World Geomorphological Landscapes

Gonçalo Vieira
José Luís Zêzere
Carla Mora *Editors*

Landscapes and Landforms of Portugal

Springer

World Geomorphological Landscapes

Series Editor

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Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, Nature often surprises us by creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they have received the highest possible recognition—they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to natural forces. For centuries, or even millennia, they have been shaped by humans who modified hillslopes, river courses, and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by Geomorphology—'the Science of Scenery'—a part of Earth Sciences that focuses on landforms, their assemblages, the surface and subsurface processes that moulded them in the past and that change them today. The shapes of landforms and the regularities of their spatial distribution, their origin, evolution, and ages are the subject of research. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations and not uncommonly result in considerable damage or even casualties.

To show the importance of geomorphology in understanding the landscape, and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a new book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume covers Portugal—a country which is not large in terms of area, but extremely endowed with magnificent landscapes. Its territory integrates all aspects of geomorphology, from varied coastal sceneries, including spectacular coves and rock arches of Algarve, through denudational plains and karstic massifs, residual mountain ranges and inselbergs, deeply entrenched valleys, to wild mountain environments of Serra da Estrela and Serra do Gerês which both host impressive evidence of Pleistocene glaciation. Some of them are better known to the international community than others, but all deserve to be shown to the world and this goal is fulfilled by this latest addition to the *World Geomorphological Landscapes* series.

The *World Geomorphological Landscapes* series is produced under the scientific patronage of the International Association of Geomorphologists—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union and the International Union of Geological Sciences. Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which sticks to the scientific rigour, is the most appropriate means to fulfill these aims and to serve the geoscientific community. To this end, my great thanks go to the editors of the volume, Profs. Gonçalo Vieira, José Luís Zezêre and Carla Mora, who agreed to coordinate the book and ensured that the final product is of high quality. I am also grateful to all individual contributors who agreed to add the task of writing chapters to their busy agendas and delivered excellent final products.

On more a personal note, I am particularly pleased to see the Portugal volume joining the series. I had the privilege to work in Portugal myself, exploring geomorphology of Serra da Estrela—the highest mountains of the country—in the stimulating company of Prof. Gonçalo Vieira. He was also kind enough to show me many other places and these trips leave no doubt that Portugal is a geomorphological destination not to be missed.

Wrocław, Poland

Piotr Migoń
Series Editor

Preface

Landscapes and Landforms of Portugal volume presents, for the first time, a series of synthesis chapters on landscape highlights of mainland Portugal, covering a wide diversity of geomorphological settings. These are presented with language and graphic styles that try to bridge-the-gap from professional scientists to undergraduate students, while being also accessible to all those interested in the earth sciences, to help for a better understanding of landscape evolution and specific features of the Portuguese landforms. The authors are physical geographers and geologists, mostly from Portuguese research institutions, all of them having had conducted research in the regions which they present. The main objective of the book is to provide a good overview of the geomorphology of Portugal, but also of its links with human occupation of the territory, geohazards and geoheritage management. This book is a tribute to Prof. António de Brum Ferreira, who has been an inspiration for generations of geomorphologists and students.

Landforms and Landscapes of Portugal volume is organized in five thematic parts, i.e. 1. geomorphological setting, dynamics and hazards, 2. coasts, 3. mountains and valleys, 4. urban areas, 5. geoconservation and geoparks. In each part, chapters are ordered geographically from north to south, covering most of mainland Portugal (Fig. 1).

Part I (*Geomorphological Setting, Dynamics and Hazards*) aims at presenting an introduction to the landscapes of Portugal, starting with a geomorphological synthesis by C. Ramos and A. R. Pereira (University of Lisbon, Chap. 1), followed by an overview of climate of Portugal by C. Mora and G. Vieira (University of Lisbon, Chap. 2), aiming to better understand geomorphological dynamics, especially the present-day one, but also providing a glimpse into Pleistocene and Holocene environmental conditions. J. L. Zêzere (University of Lisbon) presents a synthesis of geomorphological hazards at the national level (Chap. 3), while R. A. C. Garcia and S. C. Oliveira (University of Lisbon) present two examples of landslide hazardscapes (Chap. 4). Finally, S. C. Oliveira and co-authors (University of Lisbon) present a synthesis on land use planning and emergency management associated with geomorphological hazards in Portugal (Chap. 5).

Part II (*Coasts*) includes reviews of several important sectors of the Portuguese coastline, its geomorphological characteristics and evolution. M. A. Araújo (University of Oporto) presents interesting features of the coast north of the city of Espinho, covering the morphostructure, rock control on landforms, the littoral platform and also the Cenozoic deposits and geomorphological evolution (Chap. 6). C. Neto and colleagues (University of Lisbon) focus their review on the Tróia Peninsula, a sand spit located at the Sado Estuary, close to Setúbal, and discuss its geomorphological characteristics and dynamics, linking it to the littoral drift and Holocene sea-level change (Chap. 7). Moving southwards, A. R. Pereira (University of Lisbon) presents the remarkable southwest coast of Portugal, marked by its littoral platform, tectonics and sediments (Chap. 8). Finally, D. Moura (University of Algarve) and colleagues introduce the rocky section of the Algarve, marked by its scenic cliffs, but also depositional environments and karstic terrains (Chap. 9).

Part III (*Mountains and Valleys*) covers most interior Portugal and also some coastal mountains. P. Pereira and D. I. Pereira (University of Minho) present the landforms of the Peneda and Gerês mountains, located in the only National Park in Portugal and focus on

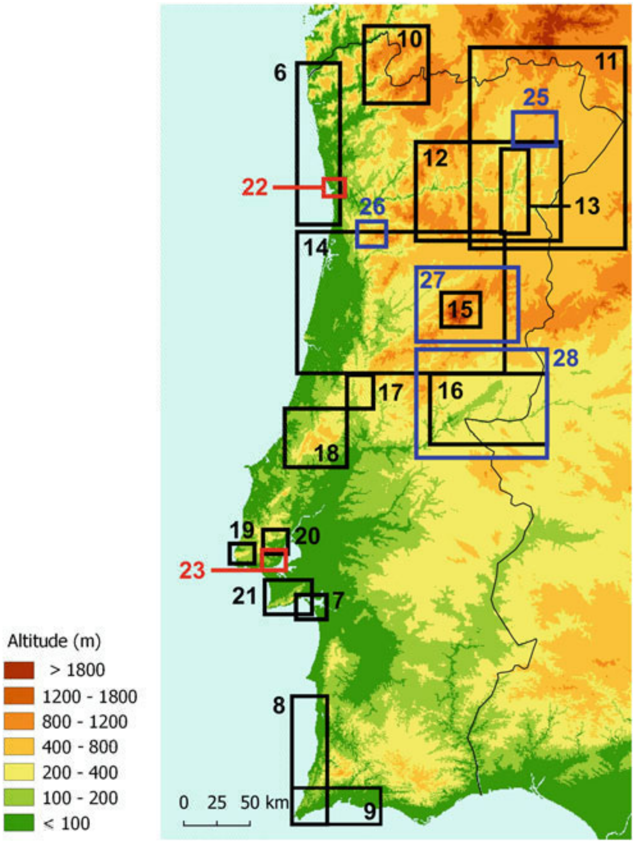

Fig. 1 Approximate location of the areas presented in the book with indication of the chapter numbers. Black—coasts (Chaps. 6–9) and mountains and valleys (Chaps. 10–21), red—urban areas (Chaps. 22–23), blue—geoparks (Chaps. 24–28). The limits are not exact, and especially in the geoparks, boundaries are irregular and correspond to administrative limits

granite and glacial landforms (Chap. 10). The same authors provide an overview of geomorphological landscapes of Trás-os-Montes and Alto Douro in north-east Portugal, focusing on long-term geological and landform evolution and on the interplay between planation, tectonics and fluvial erosion (Chap. 11). S. Pereira (University of Lisbon) presents geomorphology and its interplay with anthropogenic action in the scenic Alto Douro valley, with its impressive terraces associated with the famous vineyards of this UNESCO World Heritage (Chap. 12). S. Daveau (University of Lisbon) zooms in at the Vilariça and Longroiva tectonic basins, discusses their genesis and significance of landforms for the evolution of the human settlement in the territory, comparing both basins (Chap. 13). P. P. Cunha and colleagues (University of Coimbra and San José State University) show the geomorphology of the Mondego river valley, including its hydrological dynamics and fluvial terraces (Chap. 14). G. Vieira and A. Nieuwendam (University of Lisbon) discuss the main features of glacial and periglacial landforms and deposits of the Serra da Estrela, a landscape which surprises all geomorphologists due to the clear imprint in the landscape of cold Pleistocene dynamics (Chap. 15). P. P. Cunha and colleagues (Universities of Coimbra, Évora, Porto and Durham) introduce landforms of the Beira Baixa, mainly between Sarzedas and Monfortinho, a region with a very interesting evolution linking planation, tectonics, fluvial dynamics, Cenozoic deposition and residual relief (Chap. 16). The Sicó massif is presented by P. P. Cunha and colleagues (University of Coimbra), evidencing the significance of limestones, dolomites and marls, together with tectonics, for the evolution of the mountains, as well as of numerous landforms and deposits, which include fluvial and karstic phenomena, as well as marginal periglacial deposits (Chap. 17). M. L. Rodrigues (University of Lisbon) presents the limestone massif of Estremadura, its morphostructures and karstic landforms at different scales, showing also evidence of different generations of slope deposits and examples of geomorphosites (Chap. 18). M. C. Kullberg and J. C. Kullberg (University of Lisbon and New University of Lisbon) discuss the geological evolution and landforms of the Serra de Sintra, resulting from an igneous body intrusion and subsequent uplift deforming the surrounding, predominantly Mesozoic sedimentary rocks (Chap. 19). The area also shows significant testimonies of its Quaternary dynamics, including raised beaches and aeolianites, as well as excellent examples of granite landforms. J. L. Zêzere presents the geomorphology of the north of Lisbon region, a typical cuesta landform area, developed in Mesozoic and Cenozoic sedimentary terrains (Chap. 20). The author presents its geomorphological evolution dominated by fluvial incision and differential erosion and also the present-day contemporary geomorphological dynamics, dominated by mass movements triggered by earthquakes and, more frequently, by different types of rainfall events. Finally, the Arrábida Chain, presented by Fonseca and co-authors (University of Lisbon), is dominated by the small but very interesting Serra da Arrábida, a limestone massif showing an almost perfect structural control, coinciding with an anticline, southbound by a fault scarp (Chap. 21). This mountain has been described as one of the finest examples of the Alpine orogenesis in Portugal.

