaces that are key geomorphological features of the Iberian Massif today, with the oldest correlative deposits being the Coja arkoses (Upper Eocene). These deposits cover patches of the Paleogene planation surface, which is present from northern to southern Portugal and from which the main present-day mountains in the Iberian Massif developed. In the Estrela UGGp, these Paleogene deposits occur in the NW piedmont, mainly in the Seia-Pinhanços graben where they were protected from erosion.

Planation surfaces are divided in two major types (Ferreira, 1978, 2005): i. polygenic surfaces formed in tectonically stable areas, where deformation was consistently planated by prevailing erosional processes, and ii. stepped surfaces, where deformation was stronger and the various planation phases did not fully erode the newly formed relief, resulting in several planation surfaces forming at lower positions.

Polygenic surfaces are well represented in the Iberian Massif, with good examples being the Meseta Surface and the Mondego Platform, while stepped surfaces are also frequent, for example in the Central Portuguese Plateaux in the northern edge of the Estrela UGGp (Ferreira, 1978, 1991). Stepped surfaces prevail to the north of the Estrela UGGp, where uplift has been stronger, while polygenic surfaces prevail to the south, such as is the case of the Castelo Branco Surface (Ribeiro, 1949) in the Naturtejo Geopark or the Baixo Alentejo Peneplain (Feio, 1952). The planation surfaces, especially to the south of the Serra da Estrela, show some good examples of residual reliefs (inselbergs) such as the Belmonte inselberg at the Estrela UGGp.

1.6. Collision with Africa and the rise of a new mountain

Regional compression in the Oligocene caused by the collision with the African plate initiated crustal shortening and rejuvenation of the Variscan tectonic structures (De Vicente and Vegas, 2009). One of the main features uplifting from the Central Iberian Zone Paleogene planation surface was the Iberian Central System (Cordilheira Central in Portugal), taking place possibly from the Middle to Upper Miocene (Martin-Gonzalez, 2009). Some authors, consider that the westernmost part of the Iberian Massif maintained continuous uplift during the whole Cainozoic (De Vicente *et al*., 2007), while others place the peak of the Alpine compression in the Portuguese mainland in the Tortonian (Pais *et al*., 2012, Cunha *et al*., 2000). These changes were drastic for the continental topography of Iberia, which had an elevation close to the sea-level until the end of the Cretaceous [Cunha and Pena dos Reis, 1995; Dinis *et al*., 2008) and suffered a general uplift of the planation surface between 100 and 600 m (De Vicente *et al*., 2011).

During the so-called Alpine compression, several fault directions were reactivated: i. NE-SW to ENE-WSW oriented, as thrusts, ii. NNE-SSW, as sinistral strike-slip faults, and iii. NW-SE, as dextral strike-slip faults (Pais *et al*., 2012). Thrusts controlled the uplift of the Central System, since they were reactivated as reverse faults. South of the Central System, the SE-verging and NW-dipping Ponsul fault flattens at depth while converging with the Seia-Lousã fault that is NW-verging and SE-dipping and located in the north (Fig. 6). The result was the formation of a large horst uplifting as a pop-up structure along a system of parallel faults (Ribeiro *et al*., 1990). A whole section of the planation surface was displaced and is still visible in the summits of the Estrela forming a plateau, which dips slightly to the northeast, but which is well-preserved in granites. This plateau is quintessential for the Pleistocene evolution of the Estrela, due to its controls on climate and snow regime, influencing the glaciation style, dynamics and geomorphological features, key elements of the Estrela UGGp.

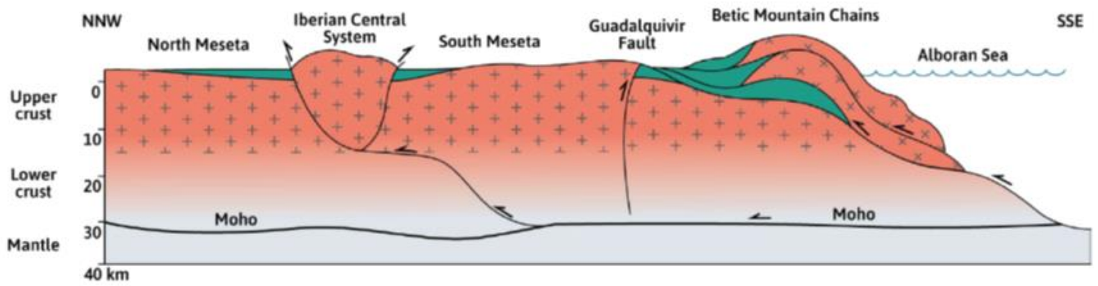


Figure 6. Schematic cross-section showing the pop-up structure of the Iberian Central System following the reactivation of Variscan faults (adapted from Ribeiro 1988).

The strike-slip fault systems show predominantly horizontal displacements that weakened the basement rocks, enabling differential erosion to carve long, deep and linear valleys, especially where the faults affect granites. One of such examples is the 250 km long Bragança-Vilariça-Manteigas fault (BVMF) that cross-cuts the Estrela along a NNE-SSW direction giving origin to the valleys of the Zêzere and Alforfa (Daveau, 1969, Migon and Vieira, 2014) (Fig. 7). The BVMF also suffered a vertical component in the deformation that displaced the upper Estrela plateaus by about 150-200 m (Ribeiro *et al.*, 1990).

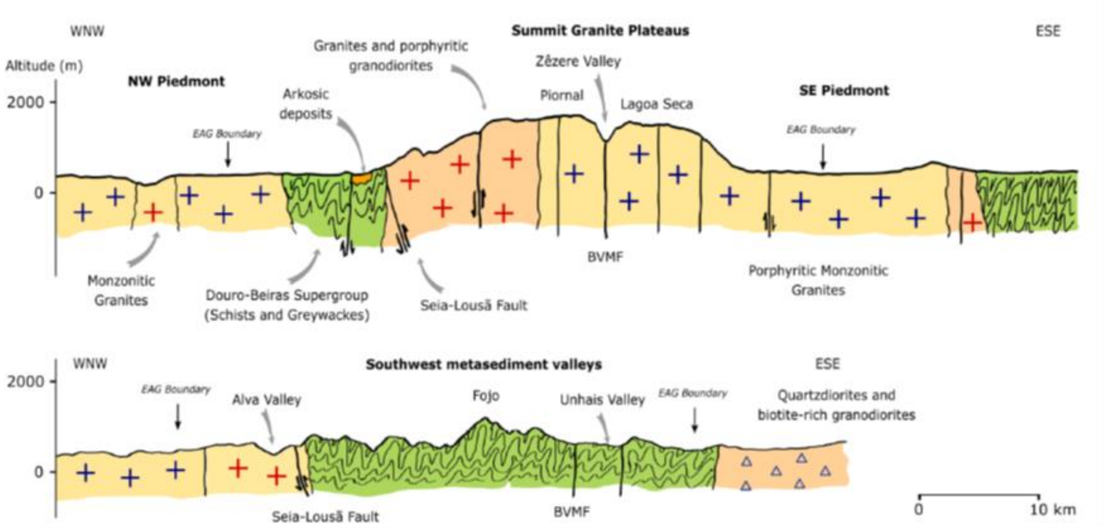


Figure 7. Simplified geological cross-sections of the Estrela UNESCO Global Geopark showing the controls of tectonics and rock type on morphology (base data from the Geological map of Portugal 1:500.000).

1.7. Towards the present-day relief organization

The Late Miocene and the Zanclean were characterized by a hot climate with marked seasonality, resulting in sedimentation occurring mainly at the foot of the fault scarps (Pais *et al.*, 2012). At the time, the main fluvial systems were endorheic draining into the interior of Iberia. In the Piacenzian the climate became hot and very wet and an exorheic fluvial network developed, with broad valleys developing in the mountains and numerous catchments forming in endorheic inland basins. In the Upper Pleistocene, the climate became colder and the continuing uplift and sea-level changes promoted a strong fluvial incision, regressive erosion and stream piracy (Pais *et al.*, 2012), defining the landform organization in Central Portugal and in the Estrela UGGp.

The tectonic deformation continued during the Quaternary with vertical movements resulting both from large scale folding and isostatic adjustments, and from active faulting. Inferred uplift rates for the last 3 Ma are of 0.1-0.2 mm/yr, with the largest deformation occurring in the centre and north of Portugal, with the Estrela UGGp territory showing values of up to 600 m, especially in the higher parts of the Estrela (Cabral, 2012; Rockwell *et al.*, 2009). Active faulting shows a predominance of ~E-W to NE-SW faults with reverse component and left-lateral strike-slip faults ~N-S to NNE-SSW.

The Seia-Lousã fault that bounds the Serra da Estrela in the north is an example of the former, while the BVMF fault is an example of the later.

