World Geomorphological Landscapes

Francisco Gutiérrez
Mateo Gutiérrez *Editors*

Landscapes and Landforms of Spain

Springer

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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 creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they 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 the natural forces. Since 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, surface and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and 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, the second in the series, introduces the geomorphology of Spain—a country with highly diverse landscapes, from coastal flats and deltas to very high mountains of different origin. More than 20 selected examples from mainland Spain and its islands are presented, along with fascinating stories behind the marvellous sceneries. Thus, the book is not only suitable for scientists and students of Geography and Earth Science, but can also provide guidance to holidaymaking geoscientists as to where to go to enjoy the very best scenery.

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 fulfil these aims and to serve the geoscientific community. To this end, my great thanks go to Prof. Francisco and Prof. Mateo Gutiérrez for coordinating the efforts of Spanish geomorphological community and expertly editing the book, as well as to all individual contributors who worked together to show us the Spanish landscape at its best.

Piotr Migoń

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Short Biodata of Authors

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The Geology and Geomorphology of Spain: A Concise Introduction

1

Francisco Gutiérrez, Mateo Gutiérrez, and Ángel Martín-Serrano

Abstract

Spain has a remarkable geomorphological diversity largely due to its geological and climatic variety. From the geological perspective, the Iberian Peninsula may be divided in two broad geological domains; the Iberian Massif in the western sector, and the mountains belts and Cenozoic basins related to Alpine tectonics in the eastern sector. The Iberian Massif (Variscan Spain) mainly consists of Paleozoic metamorphosed sedimentary formations intruded by plutonic rocks. This region is characterised by extensive planation surfaces locally interrupted by inselbergs, and includes outstanding examples of granitic landscapes. The Alpine Mountain Belts, related to the convergence between Europe, the Iberian microplate, and Africa, contain excellent examples of landscapes controlled by active tectonics. In these Alpine orogens, extensive limestone outcrops have favoured the development of outstanding poljes, dolines and karren fields Glacial landscapes are best developed in the Pyrenees, which still contain a number of active cirque glaciers. The Cenozoic Basins include some of the finest areas to examine stunning conglomerate monoliths, dramatic badlands, dune fields, deflation basins associated with lunette dunes and yardangs, and a wide variety of features related to evaporite dissolution. The Canarian Archipelago is a late Cenozoic chain of hot-spot-related volcanic islands located in the Atlantic Ocean west of the Sahara coast. The evolution of the Canaries is characterised by the growth of large volcanic edifices, punctuated by the development of giant landslides. The Teide volcano (3,718 m a.s.l.) in Tenerife rises more than 7 km above the adjacent abyssal plain. A total of 18 eruptions have been documented over the last 500 years, some of them with great societal impact; the 1730-1736 Timanfaya eruption covered more than 20 % of Lanzarote island. The around 10,000 km-long coastline of the Spanish territory display a wide variety of coastal landscapes, including rías, estuaries sequences of raised beaches, deltas, lagoons and spit bars, and dune fields.

Keywords

Spain • Geomorphological diversity • Regional geomorphology • Geoheritage

1.1 General Physiographic Features

Spain is the southernmost country in Europe and covers an area of 505,990 km^2, of which 12,465 km^2 corresponds to the Balearic Islands in the Mediterranean Sea and the Canary Islands in the Atlantic Ocean (Fig. 1.1). The Spanish territory has a remarkable geomorphological diversity largely due to its geological and climatic variability (Gutiérrez 1994;

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Fig. 1.1 Physical map of Spain. Numbers correspond to the chapters of the sites and areas covered by the book. *2* Guadalentín tectonic depressions; *3* Neogene sedimentary basins of Almería; *4* Granite landforms in Galicia; *5* La Pedriza granitic massif; *6* Conglomerate monoliths in the Ebro Basin (several sites); *7* Tramuntana Range; *8* Atapuerca karst and palaeoanthropological sites; *9* Evaporite karst of Calatayud; *10* Gypsum karst of Sorbas; *11* Gallocanta Lake; *12* Playa lakes of Bujaraloz-Sástago; *13* Picos de Europa National and Regional Parks; *14* Ordesa and Monte Perdido National Park; *15* Maladeta Massif; *16* Block streams in the Tremedal Massif; *17* Badlands in the Tabernas Basin; *18* Ebro River Delta; *19* Doñana National Park; *20* Raised beaches in the Cantabrian coast; *21* Olot volcanic field; *22* Teide Volcano; *23* Timanfaya and Montañas del Fuego in Lanzarote; *24* Structural collapses in the Canary Islands

Martín-Serrano 2005; Benito-Calvo et al. 2009). Moreover, the pressure on the environment caused by long-sustained human activity and the dynamics of a wide variety of hazardous surface processes, make this country an excellent natural laboratory to investigate anthropogenic impacts on geomorphic systems and geohazards (e.g. Vilaplana 2008; García-Ruiz and López-Bermúdez 2009; Bruschi et al. 2013; Chap. 26).

The wide climatic variability is related to several geographical factors (Font 1983; Instituto Geográfico Nacional 1995): (1) The territory covers a wide latitudinal range, from around 44°N in northern Spain to 28°N in the Canary Islands, coinciding with the latitude of the Sahara Desert (Fig. 1.1). The annual average precipitation in the eastern islands of the Canaries and in the southern leeward flank of the western islands may reach values below 100 mm (Fig. 1.2). (2) The Iberian Peninsula is located between the Atlantic Ocean and the Mediterranean Sea. A large proportion of the precipitation in Spain is related to fronts coming from the Atlantic Ocean that typically traverse the Peninsula from NW to SE. The annual precipitation in most of the northern sector of the Peninsula exceeds 1,200 mm, whereas there is an extensive sector in the south-east where the yearly rainfall is below 400 mm. The Gata Cape, Almería Province, has a mean