Part IV is dedicated to the geomorphology of the two largest cities in Portugal: Lisbon and Oporto. In Oporto, L. Soares and C. Bateira (University of Oporto) discuss the geomorphological setting of the town, built over granites associated with a narrow belt of metasediments, and marked by the deep incision of the Douro valley (Chap. 22). These conditions favour the occurrence of slope movements, major river flooding and erosion associated with ocean dynamics. T. Vaz and J. L. Zêzere (University of Lisbon) present the geomorphic setting of Lisbon and discuss the main geohazards affecting the urban area, which are dominated by earthquakes and also by landslides induced by earthquakes (Chap. 23).

Part V aims at covering geoconservation in Portugal and includes chapters on UNESCO Global Geoparks of mainland Portugal, as well as on the recent candidate that will be classified in early 2020. Portugal has been one of the leading countries in the promotion of UNESCO Global Geoparks, and although not all focusing on geomorphological phenomena *per se*, Geoparks always include geomorphic geosites. Their role in regional sustainable development and promotion of geology and geomorphology, and geoconservation makes them excellent examples of the applicability of the science of geomorphology. Part V initiates with an overview of geoconservation in Portugal, mainly targeting at geomorphological heritage, by J. Brilha and P. Pereira (University of Minho, Chap. 24). This initial chapter is followed by four chapters on the Geoparks, which are, from north to south: the Terras de Cavaleiros Global Geopark: A UNESCO Global Geopark by D. I. Pereira and P. Pereira (Chap. 25), the Arouca UNESCO Global Geopark: Geomorphological Diversity Fosters Local Development by A. Sá (University of Trás-os-Montes and Alto Douro Chap. 26), The Estrela Geopark—From Planation Surfaces to Glacial Erosion by G. Vieira and colleagues (University of Lisbon and Association Geopark Estrela, Chap. 27), and the UNESCO Naturtejo Global Geopark: The Culture of Landscape by C. N. Carvalho and J. Rodrigues (Geopark Naturtejo da Meseta Meridional, Chap. 28).

Lisbon, Portugal
November 2019

Gonçalo Vieira
José Luís Zêzere
Carla Mora

Acknowledgements

This book was only possible to prepare thanks to the invitation and continuous support provided by Prof. Piotr Migoń, who visited Portugal several times and is, clearly, a friend of the Portuguese geomorphology. We are sincerely thankful for this opportunity.

The numerous co-authors of the chapters are the soul of the book and have openly accepted to collaborate in this challenge, which took significantly longer to prepare than we envisaged. They have been patient and understood well the challenges associated with bringing together so many different authors, in hectic times for most scientists. We are thankful for their contributions and support.

Mr. Duarte Fernandes Pinto has agreed to provide, free of charge, his excellent aerial photographs from Portugal, which he makes available at the blog "A Quinta Dimensão" (http://portugalfotografiaaerea.blogspot.com). We are extremely thankful for his contribution to several chapters of the book.

Finally, we thank Springer for their continuous editorial support during the preparation of the manuscripts and editorial work.

Lisbon, Portugal
November 2019

Gonçalo Vieira
José Luís Zêzere
Carla Mora

In Memoriam—António De Brum Ferreira

Prof. António de Brum Ferreira at a till outcrop in the Serra da Estrela in June 2001

António de Brum Ferreira (1941–2013) was born in the island of São Miguel (Azores) in February 1941. In 1960, he started studying geography at the University of Lisbon and was part of a generation of prestigious Portuguese geographers. In 1966, he began his career as assistant in the Department of Geography, at the Faculty of Letters of the University of Lisbon, and went through all academic categories until he was appointed Full Professor of Physical Geography in 1990.

António de Brum Ferreira was Director of the Research Area on Physical Geography and Environment at the Center of Geographical Studies, and was a founding member and the first President of the Portuguese Association of Geomorphologists. In addition, he was a founding member of the European Center on Geomorphological Hazards (CERG), supported by the Council of Europe.

He authored numerous scientific papers, including tens of articles in international and national journals, in the fields of landform evolution, morphotectonics, glacial and periglacial geomorphology, slope movements, natural hazards, climatology and regional geography.

In 1966 he wrote “The Graciosa Island”, his dissertation of graduation, still very influenced by the Regional Geography methods of the 1960s. From 1968 to 1970, António de Brum Ferreira had an internship at the Universities of Toulouse and Clermont-Ferrand in France and became interested in detailed geomorphological mapping, bringing to Portugal the concept and the methodology. In 1978, he published “Plateaus and mountains of the North of Beira. Study of Geomorphology”, his Ph.D. thesis, a work on evolutionary geomorphology that is still a reference work in Portugal, followed by geographers, geologists and other Earth scientists.

In the 1980s and 1990s, António de Brum Ferreira became interested in periglacial and glacial morphogenesis, coordinating a large survey on the Pleistocene glaciation of Serra do Gerês, published in 1999 (in co-authorship with Juan Ramón Vidal Romani, José Luís Zêzere and Maria Luísa Rodrigues). He also coordinated the Portuguese Science and Technology funded project (Program Praxis XXI) “Estrela—Geomorphological and Biophysical Processes and Landscape Units in Mediterranean Mountain Environment. Application to Serra da Estrela", which started in 1998.

In 1979 António de Brum Ferreira accompanied and surveyed the events of slope instability in the region north of Lisbon, namely at Calhandriz and Adanaia, and deepened research on the subject since the mid-1980s. This topic, including issues of hazard and risk, focused his attention until the end of his scientific career. In 1984 he presented "Mouvements de terrain dans la Région au Nord de Lisbon" at the first major world conference dedicated to the subject, held in Caen (France). Integrated in a network of European researchers structured around the CERG, António de Brum Ferreira was the coordinator of a Portuguese team that participated in several European projects, which resulted in many publications in international reference journals. The list of projects includes the TESLEC—*The temporal stability and activity of landslides in Europe with respect to climatic changes* (1994–1996), the Newtech—*New technologies for landslide hazard assessment and management in Europe* (1996-98) and the ALARM—*Assessment of Landslide Risk and Mitigation in Mountain Areas* (2001–2004).

Still within the scope of the CERG, António de Brum Ferreira involved the Department of Geography of the University of Lisbon in an ERASMUS network consisting of major European universities, promoting high-level teaching and internationalization of several generations of young researchers of the Center of Geographical Studies. Within the framework of this ERASMUS network, the "Fifth European intensive course on Applied Geomorphology: Mediterranean and urban areas" was organized in Lisbon in 1996, with 46 participants from 10 European universities.

António de Brum Ferreira's involvement in advanced training is evident in the list of his doctoral students which pursued academic careers in physical geography: Maria João Alcoforado, Ana Ramos Pereira, Catarina Ramos, José Eduardo Ventura, José Luís Zêzere, Maria Luísa Rodrigues, António Martins, and Gonçalo Vieira.

Those who had the privilege of working with António de Brum Ferreira, have strong and good memories of him as an extremely rigorous and demanding researcher and professor with a remarkable intellectual honesty and an enormous passion for geomorphology. The ability to create a school, based on solid scientific knowledge, is an invaluable legacy that Prof. Brum Ferreira left to the Portuguese Geomorphology and this book is a tribute to him from a large number of Earth Scientists who have either directly collaborated with him, or benefited directly or indirectly from his influential work.

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Part I

Geomorphological Setting, Dynamics and Hazards

Landscapes of Portugal: Paleogeographic Evolution, Tectonics and Geomorphology

1

Catarina Ramos and Ana Ramos-Pereira

Abstract

This chapter synthesizes the most relevant aspects of geology, tectonics and geomorphology of Portugal. Its main purpose is to frame, in a morphostructural point of view, the more specific chapters on Portuguese geomorphological landscapes. It includes a summary of (i) the main evolutionary stages of the Portuguese territory, as well as the present tectonic framework of Portugal's mainland, Azores and Madeira archipelagos, and (ii) the main regional features of the geomorphological units. The synopsis is based on the scientific publications of many colleagues, physical geographers and geologists, who with their work contributed, over the years, to the geomorphologic knowledge of the country. Professor António de Brum Ferreira was the "greatest teacher" of Portuguese geomorphologists, to whom many of us owe the taste, rigour, the practice and the knowledge of geomorphology.