The long-term geological evolution explains the general organization of the landforms in the Estrela UGGp, with the important control exerted by Alpine tectonics over reactivated Variscan faults, which generated the segmentation of the Paleogene planation indifferent steps up to the summit of the mountain (Fig. 8). One of the main geomorphological differences within the Estrela UGGp is the contrast between granites and the shales, schists and greywackes (Ribeiro, 1954; Daveau, 1969). Granite terrains show typically well-preserved remnants of the planation surfaces, both in the summit areas and in steps and erosional terraces. The valleys are rectilinear, with sharp bends, reflecting the tectonic control. On the other hand, metasedimentary terrains show sharp ridges and a dense drainage network, with scarce remnants of planation surfaces and deeply incised meandering valleys.

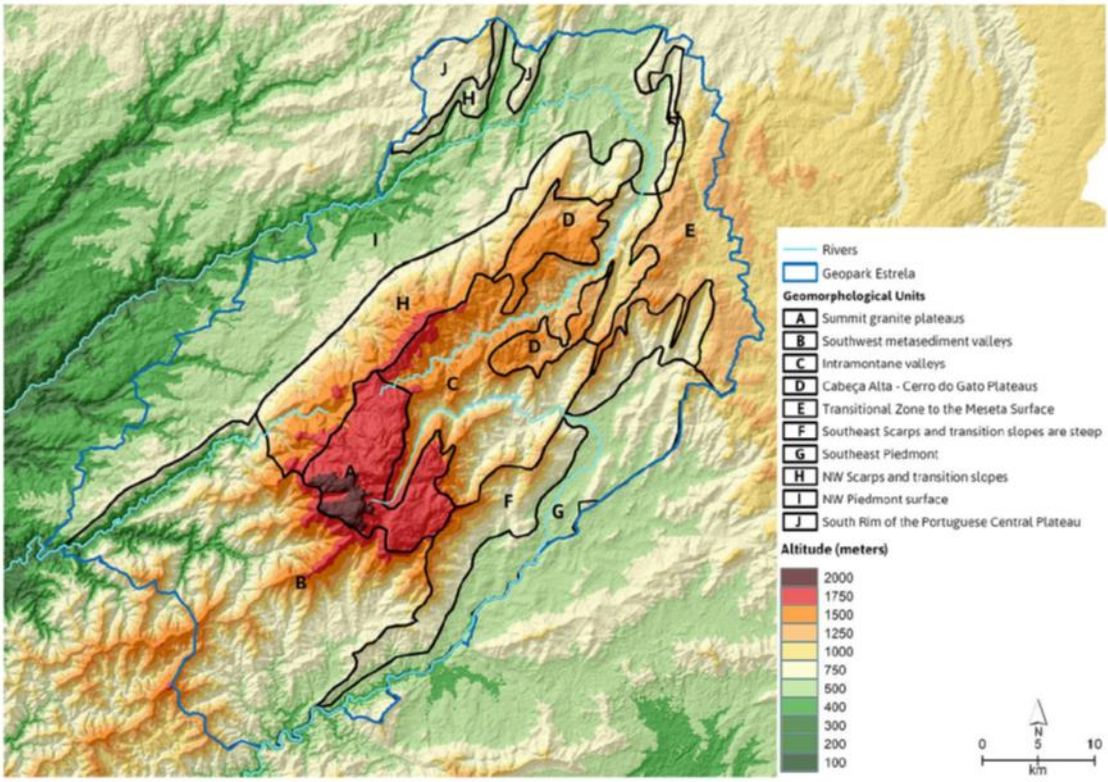


Figure 8. Geomorphological units of the Estrela UNESCO Global Geopark.

1.8. The richness of granite types and the diversity of landforms

The richness of the Estrela UGGp in granite types (Table II) with different geochemistry, age and tectonic history has allowed researchers to dig deeper into rock control on the granite geomorphology across different spatial scales. Such a granite diversity within a small area facing similar climate conditions makes the Estrela unique for assessing the effects of rock control on landforms (Migon and Vieira, 2014). Differences in granite texture were shown to exert a major control on the occurrence of relict periglacial phenomena (Vieira, 2004), an observation with important impacts for paleoenvironmental reconstruction in granite terrains. At similar topographical settings, fine-grained granite variants show the development of blockfield and blockslopes, while coarse-grained granites show evidence of granular weathering, generating stratified slope deposits instead. Granite types also result in different tor morphologies (Migon and Vieira, 2014) (Fig. 9).

Figure 9. Examples of granite landforms in the Estrela Geopark: A. Fraga das Penhas tor and castle-koppie, B. Penedo do Sino pedestal rock, C. Terroeiro.

Although tors are not unique to the Estrela UGGp they provide, together with other granite landforms, an excellent setting for research. In the Estrela plateaus, the interplay between long-term weathering in different granite variants and the Late Pleistocene glaciation, generated important landscape differences, as well as a good dating framework. Lautensach (1929) noted that tor distribution in the Estrela showed clearly the controls of glacial erosion, with tors almost completely absent within the Pleistocene glacier boundaries. Vieira (2004) mapped over 600 tors in the plateaus confirming Lautensach's observations. However, tors were also found within the glacial limits, such as is the case of the Covão do Boi columns or the tors at the upper Candieira catchment. These formed by post-glacial erosion of the granite weathering mantle which survived under the Pleistocene glaciers (Ferreira and Vieira, 1999; Vieira, 2004). In fact, the singularity of the geomorphological setting and evolution of the Covão do Boi area, makes it one of the key geosites of international significance at the Estrela UGGp.

1.9. The originality of the last glaciation in the Serra da Estrela

a) History of research

Evidence of a glaciation at the Estrela UGGp was mentioned for the first time in 1884 by Cabral in a study about glaciations in Portugal. According to Lautensach (1929), Penck, also in 1884, had pointed evidence of glaciations in the Central System, both in Estrela and Guadarrama. In 1916, Fleury worked on Cabral's observations and described the general features of the Estrela glaciation. However, the first systematic scientific analysis of the Estrela glaciation was only made in 1929 by Hermann Lautensach, a German geographer that spent three months in area in 1927 and 1928. He identified several features of the glaciation and mapped glacier extent and thickness. Following this work and for almost four decades, the Estrela glaciation did not attract new research, until the important paper by Suzanne Daveau in 1971 – "La glaciation de la Serra da Estrela". Daveau added up to previous works based on better topographic maps, on field work and on systematic aerial photo interpretation. Most of the results of Daveau's mapping are still valid today, especially in what concerns to the glacial extent outside the Zêzere valley. In the mid-1990's, Gonçalo Vieira continued Daveau's research and in the framework of a doctoral dissertation, using GIS, aerial photography, digital high resolution orthophotos and sedimentological analysis, supported by field work, presented the current view of the Estrela glaciation (Fig. 10). After the works of Vieira [2004, 2008), research on the glaciation has been more sporadic and deeply affected by research funding shortage. The implementation of the Estrela UGGp has resulted in increased research in the Estrela, with several recent publications and projects (Nieuwendam *et al*., 2020; Santos *et al*., 2020; Vieira *et al*., 2020, 2021; Vieira and Woronko, 2021; Raab *et al*., 2022).

b) Characteristics of the glaciation

Contrary to other mountains in Portugal, such as the Gerês and Peneda, where the glaciation generated controversies that lasted for decades (Ferreira, 1993), the glaciation of the Serra da Estrela shows widespread clear glacial geoheritage, of high scenic, pedagogical and scientific significance. For example, the remarkable U-shaped Zêzere valley has been frequently used in national and international scientific publications and is a text book example of a glacial trough.

The glaciation style of the Estrela is a result of both: i. its geographical setting in the western margin of Iberia, being the first mountain to affect the inland movement of the moist Atlantic air masses, but also, ii. of the altitude of the plateau between 1400 and ~2000 m. This altitudinal range, just above the paleo-equilibrium line altitude (ELA) of ~1650 m for the last maximum glacial extent, was perfect for the development of the Late Pleistocene glaciers (Vieira, 2008). The western plateau was especially significant for the glaciation and very sensitive to snow accumulation (as it is today) and hence to glacial inception. This is because once the ELA descends below the plateau surface, a very large accumulation area develops, providing enough ice mass for an ice-field to form. Since several valleys radiate from the plateau, conditions existed for ice streams to channel into valley glaciers (e.g. Zêzere, Alforfa, Alvoco, Loriga, Caniça and Covão do Urso).

However, the plateau also induces a large sensitivity for glacial retreat. A decrease in winter precipitation or an increase in summer ablation, with a resulting increase in the ELA, show rapid impacts in glacier mass balance, inducing the fast starvation of the valley glaciers and of the plateau ice-field. Hence, the Estrela has functioned in the

Pleistocene cold phases has a perfect « barometer » for climate variability in Western Iberia. On the contrary, if it would be a ridge style mountain (as most Alpine and Iberian mountains), it wouldn't show this behaviour that makes it unique.