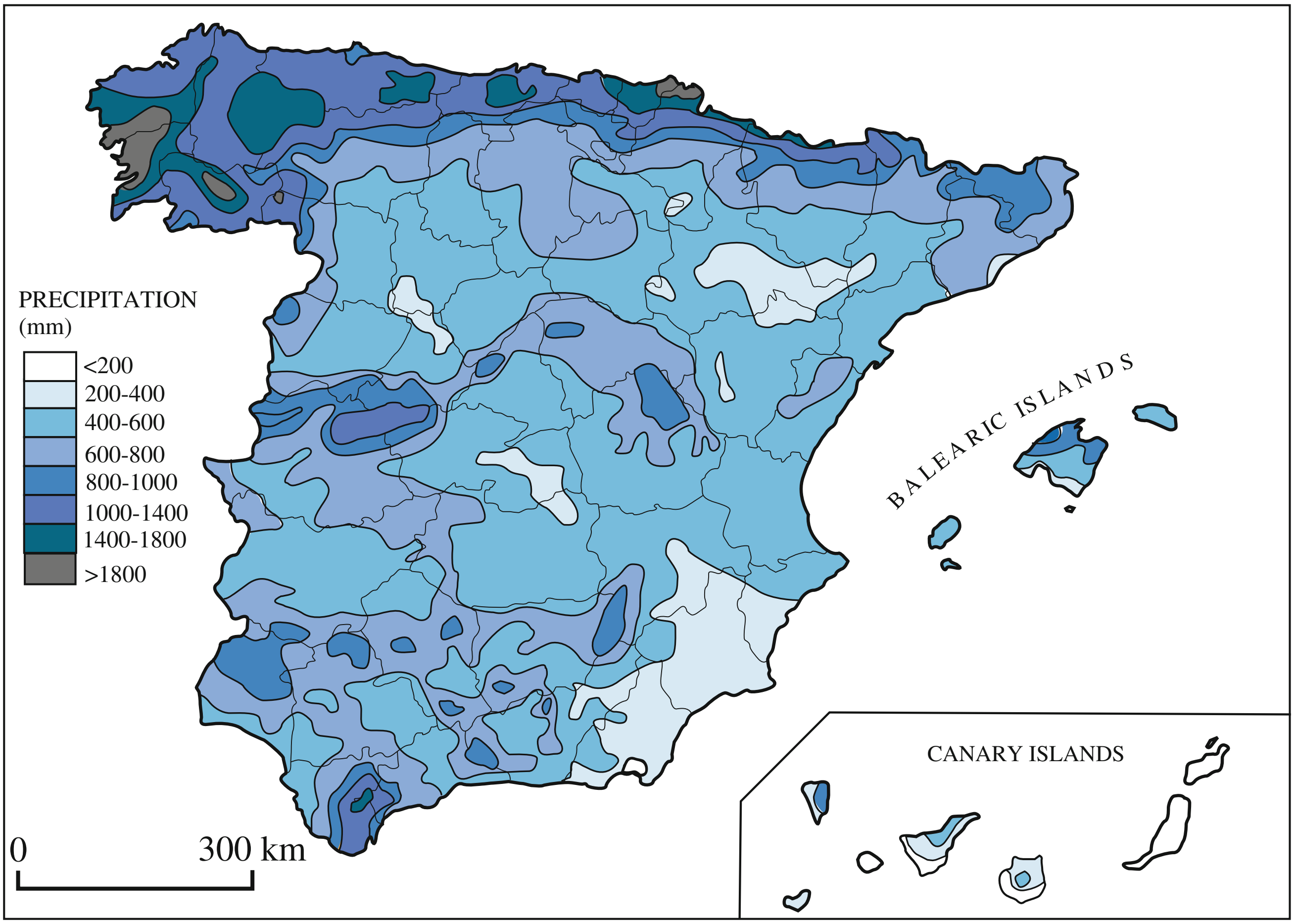

Fig. 1.2 Map of mean annual precipitation in Spain (modified from Instituto Geográfico Nacional 1995)

annual precipitation of ca. 130 mm (Fig. 1.2). Areas with annual precipitation below 400 mm also occur in the central sector of the depressions associated with the interior Cenozoic basins (Fig. 1.2). (3) The topography of the Iberian Peninsula is characterised by a mosaic of morphostructural depressions (Cenozoic basins) and mountain belts (mostly Alpine orogens), some of which are located next to the coast, acting as barriers for moist air currents (Fig. 1.1). The sharp topographic contrasts, together with the orientation of the slopes with respect to the atmospheric circulation, determine striking temperature and precipitation gradients with a decisive imprint on the geomorphology (Figs. 1.2, 1.3). For example, the distance between some active glaciers in the Pyrenees (Chaps. 14 and 15) and playa lakes with wind-fluted yardangs and evaporite deposition in the semi-arid Ebro Depression (Chap. 12) is just 150 km. (4) Spain has the second highest mean elevation in Europe (660 m), after Switzerland. This overall high altitude is related to the extensive area covered by mountain ranges and the presence of extensive elevated plateaus (*mesetas*) in central Spain (Gutiérrez 1994), largely corresponding to planation surfaces and structural surfaces (Fig. 1.1). These topographic characteristics have a significant influence on some climatic features with geomorphological significance. The average annual number of days with temperature below 0 °C exceeds 120 days/year in most of the mountain areas above 1,200 m a.s.l. in the northern half of Spain, and is typically higher than 60 days/year in the central *mesetas* (Fig. 1.4). On the other hand, the areas with the highest mean annual temperature are distributed in southern Spain and along the southern-central Mediterranean strip (Fig. 1.3).

Another important characteristics of the Spanish climate, particularly in the Mediterranean fringe and the mountain regions, are the frequent occurrence of severe rainfall events, which may have dramatic geomorphic effectiveness and are responsible for the natural disasters with the highest number of fatalities (e.g. White et al. 1997; Gutiérrez et al. 1998; White and García-Ruiz 1998; Ferrer et al. 2004; Ortega and Garzón-Heydt 2009). The maximum daily rainfall for a return period of 50 years exceeds 100 mm/day in most of the mountain areas and reaches values above 200 mm/day in some sectors on the Mediterranean strip (Fig. 1.5).