Keywords

Portugal • Paleogeographic evolution • Geotectonical framework • Regional geomorphological units

1.1 Introduction

Over time, there have been many publications, of both Portuguese and international researchers, on the geological and geomorphological characteristics of Portugal and its geodynamics, in both the fields of geology and physical geography. The majority are related to specific subjects and limited areas of the country, whose contributions to the geomorphology of Portugal were, over time, compiled in synthetic works, published in different languages. The first synthesis on the scientific Geography of Portugal (with emphasis on geomorphology) is due to the German geographer Hermann Lautensach (volume I 1932 and volume II 1937). This work, written in German, was poorly disseminated among Portuguese scientists, given the language barrier. Volume I, with some updates by Lautensach in 1944, was translated into Portuguese and later included in another synthesis by Ribeiro et al. (1987). Almost 20 years after Lautensach, in 1955, the Portuguese geographer Orlando Ribeiro updated and synthesized the geographical knowledge of Portugal, giving particular emphasis to geomorphology, in a book written in Spanish, included in the series of volumes on the *Geografia de España y Portugal*, edited by Manuel de Terán. Two decades later, nine geologists (eight Portuguese and one Polish) published, in French, in Ribeiro et al. (1979), the first synthesis of the evolution and geological characteristics of Portugal. In 1981, the first geomorphological map of mainland Portugal, at a 1:500,000 scale, and explanatory report were published in French by Ferreira (1981), with a major contribution from António de Brum Ferreira. In the same decade, the French–Portuguese geographer Suzanne Daveau compiled the texts of Lautensach and Ribeiro introducing what she called "Comments and Updates" in a Portuguese four-volume compilation, on the Geography of Portugal, of which Volume I (Ribeiro et al. 1987) relates to geomorphology. In 2004, with the coordination of Feio and Daveau (2004), the Portuguese Association of Geomorphologists published a compilation of several works, from physical geographers and geologists, on the major regional relief units of mainland Portugal.

The great advance of scientific knowledge on the paleogeographic evolution of Portugal and on the recent and present-day dynamics of its physical environment led to recent publications in the twenty-first century. There are two main syntheses written in Portuguese: "Geografia de Portugal - O Ambiente Físico" (Ferreira 2005) and "Geologia de

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Portugal" (Dias et al. 2013a, b). The first, written by physical geographers and coordinated by António de Brum Ferreira, is a volume included in a wider "Geography of Portugal" directed by Carlos Alberto Medeiros. Volume I devotes particular attention to the geomorphology of Portugal, gathering for the first time in one book, the most relevant aspects of physical geography of mainland Portugal and the Azores and Madeira archipelagos. The volume presents paleogeographic evolution of Portugal, geomorphologic contrasts, recent and present-day dynamics, as well as natural resources and risks.

The other synthetic publication (Dias et al. 2013a, b) is written mainly by geologists and was published in two volumes: volume I, on the pre-Mesozoic Geology of Portugal, and volume II, on the Meso-Cenozoic Geology of Portugal.

Pereira et al. (2014) presented a hierarchical classification of the geomorphological units of mainland Portugal, with a distinct methodology from previous authors. They define three hierarchical levels of geomorphological landscapes: (i) the first level is the morphostructural units (platforms, sedimentary basins and young Alpine mountain ranges, the latter not represented in mainland Portugal), (ii) the second level includes 10 regional geomorphological units, which are subordinate to the previous gross division, and (iii) the third level corresponds to the 56 major sub-units that subdivide the second level. This classification of the geomorphological landscape was based on a three-step methodology: (i) identification of relief patterns in 2008 SRTM (Shuttle Radar Topography Mission) radar images, with 90 m resolution, (ii) fieldwork for validation, correction or redefinition of the sub-units and (iii) analysis of quantitative parameters for each unit.

This chapter is mainly based on a review of Feio and Daveau (2004), Ferreira (2005), Dias et al. (2013a, b) and Pereira et al. (2014) and has two main objectives: (i) to present the key stages and the main geological features of Portugal, as well as to provide the background to the present geotectonic setting and, and (ii) to characterize the diversity of Portugal's large regional relief units. It is a summary of the main geological and geomorphological characteristics of the Portuguese territory, leaving further analysis of the geomorphological landscapes of Portugal to the following chapters.

1.2 Paleogeographic Evolution and Geomorphology of the Portuguese Mainland

The Portuguese territory, with an area of 92,225 km^2, comprises mainland Portugal and the Azores and Madeira archipelagos (Fig. 1.1). The mainland (89,102 km^2) is located between 37 and 42° N in the west of the Iberian Peninsula, bordered by Spain to the north and east, and the Atlantic Ocean to the west and south. In the North Atlantic, the archipelago of the Azores (2322 km^2) is set between 37 and 40° N, about 1500 km to the west of the mainland, and the archipelago of Madeira (801 km^2) lies between 30 and 33° N, 800 km southwest of the mainland.

From a morphostructural point of view, mainland Portugal consists of three units (Fig. 1.2): (i) the Iberian or Hercynian Massif (also known as the Hesperic Massif), mostly of Paleozoic age, (ii) the slightly deformed Meso-Cenozoic sedimentary borderlands of the Iberian Massif, forming the western or Lusitanian Basin and the southern or Algarve Basin and (iii) the Lower Tagus and Alvalade Sedimentary Basins, of Cenozoic age. The islands of the Azores and Madeira form a separate unit and represent the highest points of submarine mountains that rise above the ocean surface, being of volcanic origin and of Cenozoic age.

1.2.1 The Paleozoic Evolution

Portugal's geological and geomorphological characteristics are mainly due to two Wilson cycles, according to the theory of plate tectonics: the Variscan (540–270 Ma) and the Tethys/Atlantic (250–0 Ma) (Ribeiro 2013a). Although pre-Cambrian terrains outcrop in Portugal, they are of limited extent, as Variscan deformation reached a great intensity in Iberia, which somehow attenuated ante-Hercynian remains. Therefore, in the area presently occupied by Portugal, only one large orogenic cycle can be considered during the Paleozoic era (Ribeiro et al. 1979; Ferreira 2005). It is responsible for the origin of the Hercynian Massif, which resulted from the destruction of the western sector of the Hercynian or Variscan chain, at the end of the Paleozoic, which in morphostructural terms corresponds to a platform.

The Iberian Massif, extending from north to south, covers about 70% of mainland Portugal (Fig. 1.2). It is composed of magmatic and metamorphic rocks, with prevailing granitoid rocks and various types of schist and shales with varying grades of metamorphism. The latter are distributed throughout the Iberian Massif in Portugal, although with a much lower grade in the far south, while the granitoid rocks are located mainly in the northwest and central-north of the country, albeit with some outcrops in the Alentejo (Figs. 1.2 and 1.3).

In Portugal, the Variscan structures have a general NW–SE direction. The zones which show similar evolution of stratigraphy, geometry of tectonic deformations, nature of magmatism and intensity of metamorphism are arranged perpendicular to this direction. Thus, in general terms, from NE to SW, the following zones occur (Fig. 1.2): the Central Iberian Zone (CIZ), the Ossa Morena Zone (OMZ) and the

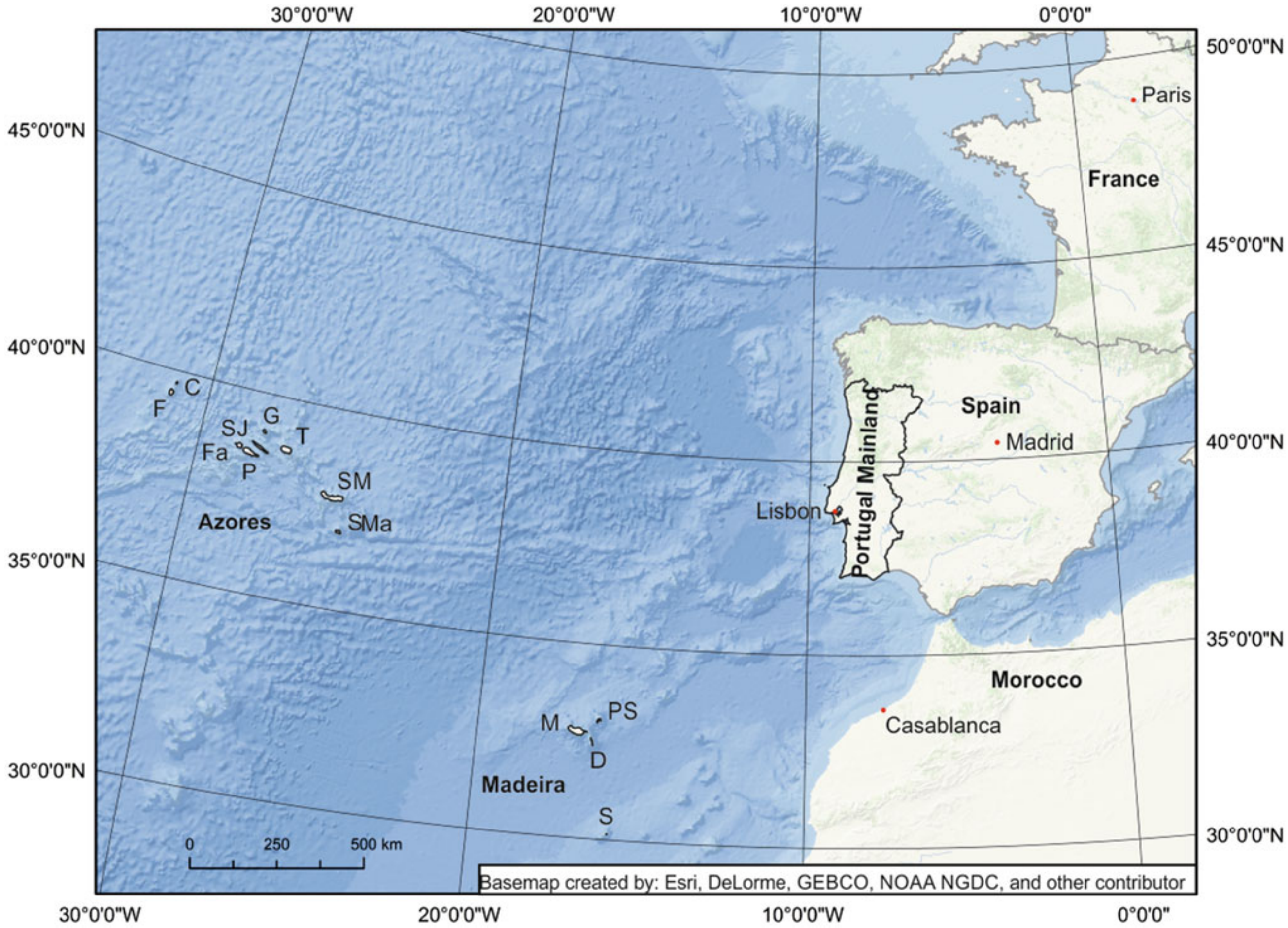

Fig. 1.1 Location of the Portuguese territory (mainland Portugal and the Azores and Madeira archipelagos). Islands of Azores: C (Corvo), F (Flores), Fa (Faial), G (Graciosa), P (Pico), SJ (São Jorge), SM (São Miguel), SMa (Santa Maria), T (Terceira). Islands of Madeira: D (Desertas), M (Madeira), PS (Porto Santo), S (Selvagens)

South Portuguese Zone (SPZ). The CIZ corresponds to the axial zone of the Variscan chain and together with the OMZ composes the inner part of the Variscan Orogen. In these two zones, the rocks are older, more deformed and more intensely metamorphized, showing also extensive magmatic intrusions. The SPZ corresponds to the external part of the Variscan Orogen, with the most recent and lower-grade metamorphic Paleozoic sedimentary series, with fewer magmatic intrusions.