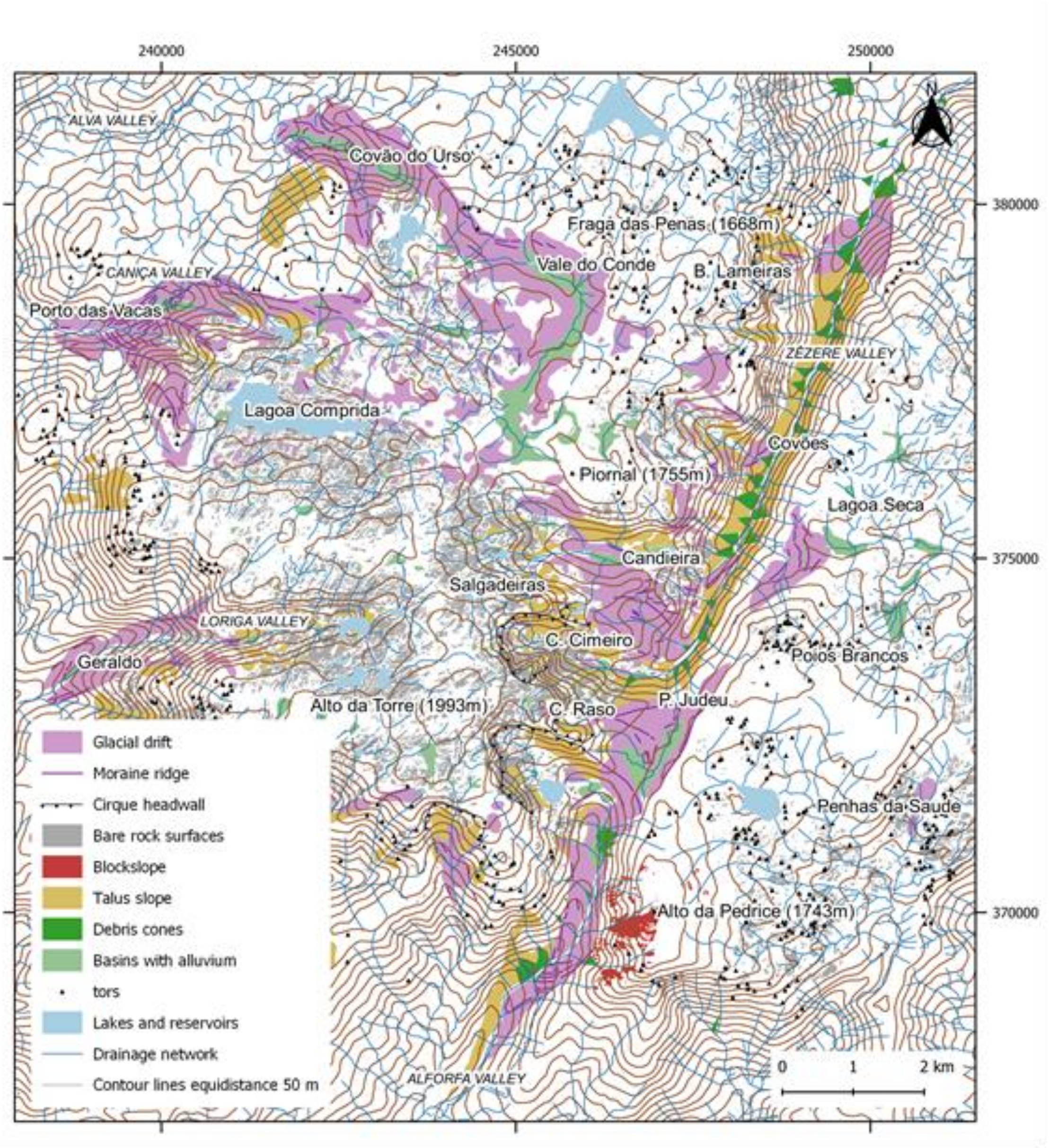


Figure 10. Main features of the glacial and periglacial geomorphology of the Serra da Estrela (after Vieira, 2004).

The Last Maximum of the Glaciation of the Serra da Estrela (LMGSE) was initially dated using thermoluminescence of fluvioglacial sediments from the Lagoa Seca at ~30 ka BP (Fig. 11, Vieira, 2004). More recent cosmogenic isotope exposure dating from moraine boulders at the same site, support a similar age (Vieira *et al.*, 2021). This shows that the LMGSE pre-dates the LGM, a fact also supported by glacial evidence from southwest Europe and Iberia, showing that the LGM was probably cold and dry in Iberia, thus generating glacier recession.

Figure 11. The Lagoa Seca intermoraine basin and moraine ridges.

At the LMGSE, the western plateau of the Estrela had a plateau ice-field with several valley glaciers, from which the Zêzere glacier, ending close to the village of Manteigas, was the longest, with 11.3 km. The ice-field and glaciers were 66 km2, with about 90 m ice thickness at the Alto da Torre and with ice thickness reaching 340 m at the Zêzere glacier (Vieira, 2008).

Glaciers left clear erosional marks in the extensive bare granite outcrops of the western plateau and valley heads, originating diverse glacial landforms, such as roches moutonnées, polished surfaces, grooves and striations (e.g. Salgadeiras and Lagoa Comprida. The contact zones between the western plateau and the main glacial valleys are marked by steep and deep cirques, especially in the eastern side, where snow accumulation was favoured by the prevailing west-winds. The best examples, are the Covão do Ferro and Covão Cimeiro, which are over 1 km wide, 240 to 290 m deep.

The glacial valleys of the Estrela show steep slopes and frequently U-shape cross-section, with the most typical being the Zêzere valley. Overdeepenings occur especially above the paleo-ELA and are infilled by post-glacial deposits that are a mixture of moraine boulders, rockfalls and sandy-gravels washed from the slope taluses. Organic sediments from overdeepenings in the plateau and at Charco da Candieira enabled the paleoenvironmental reconstruction since 14.8 ka BP. Peaks rising above the glacier surface where the ice-field drained into the Zêzere and Alforfa valleys, with nunataks at the Cântaros (pots) Gordo (fat), Raso (flat) and Magro (thin) and Piornal.

Moraines are widespread in the Estrela UGGp, occurring both along the glacial valleys and in several sectors of the western plateau (Lagoa Comprida and Vale do Conde), away from the dispersion centres of the ice-field. Most moraines are composed of large boulders (1 to over 5 m), lying on a coarse sandy-gravely-bouldery deformation till. Most moraines show the effects of post-glacial runoff that eroded fines, sands and gravels.

Four types of moraines occur in the Estrela UGGp: i. lateral moraines, present along the larger valleys, with the best examples at Covão do Urso (4 km long), Covão Grande and Nave de Santo António, ii. Latero-frontal moraines, close to the terminus of the main valley glaciers (e.g. Manteigas and Alforfa), iii. Recessional moraine groups, present in most valleys as a series of frontal moraines, forming sets of up to 12 ridges (Caniça, Nave Travessa, Alforfa, Loriga and Lagoa Seca), iv. Marginal moraine complexes (Vale do Conde and Teleférico moraine at Nave de Santo António), and v. Sparse moraine covers, normally below 1650 m and without ridges (e.g. Lagoa Comprida, Azimbres, Vale do Conde).

Till exposures occur at the Estrela UGGp, but due to the mountain setting, limited number of outcrops and fast shrub growth, most are not easily to observe. Key outcrops such as the Cerro Rebolado flow till at the northern margin of the plateau ice-field, the Alforfa lodgement and flow tills, and the Lagoa Seca lodgement and flow tills, are excellent examples of mountain tills and of the wet-based dynamics of the glacial environment. The analysis of quartz grains from the later provided evidence that subglacial transport and erosion mobilised grains that had previously evolved in the regolith, controlled by chemical weathering (Vieira, 2004). This supports Daveau's interpretation for the saprolitic origin of the very large rounded boulders, so typical of the Estrela moraines. Such saprolites are still visible at some sites outside the glaciated area, even in the highest parts of the mountain.

Kame terraces that allow to infer the paleo valley glacier position are present in many valleys and their relation to human occupation is noteworthy, being typically used for agriculture, due to their gentle sloping surfaces, soil development and water availability.

Fluvioglacial terraces occur in Manteigas, Unhais da Serra, Alvoco and in the Alva valleys, being formed by decametric sub-rounded boulders, gravels and coarse sands, poorly stratified and forming terraces (used for agriculture and more recently to urban settlements) a few meters above the current valley floor. Three terrace generations occur in Manteigas, with a post-glacial fluvial incision of about 6 to 8 m. Fluvioglacial deposits in filling the intermorainic depression of Lagoa Seca allowed to identify the age of the last maximum glacial extent in the Estrela (Vieira, 2004).