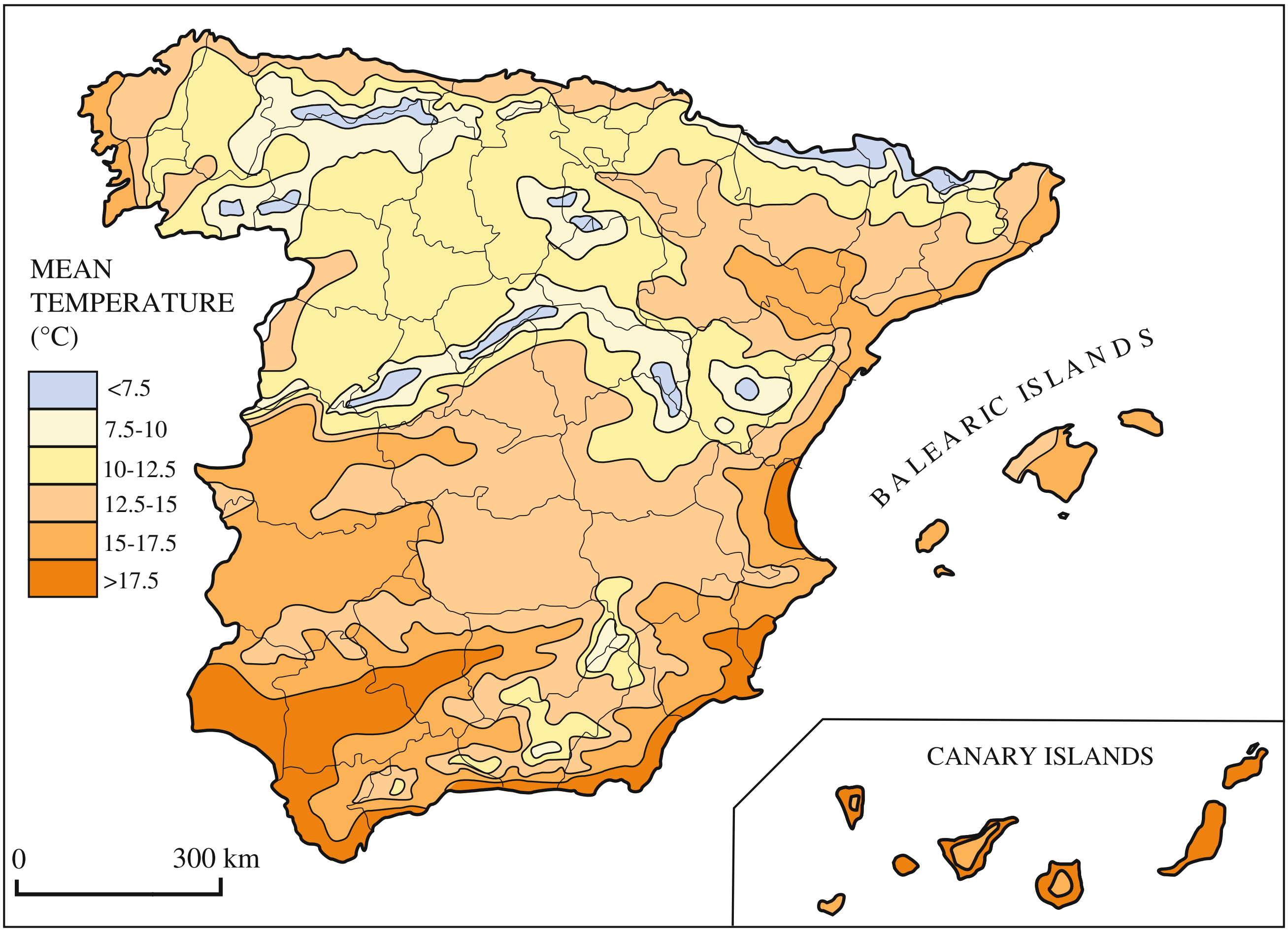

Fig. 1.3 Map of mean annual temperature in Spain (modified from Instituto Geográfico Nacional 1995)

The available records include a large number of rainfall events exceeding 400 mm/day, with top values higher than 800 mm/day (Martín-Vide 2002).

An additional underlying reason why Spain has a great potential for geomorphological investigations is its outstanding geological diversity (Pérez-González et al. 1989; Gutiérrez 1994; Gibbons and Moreno 2002; Vera 2004; Martín-Serrano 2005). The Iberian Peninsula is commonly divided into two broad geological areas (Fig. 1.6): (1) The Iberian (or Hesperian) Massif in the western sector, frequently regarded as Variscan (or Hercynian) Spain. (2) The Alpine mountain belts and Cenozoic basins of the eastern sector, related to the general N–S convergence and collision between Europe, the Iberian microplate and Africa since the late Mesozoic. The "Geomorphological Map of Spain and the Continental Margin at 1:1,000,000 scale" (Martín-Serrano 2005) constitutes an excellent companion for this publication (downloadable at http://www.igme.es/internet/cartografia/cartografia/tematica.asp?mapa=geomorfologico1000).

1.2 The Iberian Massif

The Iberian Massif is by far the least known area of Spain from the geomorphological perspective. It is the best exposure of the European Variscan orogen, generated by the collision between Laurasia and Gondwana in the late Palaeozoic. This structurally complex area mainly consists of Palaeozoic metamorphosed sedimentary formations intruded by plutonic rocks, chiefly granitoids. The Mesozoic was a period dominated by erosion, which led to the development of extensive planation surfaces. They are particularly frequent in the southern half of the Iberian Massif and are commonly preserved in elevated areas. Compressional Alpine tectonics in this portion of Iberia has been accommodated by the development of intraplate mountain systems (e.g. Central System, Montes Galaico-Leoneses), large peripheral Cenozoic basins (Tajo and Duero) and small internal Cenozoic basins controlled by reverse and strike-slip faults, locally showing evidence of recent activity (e.g.