The Variscan cycle in Iberia consisted of four phases (Ribeiro 2013a): Phase 1 (540–420 Ma, Cambrian, Ordovician and Silurian) was dominated by a plate divergence regime that led to the opening of Paleozoic oceans, bordered by passive margins; Phase 2 (420–390 Ma, Upper Silurian to Middle Devonian) showed the beginning of subduction in the margins of the Paleozoic oceans; obduction of ophiolitic blades and high-pressure thermal metamorphic events occurred; Phase 3 (390–300 Ma, Middle Devonian to Upper Carboniferous) showed continental collision and orogenesis, with abundant granitoids and high-temperature metamorphism; Phase 4 (300–270 Ma, Upper Carboniferous to Middle Permian) showed intracontinental transcurrent deformation followed by orogenic collapse.

The lithostructural characteristics of the Hercynian Massif depend on the various phases of the Variscan cycle. Phase 1 (540–420 Ma) was dominated by extensional regime, with expression in the sedimentary record and in the magmatism. The lithospheric stretching process formed deep basins in the CIZ that were filled by thick marine facies formations, which integrate the Dúrico-Beirão Supergroup (Ferreira 2005), previously known as ante-Ordovician Schist–Greywacke Complex (Ribeiro et al. 1979). This deposition of turbidite and interturbidite sediments is typical of deep marine and continental margin (shelf and slope) environments. At the same time, but further south, in the Ossa Morena Zone, several shallow basins formed, which were filled over time by sediments of different facies: terrigenous at the base,

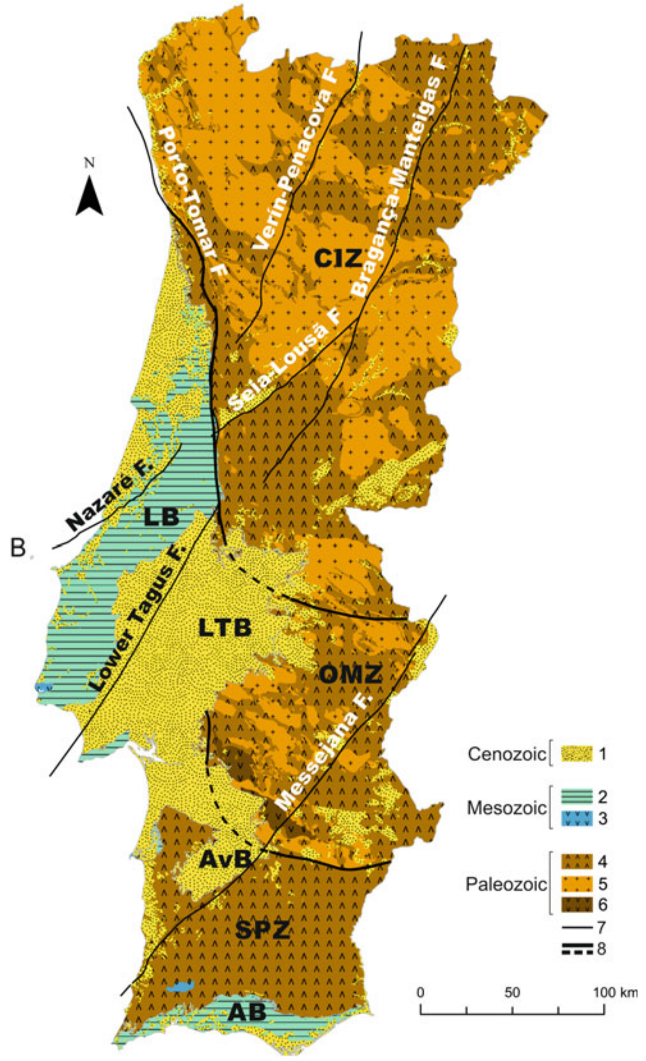

Fig. 1.2 Morphostructural units and lithology of mainland Portugal. 1 Cenozoic sedimentary rocks (mainly sands, sandstones, clays, limestones and marls), 2 Mesozoic sedimentary rocks (mainly limestones, marls, sandstones and clays), 3 Mesozoic igneous rocks (mainly granites and syenites), 4 Paleozoic metasediments, 5 Paleozoic plutonic rocks (mainly granites), 6 Paleozoic volcanic rocks (porphyry and others), 7 main faults, 8 Variscan unit boundary of the Iberian Massif, B Berlengas islands location, AB Algarve Basin, AvB Alvalade Basin, CIZ Central Iberian Zone, LB Lusitanian Basin, LTB Lower Tagus Basin, OMZ Ossa Morena Zone, SPZ South Portuguese Zone, F fault

Fig. 1.3 Localities mentioned in the text: dots—localities and places, numbers—mountains; lines—main rivers. Mountains: 1 Açor, 2 Aire, 3 Alvaiázere, 4 Alvão, 5 Alvelos, 6 Amarela, 7 Arada, 8 Arrábida, 9 Barroso, 10 Boa Viagem, 11 Bornes, 12 Cabreira, 13 Caldeirão, 14 Candeeiros, 15 Caramulo, 16 Cercal, 17 Coroa, 18 Estrela, 19 Freita, 20 Gardunha, 21 Gerês, 22 Grândola, 23 Larouco, 24 Lousã, 25 Marão, 26 Mesquita, 27 Monchique, 28 Monte Figo, 29 Montejunto, 30 Montemuro, 31 Montesinho, 32 Muradal, 33 Nogueira, 34 Peneda, 35 Portel, 36 S. Mamede, 37 Sicó, 38 Sintra, 39 Vigia

carbonates and terrigenous again at the top. It shows an evolution from a clearly continental environment to a coastal carbonate platform and then again to a continental environment (with sandstones and mudstones; Mata et al. 2006). In some of the OMZ basins, intense magmatic activity also occurred (in the Cambrian), giving rise to volcanic rocks and volcano–sedimentary complexes. In the Cambrian, the CIZ basins were deeper than those of the OMZ, but in the Ordovician the situation was reverse, increasing the depth of the latter relatively to the CIZ basins (Ribeiro et al. 2007). From the Cambrian to the Ordovician, the crustal stretching process intensified in the OMZ but, on the contrary, practically ceased in CIZ, with a decrease in basin subsidence. The deep sea that existed during the Cambrian became narrower and lost depth. It then began receiving quartz sands, usually deposited in continental shelf environments (passive margin). These would undergo metamorphism by the end of the Variscan cycle, so that the well-known Armorican quartzites, outcropping in different areas in Portugal, came into being (Bolacha 2014). These quartzites presently form higher relief due to its resistance against erosion. In the Lower Ordovician, a transition to coastal facies occurred from southwest to northeast, from a distal and deeper continental shelf of the OMZ to a shallower one in the NE sector of the CIZ. During the Lower Paleozoic "alternating ridges and grooves were created, where the thickness (and type) of sediments may vary considerably; there are also indications of tectono-sedimentary instability that produced gaps in the Paleozoic series" (Ribeiro 2013a: 25). In the Silurian, the increase in paleogeographic differentiation is shown in the sedimentary and magmatic records. The various sedimentary gaps recorded during the Silurian seem to reflect tectonic instability, preceding the Variscan tectonogenesis (Ferreira 2005).

Phase 2 of the Variscan cycle (420–390 Ma, Upper Silurian to Middle Devonian) was dominated by the closing of the Paleozoic oceans (Rheic and Paleo-Tethys), resulting in the area now occupied by the Portuguese territory in the transformation from passive to active continental margins. The autochthonous sediments of the Dúrico-Beirão Supergroup were the first to deform and to be subjected to metamorphism. Being a continental margin deposit, it forms a thick sequence of shales and metagreywackes, which make up a large part of the CIZ substrate (Fig. 1.2). Subduction is widespread in all active margins, and obduction occurred in restricted segments of these margins. As a result, intrusive magmatic rocks formed, with which volcanic activity episodes were also associated, as well as ophiolite complexes linked with obduction (Bolacha 2014).