But the glacial geoheritage of the Estrela UGGp is not limited to the LMGSE, as evidence shows ages from an earlier glacial (Vieira, 2004, 2021). At Penhas da Saúde the micromorphological analysis of a diamicton showed the presence of probably subglacial deformation microstructures. The lack of clear landforms associated to glacial erosion in the area, suggest a pre-LMGSE age for the deposit. At the Cântaro Raso and Barroca das Lameiras, linear accumulations of boulders without matrix have been interpreted as possible earlier moraines. At the Lagoa Seca, the most external of five moraine ridges, showing deeper weathering pits than the three internal ridges, was recently dated using 36Cl, providing minimum ages of 138.9±14.1 to 146.7±17.8 ka, supporting a pre-Weichselian age (Vieira *et al*., 2021).

c) Chronology

The following main stages in the Estrela glaciation may be (Vieira, 2004; Vieira *et al.*, 2021):

- The **external stage**, oldest and pre-Weichselian (c. 140 ka), without clear glacial landforms, but identified based on the presence of sectors of large boulders interpreted as moraines, on the till of Penhas da Saúde and with absolute age datings.
- The **Last Maximum of the Serra da Estrela Glaciation (LMGSE)**, corresponding to the maximum extent of the glaciers, as seen in well-preserved moraine features and kame terraces (c. 30 ka BP).
- The **Internal stage 1**, marked by numerous moraine ridge complexes in the valleys in positions inside the LMGSE maximum.
- The **Internal stage 2**, identifiable at some latero-frontal moraines in the Zêzere and Alforfa valleys.
- The **deglaciation of the plateau** at the Bølling-Allerød Interstadial (14.6–12.9 ka).

Contrary to other mountains in Iberia, at the Estrela UGGp moraines close to or inside the glacial cirques are very scarce. This fact should be related to the style of deglaciation associated to the plateau ice-field, which given a rise in the ELA would have quickly been affected by an ablation regime in a large area, inducing ice-stagnation in the valleys and areolar melting resulting in abandoned bodies of dead-ice. These condition would have seen limited erosion in the cirques and consequently, no significant moraine deposits.

d) The Periglaciation

The significance of relict periglacial phenomena in the Estrela UGGp area was reported for the first time by Daveau (1973, 1978) that described the Pedrice blockslope, stratified slope deposits and screes in the Zêzere Valley and showed that frost action played a role in Late Pleistocene morphogenesis. Since most phenomena occurred outside the glaciated area and very few inside it, they should be, at least, synchronous to the LMGSE or older. More recently, Vieira (2004) presented a systematic survey and analysis of the periglacial deposits and landforms and identified a wider relict periglacial activity in Estrela, with block fields, stone-banked solifluction lobes, head-type, stratified slope deposits and debris-flow deposits. Traces of permafrost action, possibly of Late Pleistocene age are present in lamellar structures in slope deposits above 1200 m (Vieira, 2004; Nieuwendam *et al.*, 2019; Vieira and Nieuwendam, 2020), together with other features, such as a bouldery accumulation interpreted as a paleorockglacier at Alforfa.

1.10. Postglacial evolution

The Charco da Candieira deposits from the Candieira valley at 1409 m offer a good insight into the paleoenvironmental evolution of the Estrela UGGp since about 14.8 ka BP (Van den Brink and Janssen, 1985; Vand der Knaap and Van Leeuwen, 1997):

- At 14.8 ka BP glaciers were still present at the upper areas of the catchment.
- Until the Younger Dryas, climate conditions varied, with altitudinal shifting of the periglacial zone, which was more active in the Bølling and in the Younger Dryas, with open grassland formations. Between both these stadials, in warmer and wetter conditions, open woodlands occupied the valleys.
- At the onset of the Holocene, open woodlands expanded in the mountain and Quercus forests colonized the lower valleys.
- Around 7.6 ka BP Cerealia pollen increased and the forest became less dense. At 5.6 ka BP humans became the main driving force on forest dynamics.
- At 3.3 ka BP large-scale deforestation took place, first at 1400 m, climbing to 1750 m at 2.8 ka BP.
- Subsequent phases reflected successive waves of deforestation, especially at 0.8 and 0.6 ka BP, culminating at 0.34 BP with increased soil erosion.

2. Introduction to the itinerary and description of the stops

The three-day field trip will allow for a very good overview of the main highlights of the ~2,200 km^2 of the Estrela Geopark. It will include visits to the main geosites, spreading over glacial, periglacial, granite weathering, fluvial, hydrogeological, petrological and tectonic themes, as well as a discussion of several issues related to the objectives and management of a UNESCO Global Geopark. We will highlight on the scientific value of the geosites, but will promote the links with cultural aspects of many of them. We will emphasize on how a rich geological heritage can be the basis for promoting sustainable development in a territory of a low-density and ageing population, suffering from complex socio-economic and environmental issues. The field trip will include 2 days based on bus travelling around the Geopark with short walks and 1 full-day of hiking in the plateau (easy but long). For those not willing to do the hike, an alternate program may be prepared.

In Day 1 we will surround the Serra da Estrela from the west and will enter it from the northwest, crossing the intramontane valleys carved in metasediments. The day will be dedicated to an introduction to the geological and geomorphological setting of the range, and to the links between the local communities and the geological heritage. We will discuss the implementation of the Estrela UNESCO Global Geopark and practical issues and challenges associated to its management.

Days 2 and 3 will be dedicated to the core of the Serra da Estrela and will focus on exploring the glacial heritage of the mountain, while also discussing the relict periglacial geomorphology and contemporary landscape dynamics. For this, in day 2, we will make a hike crossing the western plateau, between Penhas Douradas and Lagoa Comprida. In day 3, we will do a short hike in the Zêzere valley and will visit by bus several geosites of high scientific relevance, which contributed to the implementation of the geopark.

Day 1

Stop 1. Folgosinho
Regional geomorphological framework, quartz dike.

Folgosinho is a mountain village from the municipality of Gouveia. The stop allows for a first insight into the contact between the Mondego Platform and the western fault scarp of the Serra da Estrela. A massive quartz dike with a thickness of about 10 m was the chosen location for the construction of the Folgosinho castle (Fig. 12). Rising from the surrounding landscape, the dike is heavily mineralized in tin and wolfram, which were the cause of its mining in the 1940s and 1950s, with about 25 tons of wolframite and 8 of cassiterite extracted. Besides these, the dyke shows mineralizations of phosphates and sulphides, still evident in the greenish colour of the heaps.

Figure 12. Folgosinho castle atop the quartz dike.

Stop 2. Linhares da Beira
An introduction to the Estrela UNESCO Global Geopark

Built on a residual relief, the Historical Village of Linhares da Beira shows a unique architectural heritage, fruit of the legacy left by the civilizations that settled throughout the history (Fig. 13). Founded in medieval times, with foral granted in 1169 by D. Afonso Henriques, it lost this status with the liberal administrative reform, in 1855. Although the site has seen the settlement of pre-Roman peoples and there is written record of the passage of Romans, Visigoths and Muslims, the story of Linhares has its origin in the context of the Christian Reconquest. The buildings are a testimony to the use of geology by its inhabitants, with its granite constructions and medieval Castle implanted in the highest point of the residual relief. From the castle, the panorama offers views over the Mondego platform and the southern slope of the central Portuguese plateau.

Figure 13. Linhares da Beira castle.

Stop 3. Videmonte
Geological controls on landforms

Videmonte shows a clear connection between geology and the rural life of the people who live there, as testified by the houses, built in schist and granite, due to the proximity of the contact between these two rock types (Fig. 14). In the village, several traditional activities are still maintained, such as the use of the community oven to bake the tasty rye bread, with rye produced on the Videmonte plateau, with the help of the old irrigation system that was once used to distribute water through the village. Privileged by water and wind resources, the picturesque village of Videmonte also has a relevant historical and architectural heritage, such as the main church (São João Baptista Church) that was built in baroque style in the 17th century and the fountains dating from the 18th and 19th century.

Figure 14. The village of Videmonte.

Stop 4. Quinta da Taberna
Fluvial geomorphology, metasediments

The geology of Quinta da Taberna and its surroundings is characterized by the presence metasedimentary rocks, with outcrops showing intercalations of schists and metagreywackes and microfold structures (Fig. 15). The landscape shows the typical traits of an intramontane fluvial valley, cut in metasedimentary rocks, with the linear interfluves and the meandering Mondego river. The small village provides for a glimpse into the traditional life in the mountain's interior, which prevailed until the 1970's and to the close linkage between human occupation of the mountain and geology. The future use of the Quinta da Taberna geosite as an interpretation centre and educational resource will be discussed.

Figure 15. Quinta da Taberna metasedimentary outcrops.