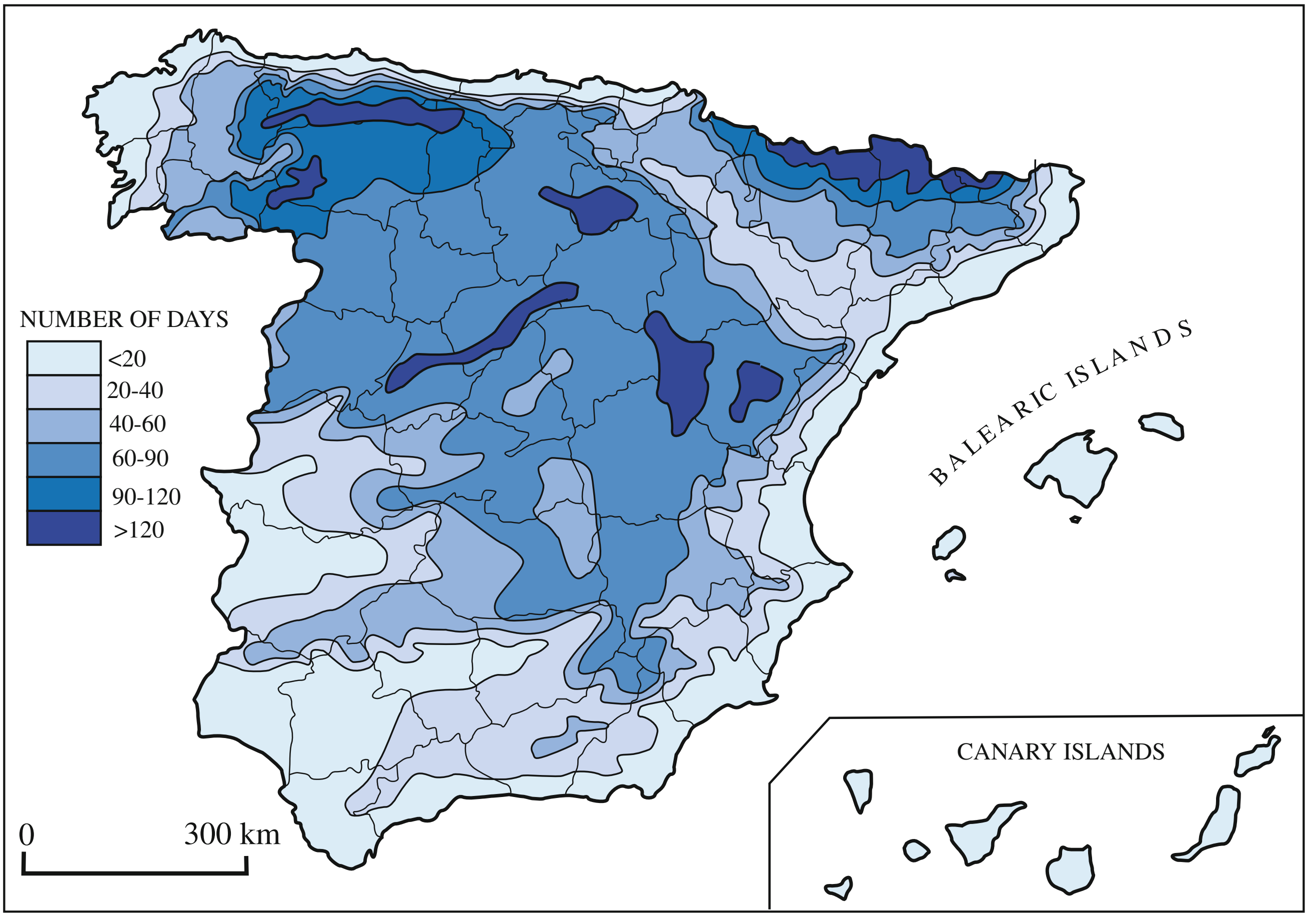

Fig. 1.4 Map depicting the average annual number of days with temperature below to 0 °C (modified from Instituto Geográfico Nacional 1995)

Martín-González 2009). The planation surfaces constitute valuable geomorphic markers to identify and assess Cenozoic tectonic deformation. In some sectors, they have been compartmentalised into uplifted and downthrown blocks, and in others they show gentle uplifts (Sierra Morena, Montes de Toledo) (Fig. 1.1). The 180-km-long Guadiana Cenozoic basin is the largest one, which has controlled the path of the Guadiana River. The 700-km-long and ENE–WSW trending Central System corresponds to an uplifted portion of the Variscan basement, bounded by double-verging reverse faults developed since the early Cenozoic (De Vicente et al. 2007). This Alpine pop-up morphostructure reaches 2,592 m in elevation and separates the Duero and Tajo Cenozoic basins, as well as the northern and southern mesetas in central Spain (Figs. 1.1, 1.6).

One of the most characteristic features of the landscape in the Iberian Massif is the presence of planation surfaces, which may form extensive plains locally interrupted by residual reliefs; inselbergs (Martín-Serrano and Molina 2005). The mature topography of this relatively stable area has favoured the development and preservation of palaeoweathering profiles that record past climate conditions and constitute a valuable correlation tool for regional geomorphology. The majority of the palaeoweathering profiles can be correlated with Mesozoic continental formations (e.g. Purbeck, Weald, Utrillas, Areniscas de Bucaço, Areniscas silíceas de Salamanca), constituting a highly useful source of information on the basin margins during those periods. The iron-rich composition of both the palaeoregoliths and the continental deposits indicates tropical conditions. The weathering profiles locally underlie the sedimentary fill of Cenozoic basins (e.g. Duero Basin; Molina et al. 1997; Martín-Serrano and Molina 2005).

Some of the most striking geomorphological features in the Iberian Massif are related to the underlying lithology and structure. In some areas, differential erosion of folded Palaeozoic rocks with contrasting resistance to erosion (e.g. quartzites and slates) has produced a distinctive Appalachian type of topography. The best example is found in the Montes de Toledo, due to the excellent preservation of the planation surface on the crest of the ranges. The development of the Appalachian topography has been favoured by intense weathering under tropical conditions during the Mesozoic and regional tectonic rejuvenation. In some