Phase 3 (390–300 Ma, Middle Devonian to Upper Carboniferous) was essentially dominated by continental collision processes and subsequent orogenesis (Hercynian or Variscan Cordillera Formation), albeit with considerable regional asymmetries. The sedimentary records, predominantly marine and of continental margin, evolved to molasses deposited in intra-mountain basins (e.g. Ribeiro et al. 1979; Ribeiro 2013a) in the north and centre of Portugal. This is the case of the Douro Carboniferous groove, which is important for the quality of its anthracite content. Concomitantly, abundant synorogenic magmas, mostly of granitoid composition, between 320 and 310 Ma old, were produced (Ribeiro 2013a). In the south of the territory, the subduction (of the Rheic Ocean) continued along the margins of the OMZ, leading to the formation of igneous complexes in the Beja region of OMZ (Figs. 1.2 and 1.3) and marine volcano–sedimentary complexes in the SPZ. In the latter, the Iberian Pyrite Belt stands out, important for its polymetallic sulphide deposits. Marine sedimentation continued in the SPZ, up to the Carboniferous, and is thus synorogenic, becoming younger from NE to SW. The last marine sediments (pelites and greywackes of the Baixo Alentejo Flysch Group; Figs. 1.2 and 1.3) are derived from erosion of inland formations, i.e. located N and NE (Oliveira 1983; Oliveira et al. 2006, 2013). Metamorphism and deformation of these formations also decreased gradually to the SW, showing the progression of the orogenic wave (Araújo 2013).

In Phase 4 (300–270 Ma, Upper Carboniferous to Middle Permian), transcurrent intracontinental deformation followed by orogenic collapse (Ribeiro 2013a, b) occurred. The persistence of compression due to the continental collision between the continents of Laurasia and Gondwana (in the north of which Iberia was located) led to: the formation of the supercontinent Pangea and the spread of deformation to the interior of Iberia. In the north and the south, Iberia was affected by E–W strike-slip faults (North Pyrenean Fault and Azores–Gibraltar Fault; Ribeiro 2002), while inland, predominantly NNE–SSW strike-slip faults were formed (Verín–Penacova, Bragança–Manteigas, Messejana faults; Ribeiro 2002, 2013a) (Fig. 1.2). This corresponds to the Late Variscan deformation (Mateus and Noronha 2010). The synorogenic magmatism, between 310 and 320 Ma, was followed by late magmatism. The granitoids of this late stage often formed zoned massifs, surrounded by aureoles of contact metamorphism (Azevedo and Aguado 2013).

Over circa 70–90 Ma at Permian–Triassic boundary, there is sedimentary gap in the west of Iberia. During part of this period, the Variscan chain was razed and a platform formed: the Iberian Massif (Fig. 1.4). This platform was affected later by tectonic movements of the subsequent cycle (Thetis/Atlantic), which completely changed its geomorphologic features.

1.2.2 The Mesozoic Evolution

During the Mesozoic Era (251–65 Ma), the paleogeographic evolution of Portugal was marked by the beginning of a new Wilson cycle (Tethys/Atlantic or Alpine) and by a predominantly distensive tectonics that led to the formation of the Lusitanian (west of the Iberian Massif) and Algarve (to the south) Sedimentary Basins. These basins were infilled by sediments of Mesozoic and Cenozoic ages (Fig. 1.2). Presently, the Algarve Sedimentary Basin comprises the extreme south of mainland Portugal and extends in a W–E direction over about 140 km, with the width varying from 3

Fig. 1.4 Angular unconformity with stratigraphic hiatus between the Paleozoic (Carboniferous pelites and greywackes) and the Mesozoic rocks (Triassic fluvial sandstones) at Telheiro Beach (western Algarve) (photograph by Diamantino Ínsua Pereira, University of Minho, Portugal)

to 25 km. It corresponds to an ENE–WSW sedimentary continental slope faulted by submeridian tectonic lines, which differentiated sedimentary conditions between the western and eastern Algarve. In general, the sedimentary series are thicker and deeper to the SSE (Ferreira 2005). The Lusitanian Basin corresponds to a continental margin distensive basin of Atlantic-type non-volcanic rift. It extends over 200 km, following roughly NNW–SSE direction, and reaches 100 km wide, 2/3 of which are emerged. Sedimentation reaches a maximum thickness of about 5000 m (Kullberg et al. 2013). The reconstruction of the key Mesozoic events in Portugal is based on evidence from this basin.

At the beginning of the Mesozoic, the Iberian Massif was part of Pangea. The lithospheric stretching and faulting affecting this supercontinent led to its fragmentation and opening of the Tethys and Atlantic oceans. Iberia was located in a hinge position regarding the new boundaries of the lithospheric plates and the two oceans. A triple junction connecting the opening of the two oceans developed in the intersection of the southern (Tethys) and western (Atlantic) margins (Ribeiro 2013b). Consequently, the formation of the western Portuguese margin depended on the divergence between the Eurasian and American plates, associated with the opening of the Atlantic; in turn, the formation of the southern margin was controlled by differential movement between the African, Eurasian and American plates, associated with the opening of the Tethys (Fig. 1.5A). "The boundary between the African and Eurasian plates in the Iberian region began to develop from the Triassic as a left-lateral transtensional boundary due to the approximately E–W movement between Eurasia and America and NW–SE between Africa and America" (Terrinha et al. 2013: 126). In the case of the Algarve Basin, the normal faults, associated with the break-up of Pangea, are E–W directed, as the Azores–Gibraltar Fault, and dip southwards, interfering with the NNE–SSW normal faults and controlling the sedimentation in the western Algarve zone (Ribeiro et al. 1996). The normal fault system is sub-parallel to the Porto–Tomar Fault in the centre and north of Portugal (Fig. 1.2), which guides the Lusitanian Basin individualization. These large Variscan tectonic lines were thus reactivated as normal faults.

The opening of the Atlantic Ocean took place in stages, from south to north, through the formation of several basins, which preceded oceanization (Terrinha et al. 2005; Kullberg et al. 2013). Kullberg et al. (2013) distinguished 4 phases of rifting (crustal swelling followed by thermal subsidence and distension) in the Iberian western margin (IWM) between the Triassic and Lower Cretaceous, which had extreme consequences on the structure and infilling of the basins.

In the IWM, rifting began in the Late Triassic (~210 Ma). As a result, between 200 and 180 Ma the Iberian Massif was crossed by dykes (e.g. along the Messejana Fault; Fig. 1.2). The distension caused the formation of grabens and half-grabens, where a detrital complex forms the base of the Mesozoic formations. These are the so-called Grés de Silves (Silves Sandstones) and the Margas de Dagorda (Dagorda Marls), deposited in semi-arid or subtropical climate conditions with a pronounced dry season (Ferreira 2005). The former are essentially red siliciclastic formations of alluvial fan type and eolianites. Evaporites (rock salt and gypsum) deposited in the centre of the lagoons are frequent in the Dagorda Marls. These formations are followed by dolomites, marls and limestones. The progressive enrichment in carbonates and evaporites is interpreted as the transition from a continental to marine

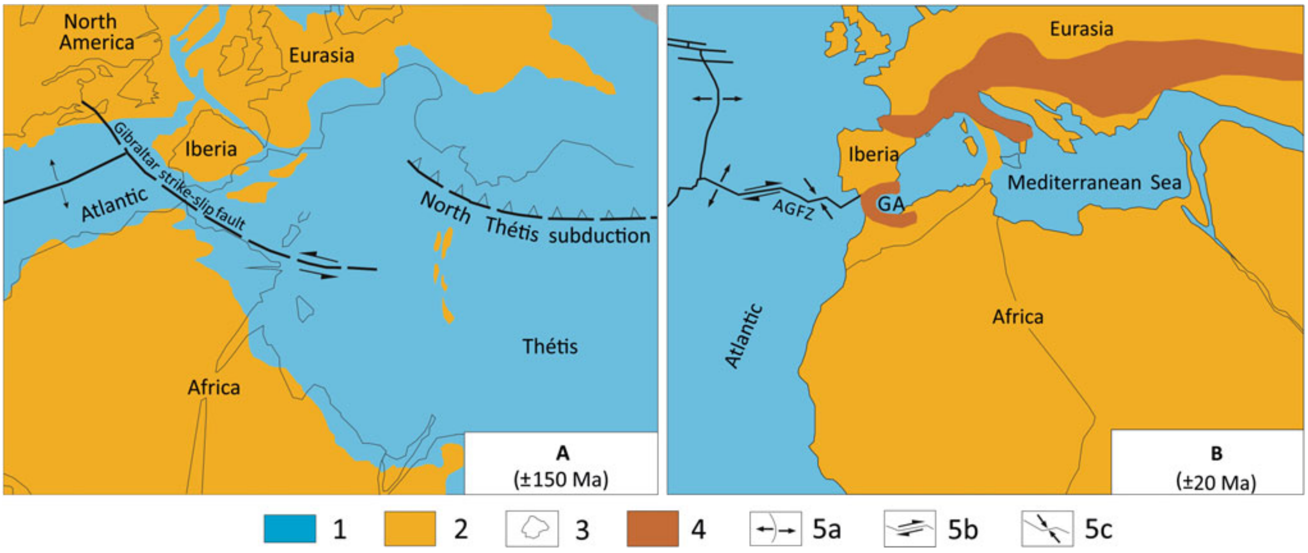

Fig. 1.5 Paleogeography of Iberia in the Upper Jurassic (**A**) and Lower Miocene (**B**). 1 Submerged areas, 2 emerged areas, 3 present continental boundaries, 4 cordilleras (continental collision), 5 tectonic plate movement: (a) divergence, (b) lateral movement, (c) convergence, AGFZ Azores–Gibraltar Fracture Zone, GA Gibraltar Arc (from Ribeiro, 2013b, simplified)

environment, with fluvial–lacustrine deposits and episodes of marine invasions.

In the second rifting phase in the Early Jurassic, the Western Basin began transforming into a westward tilted half-graben, whose western boundary is the granite-gneiss Berlengas Horst (an element of the Iberian Massif; Kullberg et al. 2013). The formation of limestones intensified at the end of the Early Jurassic and started to dominate the sedimentary sequences (Kullberg et al. 2006, 2013; Terrinha et al. 2013). The meridian faults were mainly responsible for the subsidence of the Western Basin, and significant variations of facies and thicknesses controlled by ENE–WSW to E–W faults define different compartments in the basin. Among them is the Nazaré Fault (Fig. 1.2) that separates the basin into sectors with different crustal stretching and sedimentation types (thickness and associated facies). The marine environment was predominant until the end of the Middle Jurassic, depositing thick limestone layers. The Upper Jurassic shows several discontinuities in sedimentation and depositional environments varied in time and space, from an open sea to a lagoon or fully terrestrial.