Day 2

Hike from Penhas Douradas to Lagoa Comprida (all day)
Granite landforms, moraines, glacial erosion, plateau ice-field

The hike will cross the western plateau of the Serra da Estrela from the non-glaciated area, in the Penhas Douradas/Vale de Rossim to the core of the glacial erosion area in the Lagoa Comprida (Fig. 16).

At Penhas Douradas (c. 1,500 m) the landforms are marked by the presence of the Seia granite, a coarse-grained porphyritic variant, which due to the stripping of the weathering mantle, generated a large number of granite landforms, such as boulders, tors and castle-koppjes. The Fragões das Penhas are an excellent example of the latter (Fig. 17).

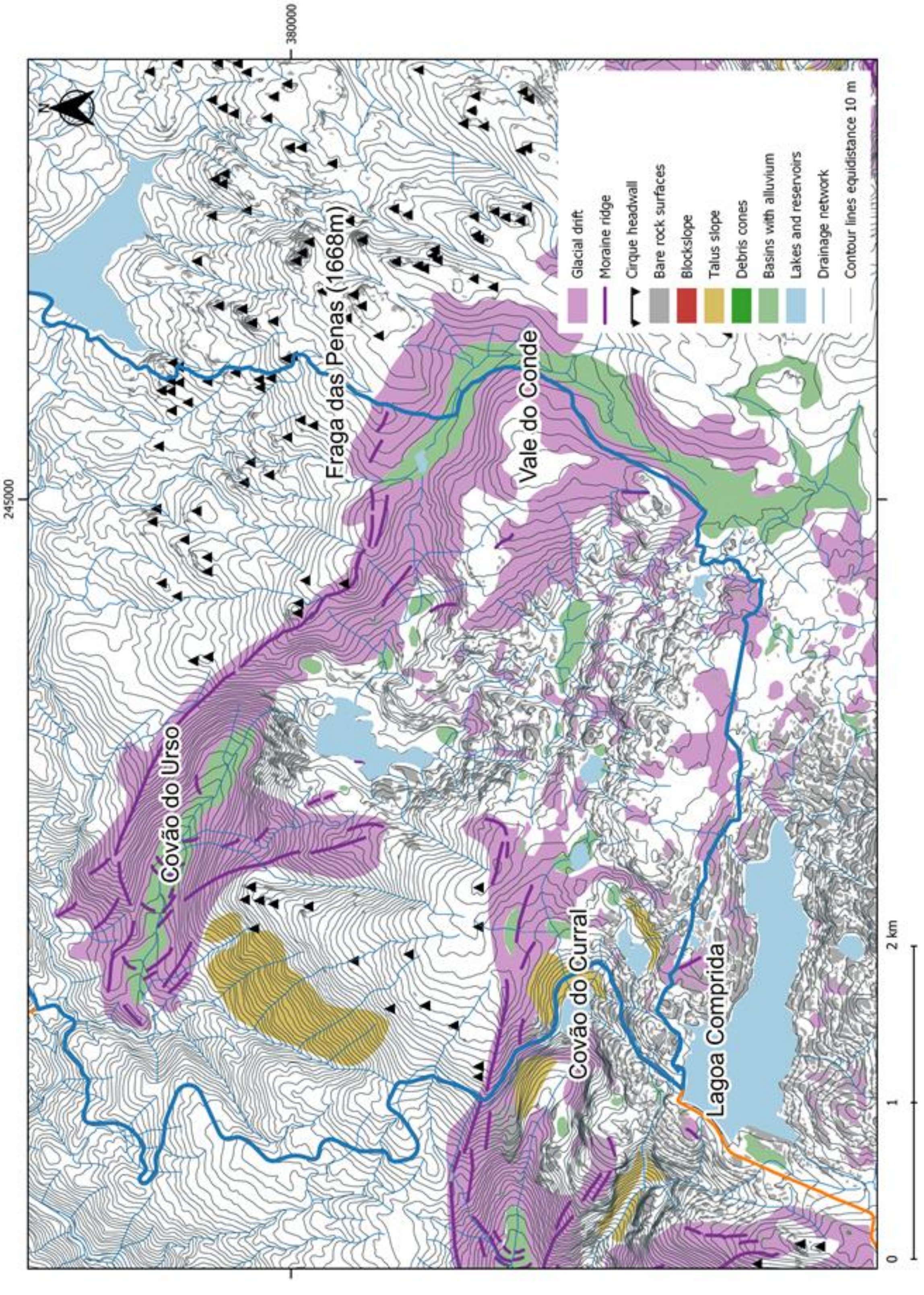


Figure 16. Main features of the geomorphology of the western plateau of the Serra da Estrela with the hike of Day 2 from P. Douradas to Lagoa Comprida (after by bus).

Figure 17. Moraine at Vale do Conde.

Stop 2. Sabugueiro/Covão do Urso Panorama
Glaciated vs non-glaciated landscape. Introduction to the Estrela glaciation. Lateral moraine of Covão do Urso and northwest limit of the plateau ice-field.

The viewpoint allows to analyse northwest sector of the plateau ice-field and the contrast between the Late Pleistocene glaciated and non-glaciated landscape. The stop is located in the non-glaciated area, where a typical granite weathering morphology prevails, with the widespread presence of boulders and tors in convex locations. Towards the southeast, the Covão do Urso valley drained the plateau ice-field, with a glacier flowing to close to the village of Sabugueiro. A 4 km long lateral moraine is visible in the north interfluve of the valley, continuing up to the Vale do Conde in the plateau. Several lateral and frontal moraine ridges occur along the valley floor. This area is currently being mapped using drones and sampled for cosmogenic isotope exposure dating in a collaboration between the universities of Lisbon (G. Vieira) and Zurich (M. Egli).

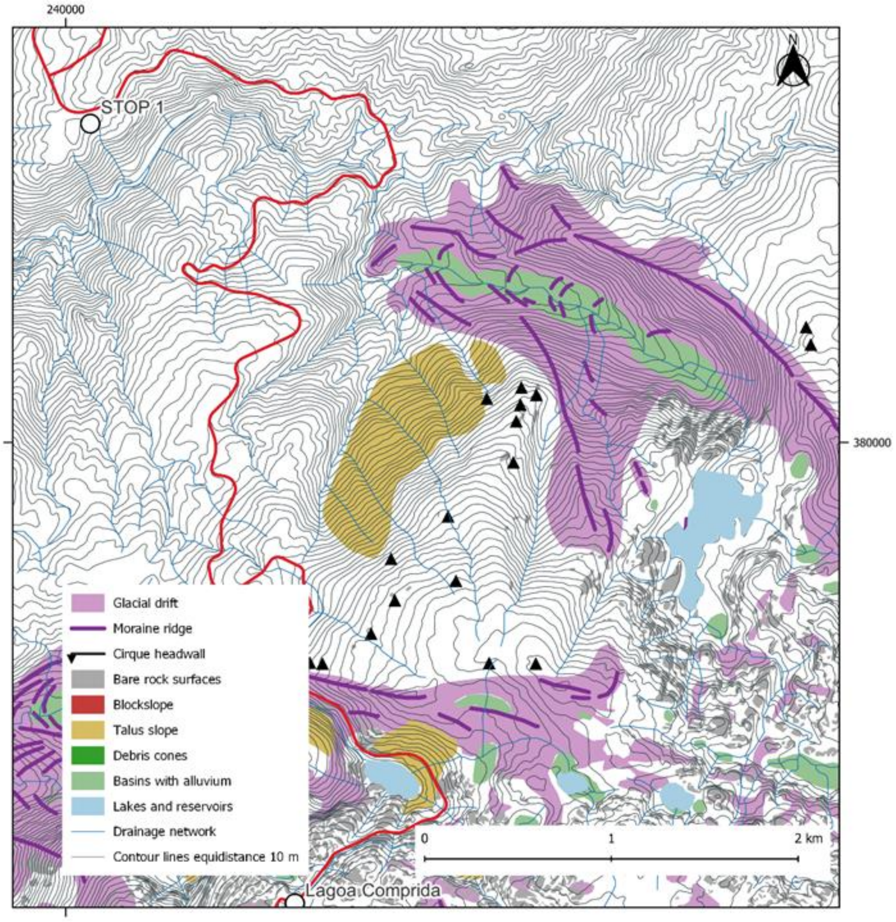


Figure 18. Main features of the glacial geomorphology of the Covão do Urso (adapted from Vieira 2004).