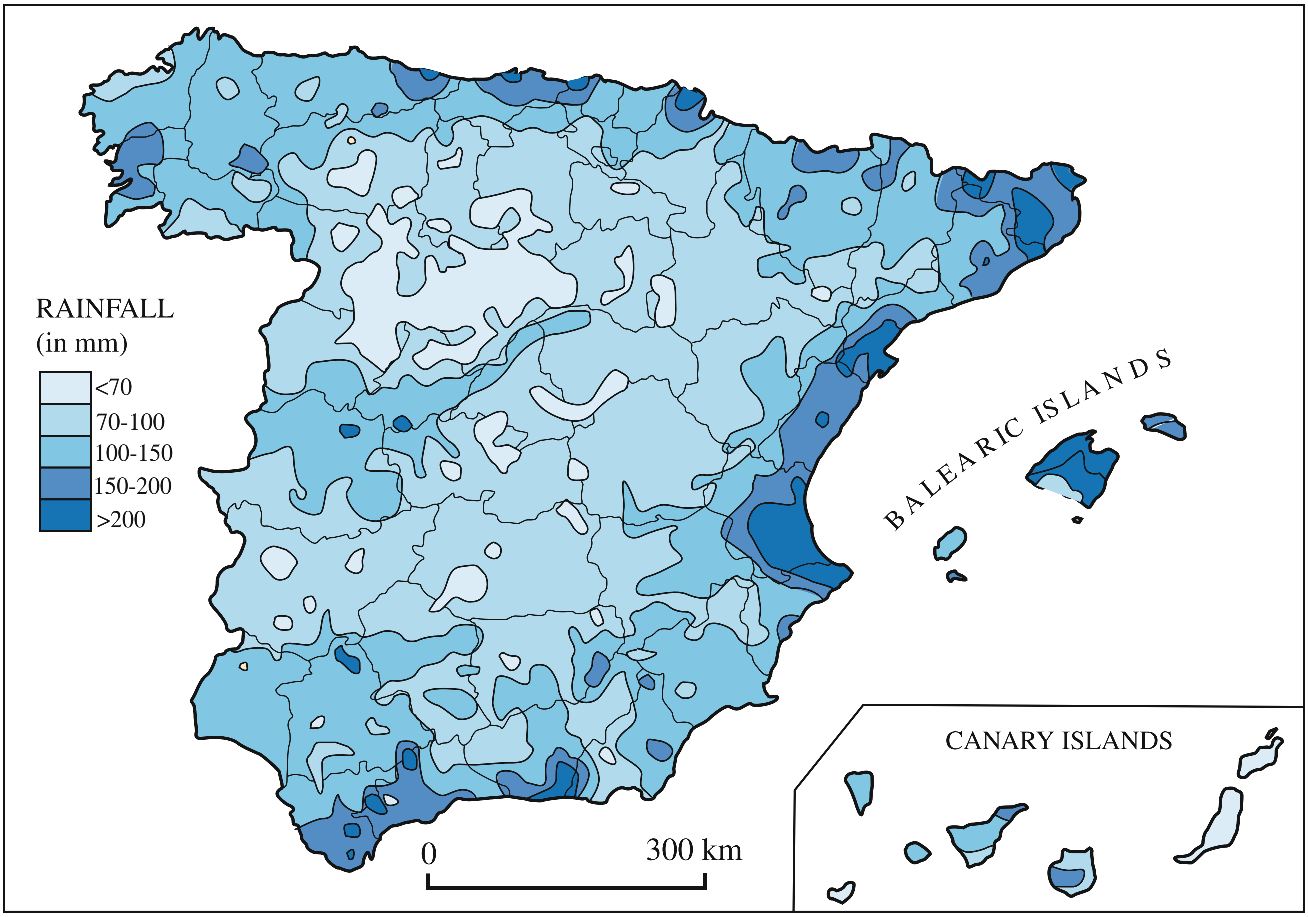

Fig. 1.5 Map of maximum daily rainfall for a return period of 50 years (modified from Instituto Geográfico Nacional 1995)

sectors, the Appalachian erosional features are buried by Mesozoic and/or Palaeogene formations, like in the western margin of the Duero Basin (Blanco et al. 1982; Molina et al. 1989) or in the SE edge of Sierra Morena, Relumbrar Range (Nozal 2002).

Some areas of Galicia and the Central System display spectacular examples of granite geomorphology with bornhardts, tors (Fig. 1.7), fields of corestones, flared slopes, etchsurfaces, pseudokarren and speleothems (Pedraza et al. 1989, Vidal-Romaní and Twidale 1998; Twidale and Vidal-Romaní 2005; Chaps. 4 and 5).

The best example of karst geomorphology in the Iberian Massif is found in the Picos de Europa Massif, with peculiar depressions of mixed karstic and glacial origin (Smart 1986), shaft-dominated caves more than 1.5-km deep, and gorges with impressive walls more than 1-km high (Miötke 1968; Chap. 13). Outstanding surface and underground karst features developed in Cambrian limestones are also found in the southern sector of the Iberian Massif, like the Gruta de las Maravillas in Aracena, Huelva, and Cerro del Hierro, Sevilla. The glaciated areas are restricted to the highest elevations in the northern and central sector of the Iberian Massif. A peculiar feature is the development in the late Pleistocene of ice caps on the planated summits of some mountain ranges, linked to radiating outlet glaciers (Cowton et al. 2009; Carrasco et al. 2013). The largest ice mass was developed in the Sanabria Lake area, Zamora, where the ice cap and outlet glaciers reached more than 400 km^2 (Cowton et al. 2009). The moraine-dammed Sanabria Lake, Zamora, which covers 319 ha, constitutes the largest glacial lake in Spain. In the Central System, the largest valley glaciers developed in the northern flanks of the Gredos and Bejar ranges (Palacios et al. 2012; Carrasco et al. 2013). Periglacial features including nivation hollows, rock glaciers, scree slopes, and patterned ground typically occur in mountainous areas above 700–800 m a.s.l. (Martín-Serrano and Molina 2005).

Another characteristic feature of the Iberian Massif is the presence of extensive piedmont alluvial deposits (*raña* surfaces). They consist of siliceous clast-supported conglomerates with fluvial sedimentological features and a limited thickness, which may overlie basement rocks or Tertiary sediments. These sediments are strongly overprinted by weathering processes, including (1) disintegration of clasts