In the third rifting phase in the Late Jurassic and at the beginning of Early Cretaceous (Fig. 1.5A), there was, for the first time, evidence of continental break-up in the North Atlantic with oceanic crust formation (~142 Ma). The Lusitanian Basin showed again a central graben with peripheral half-graben morphology. Tectonic changes in the basin, which included uplift of the Berlengas Horst, allowed for the accumulation of detrital and carbonate materials which formed important submarine deltaic fan systems in a carbonate–terrigenous platform domain, both from the W and E (Kullberg et al. 2013).

The fourth rifting phase in the Early Cretaceous is associated with magmatism (~135 Ma). It corresponds to the main phase of oceanic crust formation in the area of the Tagus Abyssal Plain, which may have favoured the progressive tilting of the Lusitanian Basin to the south, where marine influence remained (Kullberg et al. 2013). Thus, during the Early Cretaceous in sedimentary syn-rifting sequences the deposition of fluvial sands occurred, grading in the southerly direction into marine marls and limestones. This differentiation continued during the Early–Late Cretaceous, in post-rift sequences that are carbonate to the SW and fluvial to the N and E (Ribeiro 2013b).

From the Cretaceous onwards, stretching took place west of the present-day Berlengas archipelago (Fig. 1.2), separating the Lusitanian Basin from the Atlantic Ocean Basin (Bolacha 2014). The formation and spreading of the oceanic lithosphere west of Iberia and the opening of the Gulf of Gascony in the north, during most of the Cretaceous, have led to an approximate 35° anticlockwise rotation of Iberia. This rotation led to the individualization of the Iberian microplate (about ~110 Ma; Ribeiro 2013b).

In turn, the rotation of the African Plate relative to the Eurasian Plate led to the closure of the Tethys at the end of Mesozoic by subduction of the oceanic crust (NE Africa/Arabia region). The compression between the African Plate (mainly in the northwest sector—Nubian Plate) and the Eurasian Plate became dominant. This compression (N–S) started in the Late Cretaceous and reactivated a deep fault zone that extends from the submarine Tore Seamount (300 km west of Peniche) to the Gulf of Cadiz (Ribeiro 2013b). The fault acted as a dextral strike-slip, where magma ascended in zones of decompression (Kullberg et al. 2013), leading to the intrusion of the magmatic massifs of Monchique, Sines and Sintra by 74–72 Ma ago (Figs. 1.2 and 1.3). Almost contemporary is the volcanic complex of Lisbon (basalts and pyroclasts) and other volcanic occurrences that also affected the Algarve Basin.

The drastic tectonic change from predominantly extensional to compressional at the beginning of the Late Cretaceous resulted from the "rotation of the displacement vector of the trajectory of Africa relatively to Eurasia, from approximately NW-SE to SW-NE, according to the present coordinates" (Dewey et al. 1989, in Terrinha et al. 2013: 30). The Cenozoic was thus characterized by widespread compression in Iberia.

1.2.3 The Cenozoic Evolution

During the Cenozoic Era (65–0 Ma), the paleogeographic and geomorphological evolution of Portugal was mainly marked by the following factors: (i) compressive tectonic phases due to convergence between the Eurasian and African plates that affected the Iberian microplate, located between them, (ii) climate changes between the Tertiary and the Quaternary, with important consequences on the morphogenesis, and (iii) continuation of the opening of the Atlantic Ocean with the emersion of the Madeira and Azores archipelagos (see Sects. 1.3.11 and 1.3.12).

In mainland Portugal, there are no significant mountain ranges (interplate), as the territory was far from intense tectonic inversion that occurred during the Alpine orogeny (Cantabrian–Pyrenean chain in northern Iberia and Betic Chain, in the south; Fig. 1.5). Hence, it has only experienced long-distance effects of the Alpine compression (Ribeiro 2013b). From a geomorphological point of view, the Cenozoic evolution of mainland Portugal was marked by the appearance of a third morphostructural unit—the Lower Tagus and Alvalade Sedimentary Basins and by the regional differentiation of the main relief units (or regional geomorphological units; see Sect. 1.3).

Today, the Lower Tagus and Alvalade Sedimentary Basins (also called the Tagus and Sado Sedimentary Basins) show a general NE–SW trend, occupying 15% of the territory (Fig. 1.2). The Lower Tagus Basin is about 150 km long and has an average width of 75 km, with the maximum sediment thickness reaching 1400 m in the Setúbal Peninsula. The Alvalade Basin is about 75 km long and 35 km wide, and the maximum sediment thickness is less than 500 m (Ferreira 2005). The two basins formed in the Paleogene and were separated by the Valverde-Senhor das Chagas Horst (cut into Paleozoic rocks) until the Late Pleistocene. It was then that the Sado River that drains the Alvalade Basin crossed the horst and entered the Lower Tagus Basin (Pais et al. 2013). The Cenozoic sedimentary formations of the basins, spanning the period from the Middle Eocene to the Upper Pliocene, are mostly continental detrital (gravels, sandstones and lutites), with lacustrine limestones of the Upper Miocene in the Santarém region. In the Miocene and Pliocene, there were several marine transgressions in the downstream sector of the Tagus Basin and in the Alvalade Basin at the end of Late Miocene (Pais et al. 2013), leading to the deposition of lutites, sandy lutites and marine biocalcarenites. The detrital infilling phases ended with coarse material spills that make up the bulk of the basins' infill, generating the so-called culminating surfaces.

In the beginning of the Cenozoic, Iberia moved together with Africa (Ribeiro 2013b), being separated from Eurasia by the Cantabrian and Pyrenean margin. The convergence between Africa/Iberia and Eurasia trended NNE–SSW, leading to the subduction of the Tethys oceanic lithosphere near that margin. The secondary traction in the interior of the Iberian microplate generated strike-slip basins which followed this trend, among which the Tagus and Sado Basins (Fig. 1.2) between Messejana and Lower Tagus Valley Faults stand out due to their dimensions (Ribeiro et al. 1979; Ribeiro 2013b). During the Eocene/Oligocene, continental collision occurred, with the formation of the Cantabrian–Pyrenean mountain chain in northeast Iberia (Fernández-Lozano et al. 2011). As a consequence, from the Late Oligocene on, Iberia began to enclose the Eurasian plate and to converge, in the south, with Africa (Nubian sub-plate) along the Azores–Gibraltar boundary (Ribeiro 2013b; Figs. 1.5B and 1.6). The Pyrenean compressive orogenic wave had repercussions mainly in the north and the centre of Portugal, with its effects decreasing southwards. During the Paleogene until the beginning of the Late Miocene, the Iberian Massif experienced the effects of continued compressive tectonics (emphasizing the Pyrenean phase) under climatic conditions favouring erosion. During the Paleogene, the climate in Iberia became progressively less humid, partly due to the closing of the Tethys (Jiménez-Moreno et al. 2009), evolving to subtropical, with a long dry season, and hot semi-arid. These conditions favoured planation, with the formation of a Paleogene erosion surface and transport of feldspar sands to the basins (Pais et al. 2012, 2013).

During the Miocene (Fig. 1.5B), an important change of the convergence vector between Eurasia/Iberia and Africa took place, rotating from NNW–SSE to NW–SE (Ribeiro 2013b; Pais et al. 2012, 2013). It was during that period (Late Miocene) that the maximum compression was reached in Portugal, corresponding to the Betic tectonic phase. The main fault systems that were reactivated resulted in: (i) NE–SW to ENE–WSW thrusts, (ii) NNE–SSW left-lateral