Day 3

Stop 1. Barroca d'Água – Zêzere valley (easy hike - 2h30)

The Barroca de Água stratified gravelly deposit shows a trough cross-bedding, revealing the evidence of debris flows (Fig. 19). The coarsest beds are open-work and constituted by polycrystalline centimetric very angular clasts of porphyritic granite of local origin. Thick massive beds of fine and coarse granite sands, with gravels prevail. Silty-sandy greyish lenses occur in some sectors and have been interpreted as reworked glacial silt. The deposit shows a convex surface morphology and develops linearly in the lower part of the slope, towards the valley floor and perpendicular to it. Smaller deposits of similar characteristics occur downstream and on the opposite site of the valley. Nieuwendam *et al*. (2020) studied the deposit's micromorphology and confirm the deposition by debris flow activity. Given it's linear morphology, debris flow genesis involving significant volumes of water and lack of any source gully upslope, the deposit was possibly formed in an ice-marginal position or in a subglacial setting under a dead-ice valley glacier (Bezembinder and Niessen, 1989; Vieira, 2004; Vieira and Nieuwendam, 2020).

Figure 19. The Barroca de Água cross-bedded gravelly deposit.

The Zêzere glacial valley is a perfect example of glacial erosion (Fig. 20). With a U-shaped cross-section profile for c. 9 km, between Covão da Ametade and the town of Manteigas, the valley presents in its upstream sector a succession of overdeepenings, riegels and hanging valleys, as well as several types of glacial, fluvioglacial and slope deposits. At the maximum of the last glaciation, the ice thickness reached 340 meters close to Covão da Albergaria, fed by the ice-field of the Torre Plateau. A little further downstream, the Zêzere valley was also fed by glaciers from the hanging valleys of Candieira and Covões. The shape of the present valley and its rectilinear character are a result of erosion processes favoured by the Bragança-Vilariça-Manteigas-Unhais da Serra tectonic lineament.

Figure 20. Zêzere glacial valley.

Stop 2. Covão da Ametade
U-shaped glacial valleys, glacial overdeepening, riegels.

Generally, in the Estrela, the so-called “covões” correspond to glacial overdeepenings, which are normally infilled by post-glacial deposition. The Covão da Ametade provides a good view towards the Cântaro Magro and marks the contrast between the zones of glacial erosion and deposition in the upper catchment of the Zêzere valley (Fig. 21).

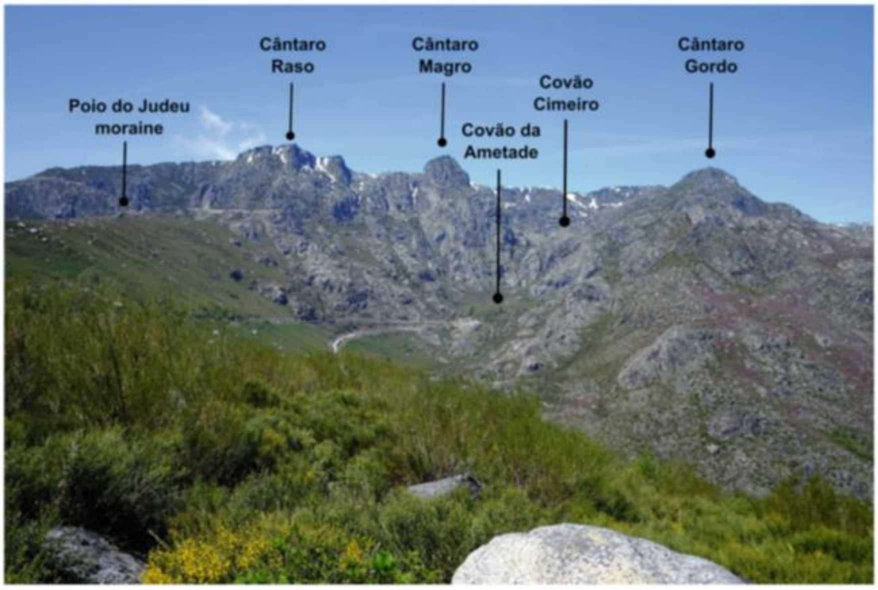


Figure 21. Zêzere glacial valley.

Stop 3. Piornos
Panorama to Nave de Santo António. Glacial cirques. Moraines. Problems of pre-Weischselian glaciations.

Piornos offers a good panorama towards the eastern margin of the Torre plateau, allowing for the observation of the Covão do Ferro glacial cirque, the three paleonunataks formed by Cântaro Raso, Cântaro Magro and Cântaro Gordo (Figs. 21 and 22), and to the complex moraine infill of the Nave de Santo António. It also allows for analyzing the contrasts of the landforms between the western (Torre) and eastern (Penhas da Saúde) plateaus, as well as an understanding of the tectonic significance of the Alforfa and Zêzere valleys.

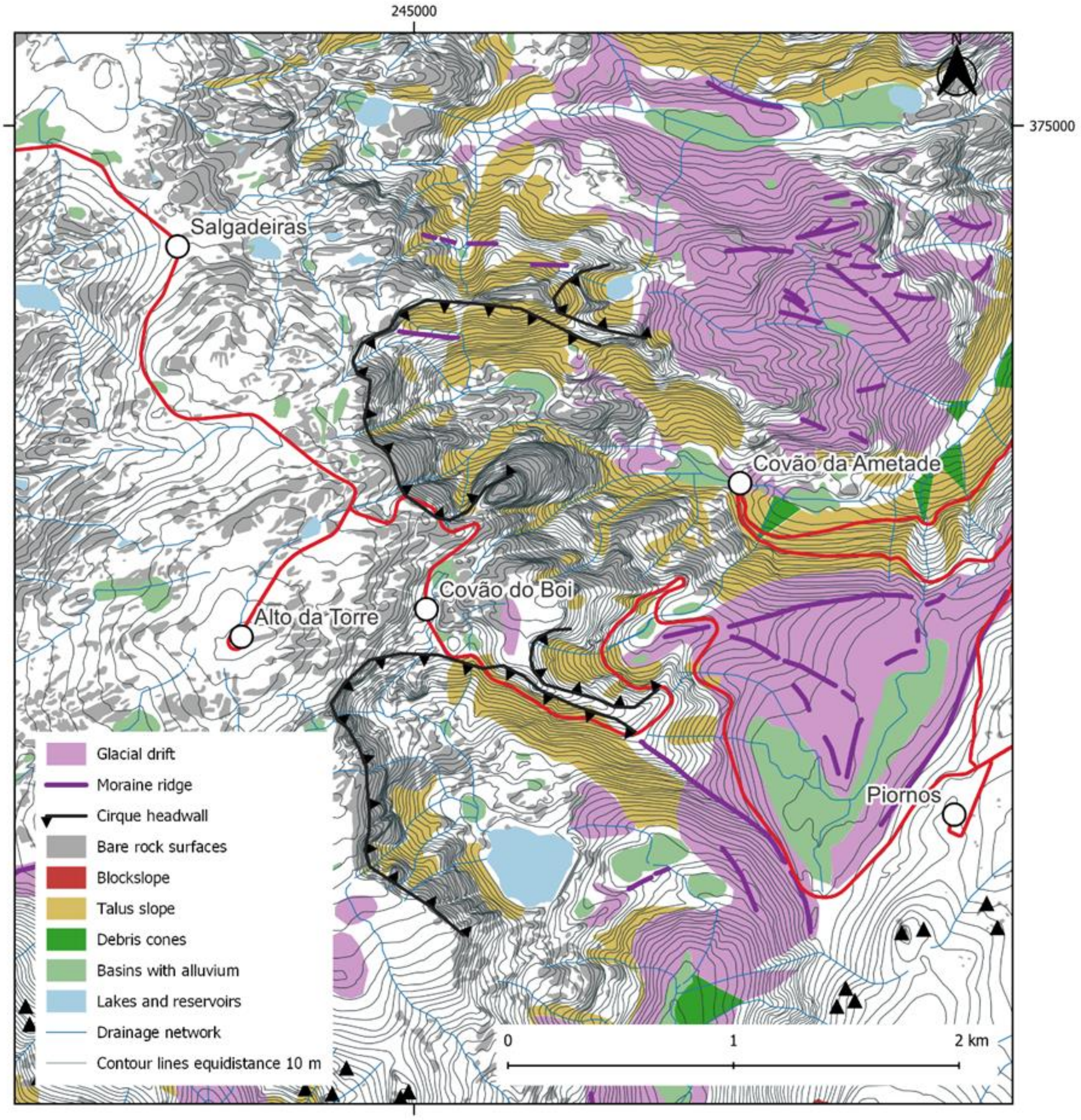


Figure 22. Main features of the glacial geomorphology of the Alto da Torre and its surroundings (adapted from Vieira 2004).

Stop 4. Covão do Boi
Granite columns, glacial and post-glacial erosion, glacial evolution of the Zêzere valley, the Lagoa Seca col, Pre-Weichselian glacial evidence.