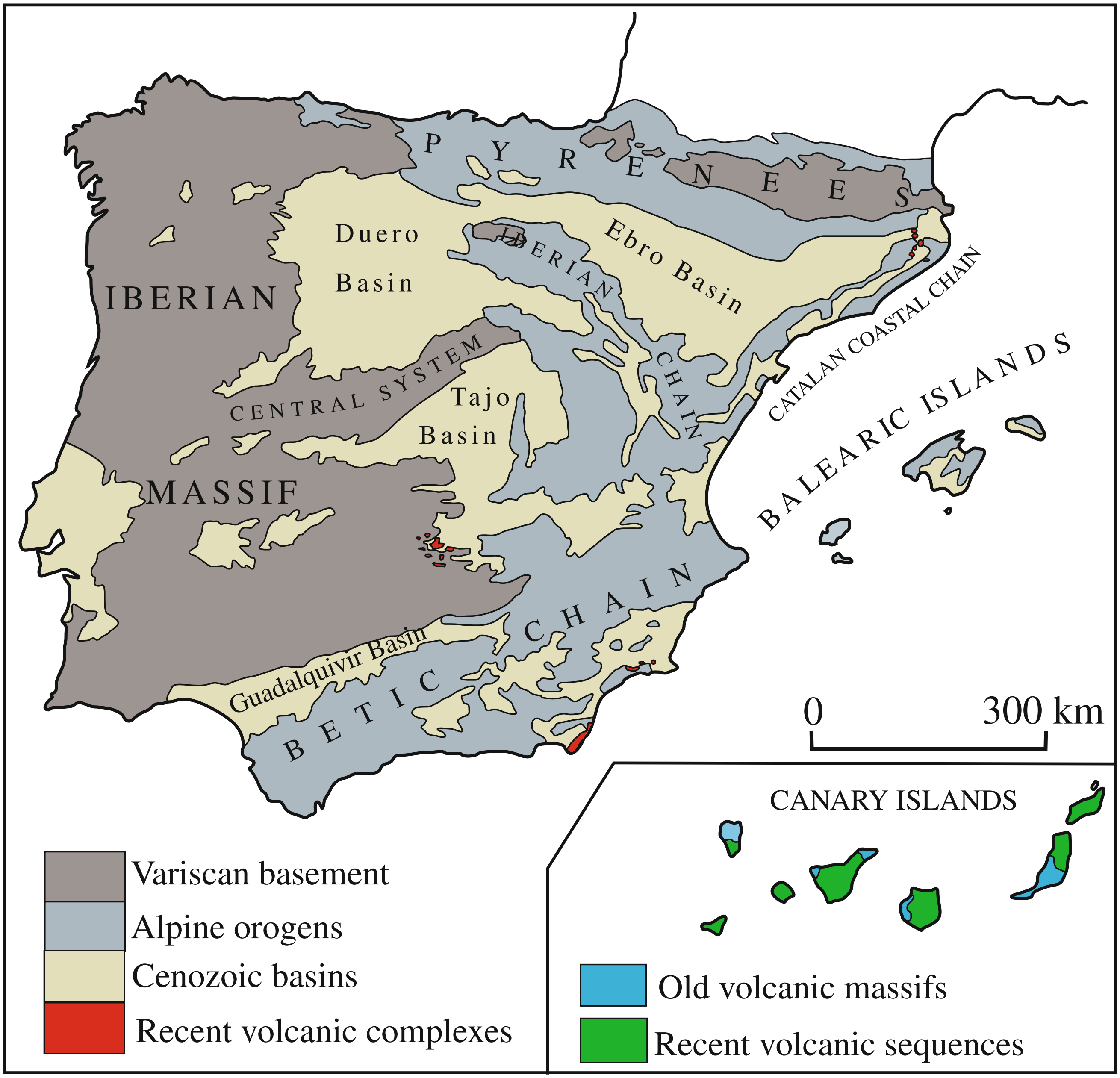

Fig. 1.6 Map illustrating the main geological units in Spain (modified from Martín-Serrano et al. 2005)

into finer-grained particles; (2) segregation of oxihydroxides, silica and other compounds that are mobilised under hydromorphic conditions and (3) transformation of clay minerals (Molina 1991). The result is a well-developed ultisol–oxisol (Espejo 1986). These thin alluvial mantles situated above the terrace sequences in water divide areas record the initial phases of development of the present-day drainage network (Martín-Serrano 1991; Pinilla 1993; Molina-Ballesteros and Cantano-Martín 2002). Fluvial incision and the development of the drainage network in the Iberian Massif progressed from the Atlantic margin towards the interior of the peninsula. The entrenchment of the drainage network and its headward expansion led to the rejuvenation of the relief, especially in the western sector of the Iberian Massif. Deep fluvial dissection affects the whole Portuguese basement, two-thirds of the Sil and Miño rivers, and the Portuguese section of the Duero and Guadiana rivers, whereas entrenchment in the Tajo Valley has reached Madrid Basin in the central sector of the Peninsula. Fluvial incision in this context has produced excellent examples of antecedent and/or superimposed drainages: (1) synorogenic gorges carved by the Cares, Deva and Sella rivers in Picos de

Fig. 1.7 Manqueospese Castle, Ávila, built on a granitic tor, northern sector of the Central System (*Photograph* C. Roqué)

Europa; (2) hanging valleys with waterfall at the mouth of numerous rivers in north-western Galicia (Xalla and Umia rivers); (3) canyons excavated by the Sil and Miño rivers in central Galicia (Birot and Solé 1954); (4) gorges in the marginal sector of the Central System (Voltoya, Alberche, Lozoya and Sorbe rivers); (5) deep discordant water gaps opened by the Tajo and Guadiana rivers in the southern Meseta across Variscan structures, most probably inherited from the Tertiary fluvial network (Martín-Serrano and Molina 2005). Perhaps, the most spectacular example of fluvial incision in the Iberian Massif is found in the Arribes del Duero, a 400-m-deep canyon carved in granitoids (Fig. 1.8).

1.3 The Alpine Mountain Belts

The Betic Chain and the Pyrenees are Alpine orogens resulting from the collision of the Iberian microplate with the European and African plates, respectively (Fig. 1.6). These are the mountain belts with highest peaks in mainland Spain. The Mulhacén in the Betics and the Aneto in the Pyrenees, have elevations of 3,482 m and 3,404 m a.s.l., respectively. The Pyrenees is essentially a "blocked" plate margin with negligible relative motion, whereas the Betics is currently affected by considerable convergence (4 mm/year) and tectonic activity (Zazo et al. 1998; Silva et al. 2003). One of the main geomorphic differences between these Alpine collision orogens and the rest of the intraplate mountain belts in Spain are the limited extent of planation surfaces, attributable to rapid deformation in a plate margin context.

The **Betics**, with a general NE–SW orientation, extend for about 1,000 km in the south and south-east of Spain, including the Balearic Islands (Fig. 1.6). The Inner Zone of the Betics is dominated by structurally complex and metamorphosed basement and cover rocks forming an antiformal stack, interpreted as an accreted terrane (Alborán microplate). The Outer Zone is essentially a suite of allocthonous south-verging structural units made up of Mesozoic and Cenozoic sedimentary sequences detached from the Variscan basement.

The Betic Chain also includes numerous postorogenic Late Miocene-Quaternary basins whose development is related to the general N–S compression associated with the ongoing convergence between Africa and Iberia (e.g. Silva et al. 1993). Most of these basins record a transition from marine to continental deposition, and some of them are currently affected by tectonic inversion. The Betics are clearly the best region in Spain to investigate the impact of active tectonics on landscape development (Chap. 2). The eastern Betics display excellent examples of fault-controlled mountain fronts and alluvial fan systems (e.g. Silva et al. 2003; Martínez-Díaz et al. 2012), whose development may be affected by multiple factors such as tectonic activity, climate variability and base level changes (Harvey 1996; Silva et al. 1992; Harvey et al. 1999; García-Meléndez et al. 2003). A number of studies conducted in this region illustrate the crucial role played by geomorphological studies in the identification of faults and the assessment of their seismogenic potential (e.g. Silva et al. 1997; García-Tortosa et al. 2011; Rodríguez-Pascua et al. 2012). In the Betic Chain, the evolution of the drainage network, largely guided

Fig. 1.8 Arribes del Duero, an impressive canyon carved by the Duero River into the granitic Variscan basement. Image taken next to the Aldeadavila de la Ribera Dam, Salamanca (*Photograph* José Bonilla)

by the postorogenic basins, has been the focus of pioneering studies addressing issues such as the impact of capture induced base-level changes (Harvey and Wells 1987; Goy et al. 1994; Mather 2000; Maher et al. 2007; Whitfiled and Harvey 2012), the transition of alluvial fan systems into fluvial systems (Silva et al. 2008), the impact of active faulting and folding on transverse drainages (Maher and Harvey 2008) or the morphostratigraphic record of incision waves (García et al. 2003). These investigations reveal the need for a regional approach for examining long-term changes in fluvial systems (Chap. 3).