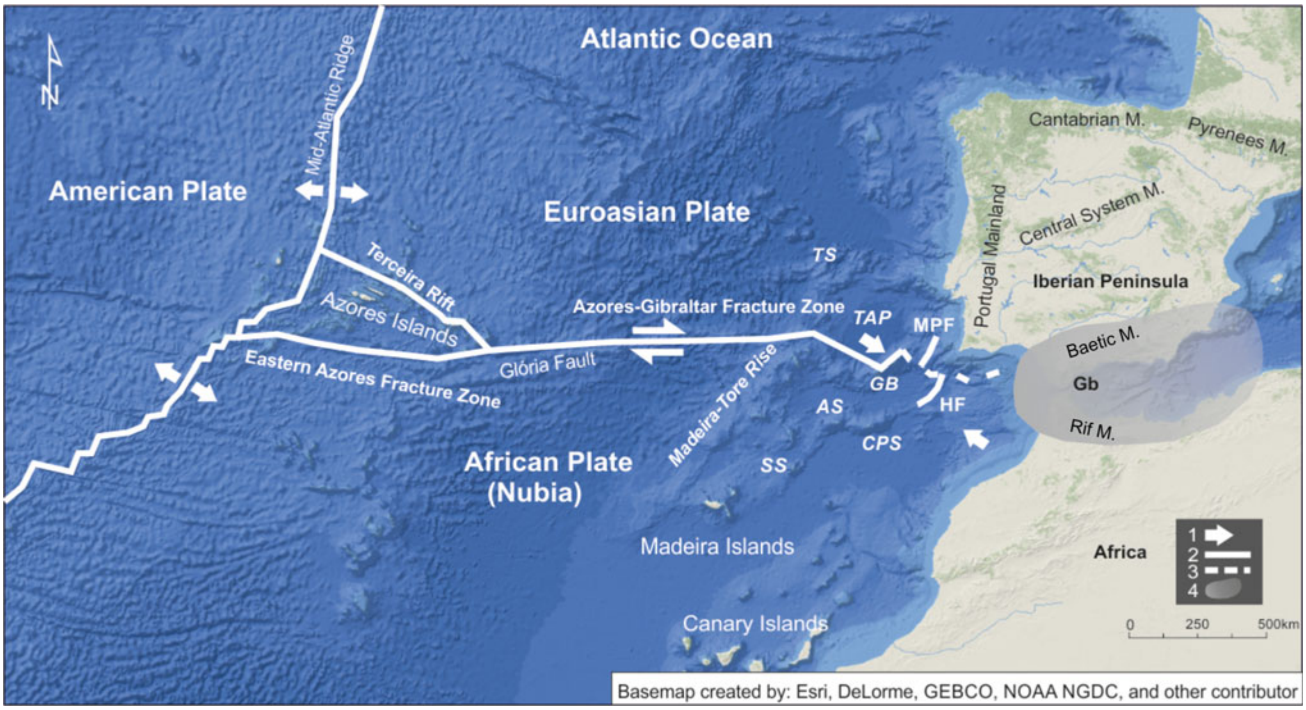

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Fig. 1.6 Geotectonic setting of mainland Portugal and the Azores and Madeira archipelagos. 1 Relative movement of the tectonic plates, 2 plate boundary faults (known location), 3 plate boundary faults (approximate location), 4 diffuse plate boundaries (continental collision). Gb Gibraltar, HF Horseshoe Fault, MPF Marquês de Pombal Fault. *Seamounts* AS Ampére, CPS Coral Patch Seamount, GB. Gorringe Bank, SS Seine, TS Tore, TAP Tagus Abyssal Plain

strike-slip faults and (iii) NW–SE right-lateral strike-slip faults (Pais et al. 2012). In Iberia, the Betic Mountain Range formed (Fig. 1.6), and in Portugal, there was the uplift of important mountains, with the main examples being the mountains of the northwest and the central massif belonging to the Central Iberia Cordillera (Figs. 1.6 and 1.7), uplifted in a pop-up structure (Ribeiro 2013b). The intraplate Central Iberia Cordillera was affected by the interferences of the induced compressions in the north of Iberia during the Paleogene and in the south during the Miocene (Ribeiro 2013b). The tectonic inversion of the Lusitanian Basin (that had been going on since the Late Cretaceous) was accentuated during the Miocene, reactivating various structures such as the Nazaré and Arrife–Montejunto Faults, delimiting in the NW and SE an uplifted tectonic compartment (Fig. 1.7), which is an extension of the central massif pop-up structure. The inversion of the Lusitanian Basin transformed the Lower Tagus Basin into a foreland basin in contact with the basement (Ribeiro 2002). This process led to an increased subsidence of the Lower Tagus Basin, expressed by a thick Miocene sedimentation (most of the infilling of the basin), with the occurrence of several sedimentary cycles. During the Middle and Late Miocene, there was an important climatic change in Iberia, with cooling, but mainly with a series of arid phases that intensified to the end of the Miocene (Jiménez-Moreno et al. 2009). In the Pliocene (3.4 Ma), a Mediterranean-type subtropical climate was established, with summer drought (Jiménez-Moreno et al. 2009).

In the Late Pliocene and the beginning of the Pleistocene, various events of climatic and tectonic nature will be crucial for the definition of the geomorphological contrasts of the Portuguese territory. From these, the following stand out: the occurrence of a wet period in the Late Pliocene—the Piacenzian (Pais et al. 2013), the submergence of the coastal zone—Piacenzian transgression (Ferreira 2005), the Ibero-Manchega compressive tectonic phase with important vertical movements in the Late Pliocene to the onset of the Pleistocene (Pais et al. 2013) and the last pre-Quaternary erosional phase extending to the beginning of the Lower Pleistocene, due to a drier and, in the Gelasian, cooler climate.

As a result of intensification of the tectonic uplift and greater availability of water in the Piacenzian wet period, there were several fluvial captures. In particular, the Tagus and Douro River systems evolved, extending into and capturing the former interior drainage systems of Iberia, giving rise to major exorheic river basins open to the Atlantic Ocean. After that, a more arid phase, but with concentrated heavy rains, during the Plio-Pleistocene transition, was associated with torrential run-off, with the resultant debris flow deposits with dominant quartz clasts and quartzite (many supplied by

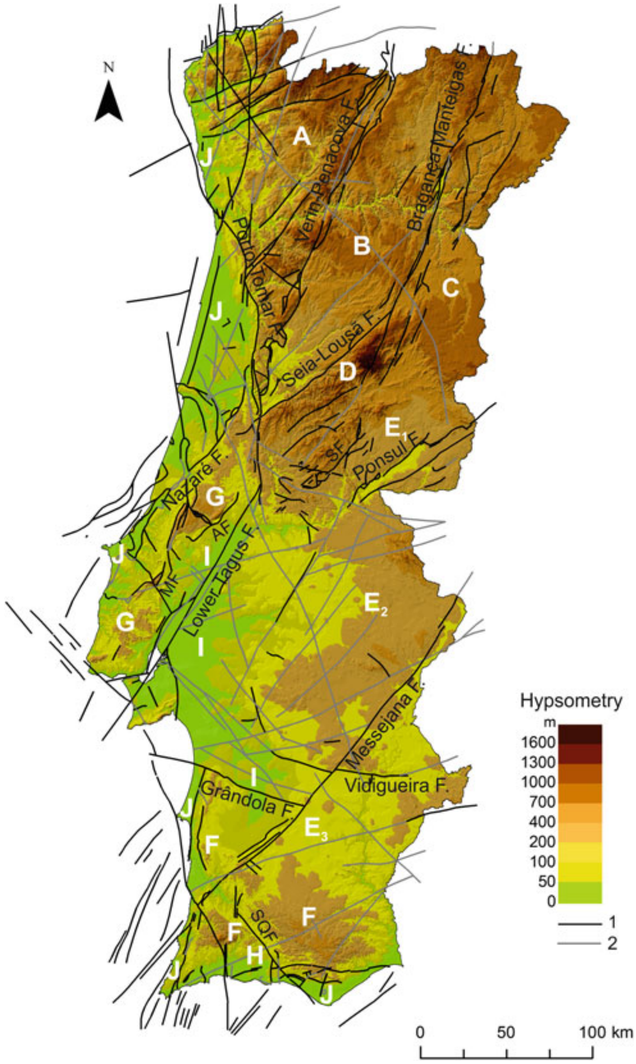

Fig. 1.7 Relief of mainland Portugal and active faults. 1 Active fault, 2 geological lineaments which may correspond to an active fault (from Cabral 1993, 2012 and Silva et al. 2008). *Faults* AF Arrife, MF Montejunto, SF Sobreira Formosa–Grade–Sobral do Campo, SQF S. Marcos–Quarteira. Regional geomorphological units: A mountains of the northwest, B central-northern plateaux, C Northern Meseta, D mountains of the central massif, E Southern Meseta (E1 Castelo Branco planation surface, E2 Alto Alentejo planation surface, E3 Baixo Alentejo planation surface), F south and southwest low mountains, G small mountains, hills and interior plateaux of the Lusitanian Basin, H low mountains, inland plateaux and depressions of the Algarve Basin, I plateaux and plains of the Lower Tagus and Alvalade Basin, and J Littoral Platform

the quartzite ridges of the Iberian Massif) in a clayey matrix, forming the so-called *Rañas* and correlative deposits (Martín-Serrano 1988). This phase led to the establishment of the Villafranchian planation surface in areas undergoing erosion (Ferreira 2005) and to the last pre-Quaternary infilling phase of the sedimentary basins, which constitutes the bulk of their current interfluves. Climate variations observed in mainland Portugal during the Cenozoic were favourable to pediplanation. These were responsible for individualization of inselbergs (especially in granitic areas), which stand out within planation surfaces in the drier interior of the country, where tectonic movements were less intense. In these areas, vast polygenic surfaces developed, which were consecutively retouched during the subsequent erosive phases (Ferreira 1996). In regions where vertical tectonic movements were more intense and where different tectonic compartments were defined, the erosive phases were imprinted in the relief by stepped planation surfaces at various altitudes.

In the Quaternary, the combined effect of continued regional tectonic uplift and climate changes, associated with the alternation of glacial and interglacial periods, led to profound changes in the mountains, in the valleys and on the coast. A progressive degradation of Tertiary planation surfaces occurred, with the incision of the fluvial systems, promoted by tectonic uplift and by periods of lower sea levels. Quaternary fluvial terraces and raised beaches provide the evidence of this geomorphological dynamics. The Littoral Platform present along the Portuguese coast, which is a polygenic surface due to continental and marine erosion in the Piacenzian, was also submitted to differential effects of regional tectonics that deformed it. This tectonic differentiation allowed for local marine transgressions in subsided tectonic compartments during the Early Pleistocene (probably Calabrian).