At 1,840 m a.s.l., between the Alto da Torre, the glacial cirque of Covão do Ferro, the Zêzere glacial valley and the Cântaro Raso, a small, but very relevant col shows up - the Covão do Boi (Fig. 23). In this remarkable geosite, we find a set of granite columns, with diameters of 2 to 5 m and between 4 and 8 m in height, constituting a rare set of landforms. Before they surfaced, the granite columns were shaped under the surface due to the deep weathering of the granite, along a dense orthogonal joint network, that formed a thick weathering mantle. During the last glaciation the col was razed by glacial erosion that removed part of the weathering mantle and cut the top of fresh granite corestones. Following glacial retreat, water erosion continued the removal of the weathering mantle and the granite columns started to form at the surface. These granite columns are locally called cheese-piles, because they resemble, in a nutshell, the form of a stack of typical Serra da Estrela cheeses. The granite columns have been sampled for cosmogenic isotope exposure dating in 2020, confirming the postglacial age of the columns, and a manuscript is currently in preparation by Raab and colleagues.

Figure 23. Granite columns of Covão do Boi.

Stop 5. Alto da Torre
Elevated planation surfaces. Panorama to the Central Iberian Cordillera.

The Western Plateau with an elevation rising from about 1,500 m in the north, at Penhas Douradas, to 1993 m at Alto da Torre, is the highest summit in mainland Portugal (Fig. 24). The area is the highest remnant of the uplifted Paleogene planation surface, which has been stripped by erosion and still preserves wide flat areas, interrupted by several steps. These are controlled by tectonics, as well as lithology. Overall in the Estrela, the differences between the metasedimentary (schists, greywackes, shales) and the granites, prevail. Wide plateaus and rectilinear valleys have developed in the latter, while the former have generated narrow linear interfluves, deeply dissected by v-shaped and irregular valley, with a dense river network and meanders. In the plateaus, the different granite-types, together with tectonics, gave origin to the different in the landscape (Migon and Vieira, 2014).

Figure 24. The Alto da Torre plateau viewed towards the north.

Stop 6. Salgadeiras – Lagoas do Covão da Clareza
Plateau ice-field, glacial erosion, hanging valleys, overdeepenings, deglaciation, Holocene evolution of the Serra da Estrela.

The Salgadeiras - Lagoas do Covão da Clareza area at c. 1800 m a.s.l. shows a typical landscape of glacial erosion in the plateau, ressembling a Scandinavian fjell. The area shows extensively glacially scoured granite outcrops, marked by overdeepenings with numerous small ponds and lakes, which provide valuable sedimentary archives of the postglacial evolution of the Estrela. The area is also part of the biogenetic reserve and part of the Natura 2000 network and protected as a RAMSAR site.

The deglaciation of the Salgadeiras has occurred after 14.2 ka (Vieira *et al*. 2021), with glacierets possibly surviving in niches for longer. New rock samples from polished rock outcrops and a small moraine in the Salgadeiras are currently under investigation for cosmogenic isotope exposure dating (Vieira and Egli).

The Holocene evolution of the Serra da Estrela has been studied from a 14 m core from the Charco da Candieira at 1,410 m a.s.l. with the reconstruction of the paleoenvironmental conditions after c. 14.8 ka (Van der Knaap and Van Leeuwen, 1997). More recently, within the project HOLMODRIVE, an international team lead by the University of Lisbon, has been analyzing new sediment cores from Lagoa do Peixão between the Charco da Candieira and Salgadeiras, at c. 1,660 m a.s.l.

References

AGE (2017). Aspiring Geopark Estrela Application Dossier for UNESCO Global Geopark. Associação Geopark Estrela, Portugal.

Azevedo, M.R; Valle Aguado, B. (2006). Origem e Instalação de Granitóides Variscos na Zona Centro-Ibérica. In: Dias R, Araújo A, Terrinha P, Kullberg J.C, (Coord.), Geologia de Portugal no Contexto da Ibéria. 107-122p.

Bezembinder L, Niessen A (1989) Palynologisch en geomorfologisch onderzoek langs de bovenloop van de Rio Zêzere, Serra da Estrela. Unpublished report. Laboratory of Palaeobotany and Palynology, Utrecht, The Netherlands.

Cabral, F.A.V.P. (1884). Vestígios glaciários na Serra da Estrela. Revista de Obras Públicas e Minas, Lisboa. 435-459p.

Cabral, J. (2012). Neotectonics of mainland Portugal: state of the art and future perspectives. Neotectónica de Portugal peninsular: estado de la cuestión y perspectivas de futuro. Journal of Iberian Geology 38 (1). 71-84p.

Capdevila, R.; Corretge, G.; Floor, P. (1973). Les granitoides varisques de la Meseta Iberique. Bull. Soc. Geol. France. 209-228p.

Capdevila, R.; Floor, P. (1970). Les differents types de granites hercyniens et leur distribution dans le nord-ouest de l'Espagne. Bol. Geol. Miner. Espana 81. 215-225p.

Carrington da Costa, M. (1950). Notícia sobre uma carta geológica do Buçaco de Nery Delgado. Comunicações dos Serviços Geológicos de Portugal. 1-28p.

Cunha P.P.; Pena dos Reis, R. (1995). Cretaceous sedimentary and tectonic evolution of the northern sector of the Lusitanian Basin (Portugal). Cretaceous Research 16. 155-170p.

Cunha, P.P.; Pimentel, N.; Pereira, D.I. (2000). Sedimentary and tectonic signature of the betie compressíon clímax in Portugal: the late Vallesian-Turolian sedimentary discontinuity. Ciências da Terra 14. Univ. Nova Lisboa. 61-72p.

Daveau, S. (1969). Structure et relief de la Serra da Estrela. Finisterra 4(7). 33-197p.

Daveau, S. (1971). La glaciation de la Serra da Estrela. Finisterra. Revista Portuguesa de Geografia 6 (11). 5-40p.

Daveau, S. (1973). Quelques exemples d'évolution quaternaire des versants au Portugal. Finisterra, Lisboa. 5-45p.

Daveau, S. (1978). Le périglaciaire d'altitude au Portugal. Colloque sur le périglaciaire d'altitude du domaine méditerranéen et abords, Strasbourg.

De Vicente, G.; Cloetingh, S.; Van Wees, J.D.; Cunha, P.P. (2011). Tectonic classification of Cenozoic Iberian foreland basins. Tectonophysics 502(1-2). 38-61p.

De Vicente, G.; Vegas, R.; Muñoz-Martín, A.; Silva, P.G.; Andriessen, P.; Cloetingh, S.; González-Casado, J.M.; Van Wees, J.D.; Álvarez, J.; Carbó, A.; Olaiz, A. (2007).

Cenozoic thick-skinned and topography evolution of the Spanish Central System. Glob. Planet. Change 58. 335-381p.

De Vincente, G.; Vegas, R. (2009). Large-scale distributed deformation controlled topography along the western Africa–Eurasia limit: tectonic constraints. Tectonophysics 474. 124-143p.

Dias, R.; Ribeiro A. (2013). O Varisco do sector norte de Portugal. In: Dias R, Araújo A, Terrinha P, Kullberg J.C, (Eds). Geologia de Portugal, vol1, Escolar Edit. 59-71p.

Dinis, J.; Rey, J.; Cunha, P.P.; Callapez, P.; Pena dos Reis, R. (2008). Stratigraphy and allogenic controls of the western Portugal Cretaceous: an updated synthesis. Cretaceous Research 29. 772-780p.

Feio, M. (1952). A evolução do relevo do baixo Alentejo e algarve. Com. ser. geológicos Portugal 32, Lisboa.

Ferreira A.B. (1991). Neotectonics in northern Portugal. A geomorphological approach. Geomorph. N.F, Berlim, Estugarda, Suppl. BD.82. 73-85p.

Ferreira A.B. (1993). Manifestações geomorfológicas glaciárias e periglaciárias em Portugal. In: Carvalho G.S, Ferreira A.B, Senna-Martínez J.C, (eds.). O Quaternário em Portugal: Balanço e perspetivas. A.P.E.Q., Ed. Colibri. 75-84p.

Ferreira A.B. (2005). O Ambiente Físico. Vol1. Geografia de Portugal, (coord.) Medeiros C.A, Lisboa, Círculo de Leitores. 495p.

Ferreira, A.B. (1978). Planaltos e Montanhas da Beira, estudo de Geomorfologia. Mem. Centro Estudos Geográficos 4. 374p.

Ferreira, N.; Iglésias, M.; Noronha, F.; Pereira, E.; Ribeiro, A.; Ribeiro, M.L. (1987). Granitóides da Zona Centro Ibérica e seu enquadramento geodinâmico. In: Bea F, Carnicero A, Gonzalo J, Lopez Plaza M, Rodriguez Alonso M, (Eds.) Geologia de los Granitóides y Rocas asociadas del Macizo Hespérico, Rueda, Madrid. 37-51p.