Limestone karst is well-developed in numerous regions, mostly in the Outer Betics (Durán and López-Martínez 1999), with magnificent examples of poljes controlled by active faults (e.g. Zafarraya Polje; Lhenaff 1986; Reicherter et al. 2003; Fig. 1.9), doline fields (e.g. Grazalema and Mágina ranges), and karren fields such as those found in the Torcal de Antequera (Pezzi 1977; Fig. 1.10) and the Tramuntana Range (Chap. 7). There is also a number of remarkable cave systems, some of them with significant economic (e.g. Nerja, Drac and Artá show caves), engineering (Hundidero-Gato Cave and the failed Montejaque Dam project) and palaeoanthropological (Finlayson et al. 2006) implications. Landforms related to evaporite dissolution are mainly developed on halokinetic Triassic halite-bearing evaporites (Calaforra and Pulido-Bosch 1999) and in the Messinian gypsum of Sorbas Basin, with a peculiar stratigraphically controlled multilevel cave system, mainly carved in argillaceous units and unique speleothems (Calaforra and Pulido-Bosch 2003; Chap. 10).

Evidence of Quaternary glaciation is restricted to Sierra Nevada, which is the southernmost glaciated area in Europe. Here, valley glaciers reached ca. 3 km in length during their maximum extent (Gómez-Ortiz et al. 2012), which apparently occurred before the global Last Glacial Maximum. Rock glaciers have been reported at the foot of the headwalls of some cirques (Gómez-Ortiz et al. 2012). The spatial distribution of large landslides in the Betics is mainly controlled by litho-structural factors, active tectonics and fluvial incision (e.g. Gelabert et al. 2003; Azañón et al. 2005; Delgado et al. 2011) and, unlike the Pyrenees, debutressing related to deglaciation has a negligible impact.

The **Pyrenean** orogen, with a prevalent E–W structural and topographic grain, extends for around 650 km in northern Spain, including the eastern portion of the Cantabrian Cordillera, underlain by post-Variscan sequences affected by contractional structures (Fig. 1.6). In this collisional plate margin, the orogenic phase and the inversion of post-Variscan basins took place from late Cretaceous to Miocene times. The Spanish sector of this double-verging mountain belt can be divided into two main structural units. The Axial Pyrenees, in the core of the orogen, constitute an antiformal stack made up of Variscan basement. The Southern Pyrenean zone is an allochthonous system of south-verging thrusts, mostly affecting post-Variscan successions and locally including Palaeogene sequences deposited in former foreland basins incorporated into the orogen. The topography shows a general decrease in elevation from the axial zone, with peaks above 3,000 m, towards the southern margin of the orogenic wedge.

Fig. 1.9 Zafarraya Polje, Málaga, bounded on its southern margin by a rectilinear and scarcely dissected fault-controlled escarpment (foreground). This active fault is considered to be the source of the catastrophic 1884 Andalucía earthquake (*Photograph* F. Gutiérrez)

Fig. 1.10 Karren field in Torcal de Antequera, Málaga (*Photograph* F. Gutiérrez)

The regional geomorphology of the Pyrenees is dominated by differential erosion processes controlled by the E–W structure and N–S glacio-fluvial transverse valleys coherent with the general topographic trend. Differential erosion of erodible sediments, mostly Palaeogene and Triassic argillaceous and evaporitic formations, has generated broad E–W trending erosional depressions which display the best developed pediment and terrace sequences (e.g. Peña 1983, 1994). The transverse drainages have carved deep and narrow valleys with local widenings associated with less resistant lithologies.

In the great part of the Pyrenees, the headwaters of the catchments were occupied by valley glaciers in the late Pleistocene (Fig. 1.11), which reached the maximum extent well-before the global Last Glacial Maximum (García-Ruiz et al. 2003, Jiménez-Sánchez et al. 2013). In the central Pyrenees, the valley glaciers, in some cases more than 500-m thick and 30-km long, reached elevations below 900 m a.s.l.

Fig. 1.11 Terminal moraines and nested debris cones at the foot of steep glacial troughs carved into an erosional escarpment underlain by folded Mesozoic and Palaeogene rocks, Partacua Range, central Pyrenees (*Photograph* F. Gutiérrez)

In the more humid Cantabrian Mountains, the front of some palaeoglaciers has been situated below 500 m a.s.l. These alpine glaciers carved cirques, over-deepened basins and deep troughs with steep slopes. Locally, lateral moraines blocked tributary drainages generating marginal enclosed basins with lacustrine deposition. In some valleys it has been possible to establish chronological associations between frontal moraines and outwash terraces and identify older glacial phases on the basis of morphostratigraphical relationships and geochronological data (Lewis et al. 2009; Jiménez-Sánchez et al. 2013). At the present time, there are about 20 cirque glaciers restricted to massifs higher than 3,000 m a.s.l. in the central Pyreenes (Fig. 1.12). These glaciers expanded during the Little Ice Age, as revealed by historical data and fresh moraines, and are currently affected by rapid recession (Chueca-Cía et al. 2005; Chaps. 14 and 15). Periglacial activity is represented by both active and relict talus slopes, protalus ramparts, grêzes litées (Peña et al. 1998; García-Ruiz et al. 2001), rock glaciers (Serrano et al. 2010) and patterned ground.

Landslides in the Pyrenees constitute a major morphogenetic process and, together with flooding, pose the main geomorphological hazard. A number of villages have been destroyed or abandoned due to landslide activity (Inza, Salinas de Jaca, Puigcercós, Montclús, Pont de Bar; Fig. 1.13). In glaciated valleys with weak lithologies, deep-seated landslides related to the debutressing of oversteepened slopes may display very high spatial frequencies (Guerrero et al. 2012). The development of most large landslides is favoured by litho-structural factors, such as the presence of thick halite-bearing evaporites (Gutiérrez et al. 2012a), or the favourable attitude of the strata (Pinyol et al. 2012). In addition to glacial debutressing, fluvial erosion, severe precipitation (Corominas and Moya 1999) and seismic shaking (e.g. González-Díez et al. 1999; Gutiérrez et al. 2008a; Rosell et al. 2010; Zarroca et al. 2013) are the main natural triggering factors. The occurrence of shallow landslides and debris flows has been largely influenced by changes in land use and land cover (e.g. Martí et al. 1997; Remondo et al. 2005; Beguería 2006; García-Ruiz et al. 2010a). Changes in plant cover have a significant influence on the magnitude and frequency of floods, erosion processes and sediment transport. Plant colonisation after farmland abandonment resulted in a progressive decline in the number of floods and in the sediment yield at both small catchment (García-Ruiz et al. 2010b) and regional scales (Beguería et al. 2006). Floods have a particularly severe geomorphic and societal impact in relatively small and steep drainage basins, where catastrophic flash floods related to convective storms may develop in a very short period of time. The 1996 Arás flood caused 87 fatalities in a campground built in the active lobe of an alluvial fan, fed by a drainage basin around 18 km^2 in area and 1,200 m in relief (White et al. 1997; Gutiérrez et al. 1998) (Fig. 1.14).