The current geotectonic framework of Portugal (2.6 Ma to present) is thus defined as follows (Cabral 2012: 72): “The Eurasia-Nubia plate boundary is clearly discernible at the western and central parts of the Azores–Gibraltar fracture zone, represented by the Terceira Ridge leaky transform, near the Azores archipelago, and by the Gloria transform fault, eastwards up to the Tore Madeira Rise (~20° W). East of the Gloria fault, the plate boundary is poorly established and its nature is matter of debate, as the interplate deformation is apparently distributed across a broad area, over 200 km wide” (Fig. 1.6). The tension trajectories in Iberia are different in space and time. Thus, in the interior of Iberia, maximum compression is NNW–SSE, gradually turning to WNW–ESE in the west and southwest margins. Ribeiro (2013b: 18) states that “the satellite geodesy data show that the current movement of Iberia relative to Nubia is directed nearly E–W; it is therefore distinct from the movement given by the kinematic model NUVEL 1A, based on the circa 3 Ma magnetic anomaly 2A, which was NW-SE”. The research carried out by several authors in the Portuguese South Atlantic and SW continental margin, south of the Algarve and west of the Alentejo, reported by Cabral (2012) and Ribeiro (2013b), using neotectonic, seismotectonic and morphotectonic data, provides strong evidence that the Atlantic continental margin of mainland Portugal is in transition from a passive margin to an active margin. In the submerged area, seismic tomography allows to follow a subduction zone down to about 100 km deep below the Marquês de Pombal—Horseshoe active thrust fault system (Fig. 1.6), with a rupture and displacement area capable of generating high-magnitude earthquakes, such as the Lisbon Earthquake of 1755. Hence, in the W and SW of the Algarve, the subduction process of the Atlantic Ocean floor beneath Iberia (the Marquês de Pombal Fault System) and of Africa over the Atlantic in the Horseshoe Fault System (Ribeiro 2013b) will have started. “According to this model, Iberia is behaving as a microplate that is rotating clockwise between Africa and Eurasia, inducing convergence across the west Iberia margin at ~1 mm/year” (Cabral 2012: 72).

1.3 The Regional Geomorphological Units of Portugal

The major morphostructural units of Portugal define the main contrasts relating to lithological assemblies and their geological structure, but they do not reflect the relief differences at the regional scale. These depend mainly on the combination of: (i) the different regional impacts of the Cenozoic tectonics, (ii) the regional asymmetries of climate in the Tertiary and Quaternary, and (iii) the response of the different regional lithostructural characteristics to the internal and external Cenozoic geodynamics that affected the territory. Thus, for the analysis of the geomorphological landscapes of Portugal, the first-order morphostructural units are subdivided into large regional relief units or regional geomorphological units (Table 1.1). The main features of these units are summarized for mainland Portugal (with a brief mention to the Azores and Madeira archipelagos).

In general, it can be stated that in mainland Portugal the areas of low altitude prevail, since over 70% of the territory is below 400 m and less than 12% is above 700 m. Another important aspect is the elevation asymmetry between the north and the south (Fig. 1.7). The area north of the Tagus River comprises 95% of the areas above 400 m, while the area south of the Tagus shows 62% of the lowlands below 200 m. In the north, most of the mountains show altitudes above 1000 m, but in the south only one, the Serra de São Mamede, reaches this altitude.

1.3.1 Mountains of the Northwest

The region occupied by the mountains of the northwest develops mainly on granitic rocks and is triangular in shape, due to its control by two large tectonic zones: the NNW–SSE to N–S Porto–Tomar Fault in the southwest and the NNE–SSW Verín–Penacova Fault in the east (Fig. 1.7). The relief is intensely fragmented by tectonic compartments, and horst and graben structures stand out. The mountains of the northwest contact in the west with the Littoral Platform and in the east with the central-northern plateaux.

The mountains of the northwest show altitudes between 1000 and 1600 m and are composed of the following mountain massifs (Figs. 1.3 and 1.7): (i) Peneda (1416 m), Amarela (1362 m), Gerês (1545 m), Larouco (1535 m), Barroso (1279 m), Cabreira (1262 m), Alvão (1283 m) and Marão (1415 m) north of the River Douro, and (ii) Montemuro (1382 m), Freita (1085 m), Arada (1071 m) and Caramulo (1076 m) south of the River Douro.

South of the River Douro, the mountains were uplifted along the Verín–Penacova Fault that borders them to the

Table 1.1 Classification of the regional geomorphological units of Portugal

Morphostructural units (at the global scale)	Morphostructural units of Portugal	Regional geomorphological units of Portugal	
Platforms	Iberian Massif or Hercynian Massif	Mountains of the northwest	Littoral Platform
		Central-northern plateaux	
		Northern Meseta	
		Mountains of the central massif	
		Southern Meseta	
		South and southwest low mountains	
Sedimentary basins	Lusitanian and Algarve Meso-Cenozoic Basins (slightly deformed)	Low mountains, hills and inland plateaux of the Lusitanian Basin	
		Low mountains, inland plateaux and depressions of the Algarve Basin	
	Lower Tagus and Alvalade Cenozoic Basins	Plateaux and plains of the Lower Tagus and Alvalade Basin	
Oceanic mountain ranges	Mountain ranges (summits of volcanic submarine ranges)	Archipelago of Madeira	
		Archipelago of Azores	

east, and tilted to the NW (Montemuro) and to the W (Caramulo). North of the River Douro, the relief resembles a grid of compartments individualized by an orthogonal network of fractures, which feature two main directions: ENE–WSW, seized by major rivers (Minho, Lima and Cávado), and N–S to NW–SE, seized by their tributaries or smaller rivers (Figs. 1.3 and 1.7). These relief compartments elevate from the coast inland, inducing the successive rising of Atlantic moist air masses and their progressive destabilization.

This orographic effect is reflected in the regional climate, giving the mountains of the northwest a hydroclimatic specificity unique in mainland Portugal, being the region with more rain and more rainy days. The average annual rainfall is larger than 1200 mm, and on the summit of the highest mountains it exceeds 3000 mm. The abundance of water and the entrenchment of the hydrographic network cause intense dissection of the relief. The short dry summer season (1–2 months) combines the edaphic humidity at the base of the slopes (and in valley floors) with high temperatures, leading to chemical weathering of the base of the granitic slopes, which induces their parallel retreat, maintaining steep profiles (Ferreira 2005). The main valleys are thus wide with flat bottoms and steep slopes. Even though dendritic drainage patterns dominate, fracturing of granitic bedrock defines fracture valleys along lineaments, with parallel to rectangular drainage patterns (Fig. 1.8).

The valleys consist of alternating narrow and wide sections due to phenomena of differential erosion between various types of granitoid rocks or between these and Paleozoic metasediments. Some cross almost closed depressions (alveoli) due to chemical weathering and differential erosion processes within the granites.

1.3.2 Central-Northern Plateaux

The central-northern plateaux are comprised between two major NNE–SSW tectonic lines: the sinistral strike-slip faults of Verín–Penacova in the west and Bragança–Manteigas Zone in the east (Fig. 1.7). These are Late Variscan strike-slip faults reactivated during the Neogene and Quaternary, leading to vertical displacements of hundreds of metres. Along these lineaments, tectonic depressions have developed. The central-north plateaux correspond to planation surfaces with dissimilar development and different altitudes, the so-called stepped surfaces and the polygenic surfaces.

The stepped surfaces (also found in the mountains of the northwest, although with less morphologic expression) prevail and have been formed due to planation phases and periods of increased tectonic dynamics that shifted them vertically between the Late Cretaceous and the Plio-Quaternary (Ferreira 1978; Ribeiro 2004). The stepped surfaces are: (i). the culmination surface, between 900 and 1200 m asl, (ii) the fundamental surface (more extensive) between 800 and 900 m asl, and (iii). one or two lower levels (depending on the area) between 500 and 700 m asl.

The preservation of these landforms depends not only on the density of fractures (if they are denser, the planation levels are reduced to narrow interfluves, Fig. 1.9), but also on mineralogy, particularly within granites. In turn, the

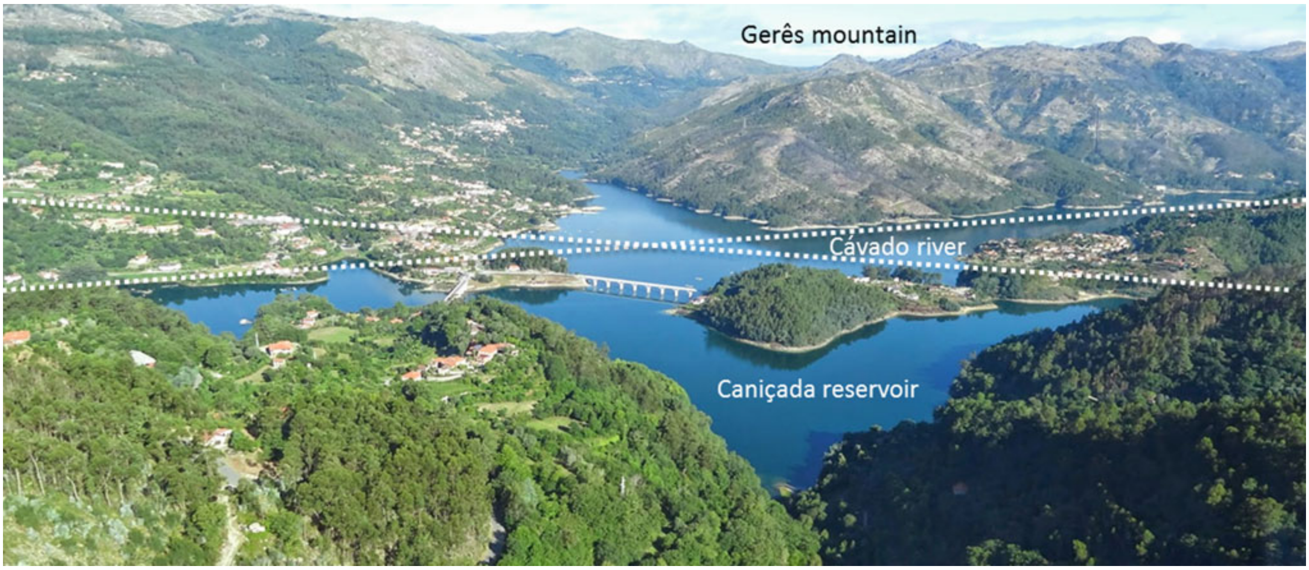

Fig. 1.8 Typical landscape of the NW mountains: tectonic compartments and dominant granite landforms. The dotted white line represents fracture lineaments, sometimes seized by rivers (fracture valleys). *Photograph credits* Duarte Fernandes Pinto, A Terceira Dimensão, http://portugalfotografiaaerea.blogspot.com