Ferreira, N.; Vieira, G. (1999). Guia geológico e geomorfológico do Parque Natural da Serra da Estrela. PNSE-ICN, Ministério da Economia, Inst. Geológico e Mineiro. 111p.

Fleury, E. (1916). Sur les anciennes glaciations de la Serra d'Estrela. Paris, 162. 599-601p.

Julivert, M., Fontbote J., Ribeiro, A., Conde, L. (1974). Memória explicativa del Mapa Tectonico de la Peninsula Iberica y Baleares, Escala 1:1000000. Instituto Geológico y Minero de España, Madrid.

Lautensach, H. (1929). Eiszeitstudien in der Serra da Estrela (Portugal). Zeitschrift für Gletcherkunde 17. 324-369p.

Martínez-Catalán J.R, Aller J, Alonso J.L, Bastida F. (2009). The Iberian Variscan orogen. In: García-Cortés A, (Ed.) Spanish Geological Frameworks and Geosites - An Approach to Spanish Geological Heritage of International Relevance. IGME.

Martín-González, F. (2009). Cenozoic tectonic activity in a Variscan basement: evidence from geomorphological markers and structural mapping (NW Iberian Massif). Geomorphology 107. 210-225p.

Martin-Serrano, A. (1988). El relieve de la region ocidental zamorana. La evolucion morfológica de um borde del macizo hespérico. Inst. Estudios Zamoranos Florien de Ocampo, Zamora. 311p.

Meireles, C.; Castro, P.; Ferreira, N. (2014). On the presence of cadomian angular unconformity in Beiras Group (Central Portugal): cartographic, lithostratigraphic and structural evidences. Comunicações Geológicas 101, Esp. I. 495-498p.

Migoń, P.; Vieira, G. (2014). Granite geomorphology and its geological controls, Serra da Estrela, Portugal. Geomorphology 226. 1–14p.

Neiva A.M.R, Teixeira R.J.S, Lima S.M, Silva P.B. (2013). Idade, Origem e Protólitos de granitos variscos de três áreas portuguesas, Academia das Ciências de Lisboa. 13p.

Neiva, A.M.R.; Williams, I.S.; Ramos, J.M.F.; Gomes, M.E.P.; Silva, M.M.V.G.; Antunes, I.M.H.R. (2009). Geochemical and isotopic constraints on the petrogenesis of Early Ordovician granodiorite and Variscan two-mica granites from the Gouveia area, central Portugal. Lithos 11. 186-202p.

Nieuwendam, A., Vieira, G.; Woronko, B., Schaefer, C., & Johansson, M. (2020). Reconstructing cold climate paleoenvironments from micromorphological analysis of relict slope deposits (Serra da Estrela, Central Portugal). Permafrost and Periglacial Processes.

Oliveira J.T, Pereira E, Ramalho M, Antunes M.T, Monteiro J.H. (1992). Noticia Explicativa da Carta Geológica de Portugal, escala 1/500000, Serviços Geológicos de Portugal.

Pais, J.; Cunha, P.P.; Pereira, D.; Legoinha, P.; Dias, R.; Moura, D., Silveira A.B, Kullberg J.C, González-Delgado J.A. (2012). The Paleogene and Neogene of Western Iberia (Portugal). A Cenozoic record in the European Atlantic domain. Springer, Heidelberg. 156p.

Raab G., Dollenmeier W., Tikhomirov D., Vieira G., Migoń P., Ketterer M.E., Christl M., Stutz J., Egli M. (2022). Contrasting soil dynamics in a formerly glaciated and non-glaciated Mediterranean mountain plateau (Serra da Estrela, Portugal). Catena. https://doi.org/10.1016/j.catena.2022.106314

Ribeiro, A. (2013). A Evolução Geodinâmica de Portugal; os ciclos ante-mesozóicos. In: Dias R, Araújo A, Terrinha P, Kullberg J.C, (Eds.). Geologia de Portugal no contexto da Ibéria. Univ. Évora. 15-57p.

Ribeiro, A.; Kullberg, M.C.; Kullberg, J.C.; Manuppella, G.; Phipps, S. (1990). A review of Alpine tectonics in Portugal: Foreland detachment in basement and cover rocks. Tectonophysics 184. 357-366p.

Ribeiro, O. (1949). Le Portugal Central (livret-guide de l'excursion C). XVI Cong. Inter. Géogr. Lisboa.

Ribeiro, O. (1954). Estrutura e Relevo da Serra da Estrela. Bol. Real Soc. Esp. Hist. Nat. (homenaje Hernández-Pacheco), Madrid. 549-566p.

Rockwell, T.; Fonseca, J.; Madden, C.; Dawson, T.; Owen, L.A.; Vilanova, S.; Figueiredo P. (2009). Palaeoseismology of the Vilariça segment of the Manteigas-Bragança Fault in northeastern Portugal. In: Reicherter K, Michetti A.M, Silva P.G, (eds.) Palaeoseismology: Historical and Prehistorical Records of Earthquake Ground

Effects for Seismic Hazard Assessment. The Geological Society London, Special Publications 316. 237-258p.

Sant'Ovaia, H.; Martins, H.C.B.; Noronha, F. (2013). Oxidized and reduced Portuguese Hercynian granites associated with W and Sn hydrothermal mineralizations. Comunicações Geológicas, 100(1). 33-39p.

Santos, J.B.; Vieira, G.; Santos-González, J.; Woronko, B.; Redondo-Vega, J.M. (2020). Macrofabric and grain size analysis of moraines and other till deposits in the Serra da Estrela Mountains, central Portugal, Physical Geography, https://doi.org/10.1080/02723646.2020.1838136

Santos, R.M.P.; Tassinari, C.C.G. (2012). Different lead sources in an abandoned uranium mine (Urgeiriça, Central Portugal) and its environment impact, isotopic evidence. Geochemistry: Exploration, Environment Analysis 12. 241-252p.

Sousa M.B, Sequeira A.J.D. (1987). Carta Geológica de Portugal à escala 1/50000, Folha 10D – Alijó. Serv. Geol. Portugal, Lisboa.

Teixeira, C. (1955). Notas sobre a Geologia de Portugal: O Complexo Xisto-Grauváquico ante-Ordovícico. Porto (Eds.) Lisboa. 50p.

Van Den Brink, L.M.; Janssen, C.R. (1985). The effect of human activities during cultural phases on the development of montane vegetation in the Serra da Estrela, Portugal. Review of Palaeobotany and Palinology 44. 193-205p.

Van der Knaap, W.O.; Van Leeuwen, J.F.N. (1997). Holocene vegetation successions, altitudinal vegetation zonation, and climatic change in the Serra da Estrela. Review of Palaeobotany and Palinology, 97. 239-285p.

Vieira, G. (2004). Geomorfologia dos planaltos e altos vales da Serra da Estrela. Ambientes frios do Plistocénico Superior e dinâmica actual. PhD in Geography. University of Lisbon, 724p.

Vieira, G. (2008). Combined numerical and geomorphological reconstruction of the Serra da Estrela plateau ice-field, Portugal. Geomorphology 97. 190-207p.

Vieira, G.; de Castro, E.; Gomes, H.; Loureiro, F.; Fernandes, M.; Patrocínio, F.; Firmino, G.; Forte, J.P. (2020). The Estrela Geopark—From planation surfaces to glacial erosion. in Vieira G., Zêzere, J.L. & Mora, C. (Eds.), Landforms and Landscapes of Portugal, Springer: 341-357.

Vieira, G.; Nieuwendam, A. (2020). Glacial and Periglacial landscapes of the Serra da Estrela. in Vieira G., Zêzere, J.L. & Mora, C. (Eds.), Landforms and Landscapes of Portugal, Springer: 185-198.

Vieira, G.; Palacios, D.; Andrés, N.; Mora, C.; Vázquez Selem, L.; Woronko, B.; Soncco, C.; Úbeda, J.; Go-yanes, G. (2021). Penultimate Glacial Cycle glacier extent in the Iberian Peninsula: new evidence from the Serra da Estrela (Central System, Portugal), Geomorphology, 388, https://doi.org/10.1016/j.geomorph.2021.107781.

Vieira, G.; Woronko, B. (2021). The glaciers of Serra da Estrela, in Oliva, M., Palacios, D. & Fernández-Fernández, J.M. (Eds.), Iberia, Land of Glaciers, Elsevier, https://doi.org/10.1016/B978-0-12-821941-6.00020-7

Index

Photo by Sérgio Brito

ORGANIZATION AND SUPPORTERS:

IAG GEOMORPHOLOGY GEOMORPHOLOGIE AIG

APGeom Associação Portuguesa de Geomorfólogos

CEGOT Centro de Estudos de Geografia e Ordenamento do Território

CÂMARA MUNICIPAL DE COIMBRA

Copernicus Meetings The Professional Congress Organizer