The Outer Zone of the Pyrenees, with thick limestone sequences, includes some of the most remarkable karst massifs in Spain with doline and karren fields (e.g. Sierra de Boumort, Lérida; Llano de Cupierlo, Guara Ranges), poljes frequently with vague structural control (e.g. Saganta, Abeles), deep canyons, ponors and springs, as well as caves with large-vertical development (Arañonera Cave, 1,350 m) (e.g. Rodríguez-Vidal 1986; López-Martínez 1986).

Fig. 1.12 Cirques separated by sharp ridges (arêtes) in the granodioritic Maladeta Massif, central Pyrenees. The Aneto Glacier in the north-facing cirque (*right*) (*Photograph* F. Gutiérrez)

Fig. 1.13 Head scarp of the landslide that caused the partial destruction and abandonment of the Puigcercós village in the second half of the nineteenth Century, eastern Pyrenees (*Photograph* F. Gutiérrez)

Evaporite karst features mainly correspond to lake basins developed in collapse structures related to dissolution of subjacent Triassic and Eocene formations (Estaña, Montcortés, Bañolas; e.g. Canals et al. 2006; López-Vicente et al. 2009; Gutiérrez et al. 2012a). Moreover, numerous dam projects have been severely affected by karst-related water leakage problems (e.g. Belsué, Canelles, Camarasa; Milanovic 2000).

The **Iberian Chain** and the **Catalan Coastal Chain** in NE Spain are intraplate Alpine orogens resulting from the tectonic inversion of Mesozoic basins during the Paleogene (Fig. 1.6). During the Neogene, extensional tectonics generated horsts and graben morphostructures superimposed on the previous contractional structures. The Neogene grabens in the Iberian Chain are filled by alluvial and lacustrine sediments, whereas those of the Catalan Coastal Chain may

Fig. 1.14 The Arás alluvial fan developed at the mouth a steep mountain torrent incised into unconsolidated moraine deposits on the western margin of the Gállego River valley, central Pyrenees. A flash flood in August 1996 killed 87 people in Las Nieves campsite (*white arrow*). This highly vulnerable resort was built on the active lobe of the fan between a pre-existing artificial channel (*right black arrow*) and the natural fan channel, which was subsequently used to construct a channelization with a much larger section (*left black arrow*). After a long litigation, the administration was condemned to compensate the victims with an economic indemnity (*Photograph* F. Gutiérrez)

include marine sequences. The Mesozoic successions have a high proportion of limestone units that form extensive outcrops. The Iberian Chain, with a general NW–SE trend, is a broad-elevated area 400-km long and 250-km wide. The Catalan Coastal Chain, with a NE–SW orientation, extends obliquely for about 200-km along the Mediterranean coast. This mountain chain displays a conspicuous horst and graben topography consisting of two ranges (Littoral Cordillera and Pre-littoral Cordillera) separated by an axial graben system (Pre-littoral Depression). In the northern sector of the chain, there are quite extensive outcrops of Variscan plutonic rocks with a well-developed granitic landforms, including inselbergs, fields of corestones, caves, tafoni, pseudokarren and spelothems (Vilaplana 1987; Roqué et al. 2011, 2013). The Catalan Coastal Chain, forming a topographic barrier adjacent to the Mediterranean Sea, is one of the most prone areas in the Spain to the occurrence of flash floods and rainfall-triggered landslides (e.g. Corominas and Moya 1999; Vilaplana 2008; Llasat et al. 2010).

One of the most outstanding geomorphological characteristics of these orogens, especially the Iberian Chain, is the presence of extensive planation surfaces cut across deformed pre-Neogene rocks, chiefly Mesozoic carbonate rocks (Gutiérrez and Peña 1994). This general plateau-like topography is locally interrupted by residual reliefs, frequently underlain by more resistant Palaeozoic rocks, neotectonic grabens, erosional depressions and fluvial valleys. The flat topography developed on carbonate rocks has favoured the development of doline fields (e.g. Villar del Cobo and Pozondón in Teruel and Los Palancares and Cañada del Hoyo in Cuenca) (Gutiérrez and Peña 1979, 1994), karren (Ciudad Encantada, Cuenca) and poljes (e.g. Gutiérrez and Valverde 1994; Gracia et al. 2003 and references therein; Chap. 11). Pleistocene glaciers were restricted to cirques carved in the hard-rock massifs higher than 2,000 m located in the northern sector of the Iberian Chain (Cebollera, Urbión and Moncayo). In the high country, active and relict periglacial features are relatively abundant, including nivation hollows, protalus ramparts, rock glaciers, patterned ground, grèzes litées and remarkable block streams (e.g. Gutiérrez and Peña 1977; Chap. 16).

The drainage network in the central sector of the Iberian Chain is largely controlled by the post-orogenic grabens and records the successive capture of different tectonic depressions by headward expansion (Gutiérrez et al. 2008b). The horst and graben topography of the Catalan Coastal Range is crossed perpendicularly by major transverse drainages (Arche et al. 2010). In the outcrops of limestone-rich Mesozoic successions, streams typically flow deeply entrenched in canyons (Fig. 1.15) with frequent tufa accumulations (e.g. Vázquez-Urbez et al. 2011). Both the Iberian Chain and the Catalan Coastal Chain have good examples of landforms associated with active tectonics and gravitational normal faults, such as mountain fronts, triangular facets and disrupted drainages (Perea et al. 2012; Gutiérrez et al. 2012b; Carbonel et al. 2013a).

1.4 The Cenozoic Basins

Spain has four large Cenozoic basins that cover around one-third of the country area (Fig. 1.6). These morphostructural depressions control the path of the main fluvial systems, from which they receive their names; Ebro, Duero, Tajo and