The Karst of the Tramuntana Range, Mallorca Island

7

Ángel Ginés and Joaquín Ginés

Abstract

Exokarst landforms, as well as caves and shafts, are common in the Tramuntana Range (Mallorca Island, western Mediterranean) owing to the presence of extensive limestone outcrops and suitable bioclimatic environmental conditions. The mountain range has excellent examples of polje-like depressions, dolines, karrenfields and karst gorges, especially in the northern sector. Karrenfields are the most remarkable landforms because of their morphological variety and widespread occurrence. They illustrate the impact of climatic gradients and soil erosion on their development and distribution.

Keywords

Karst landscape • Pinnacle topography • Karrenfields • Mediterranean karst

7.1 Introduction

The geology of Mallorca Island, largely composed of limestone rocks, together with its typical Mediterranean bioclimatic conditions, favours the development of distinctive karst landscapes. The most outstanding examples are located in the Tramuntana Range, which is the main mountainous area in Mallorca (Fig. 7.1a). It exhibits a remarkable variety of solutional landforms, including widespread karrenfields. This diversity is largely related to a broad variety of environmental conditions, mainly controlled by climatic gradients linked to the altitude, ranging from sea level to above 1,400 m. The impact of human activity on the environment over the last five millennia, together with natural deforestation (Ginés 1995), have controlled the complex evolution that records the karren features within a mid-mountain bioclimatic and geomorphological framework (Ginés and Ginés 1995, 2009).

The NE–SW-trending Tramuntana Range has a mediterranean climate characterized by a significant summer drought from June to September. Average annual rainfall reaches 1,400 mm in the central and highest sector of the range, decreasing rapidly towards the lower and peripheral zones of the mountain chain (<500 mm/year in the SW and NE ends). Thus, the rainfall pattern follows that of the elevation (Fig. 7.1a, c). Snowfalls are scarce and restricted to the highest sectors during a few winter days. High-intensity rainfall storm events (over 250 mm in 24 h) are not exceptional, particularly in autumn, due to sudden irruptions of cold air in the middle and upper parts of the troposphere over a still hot water mass in the Mediterranean Sea. Mean annual temperature ranges from 12 °C in the central and highest part of the mountains, to 17 °C in the NE and SW terminations (Formentor and Andratx) (Fig. 7.1c). Seasonal variability is noticeable, with winter and summer mean temperatures below 10 °C and close to 25 °C, respectively. In general terms, the climate in Mallorca Island is that of mid-latitudes but modified by azonal

Á. Ginés (✉) · J. Ginés
Departament de Ciències de la Terra, Universitat de les Illes Balears, Palma, Spain
e-mail: agines.gracia@yahoo.es

F. Gutiérrez and M. Gutiérrez (eds.), *Landscapes and Landforms of Spain*, World Geomorphological Landscapes,
DOI: 10.1007/978-94-017-8628-7_7,

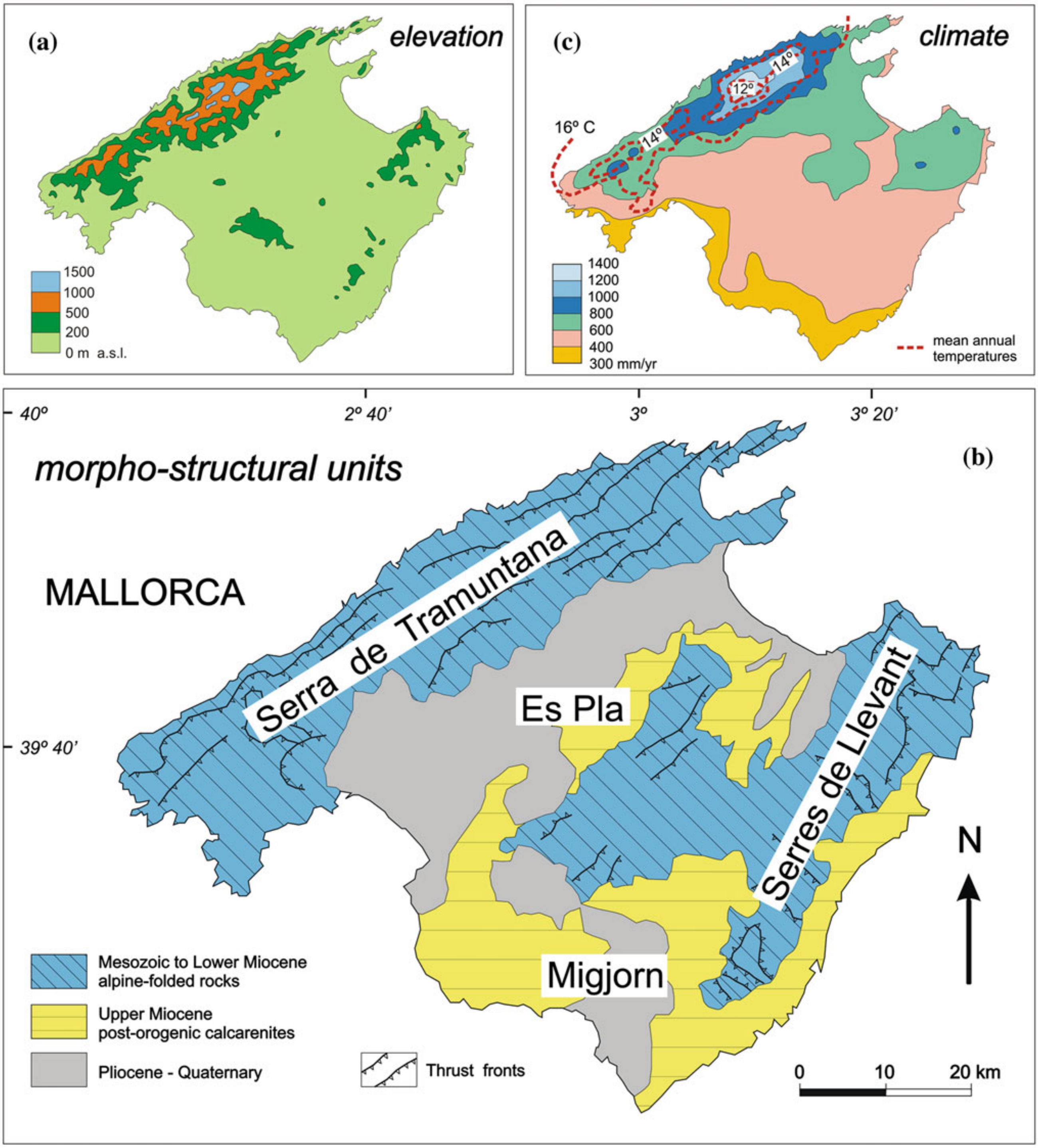

Fig. 7.1 Geographic features of Mallorca Island. **a** Simplified elevation map; **b** Main morphostructural units controlled by the geological structure; **c** Average annual rainfall and temperature

features related to the Mediterranean Sea. Within this general context, diverse microclimatic conditions related to the elevation, and ranging from humid to semiarid, control the distribution of the different karren assemblages along the Tramuntana Range.

7.2 Geological History

Mallorca is the largest and central island of the Balearic Archipelago (Fig. 7.2). The Balearic Islands are located in the western sector of the Mediterranean basin. Mallorca,

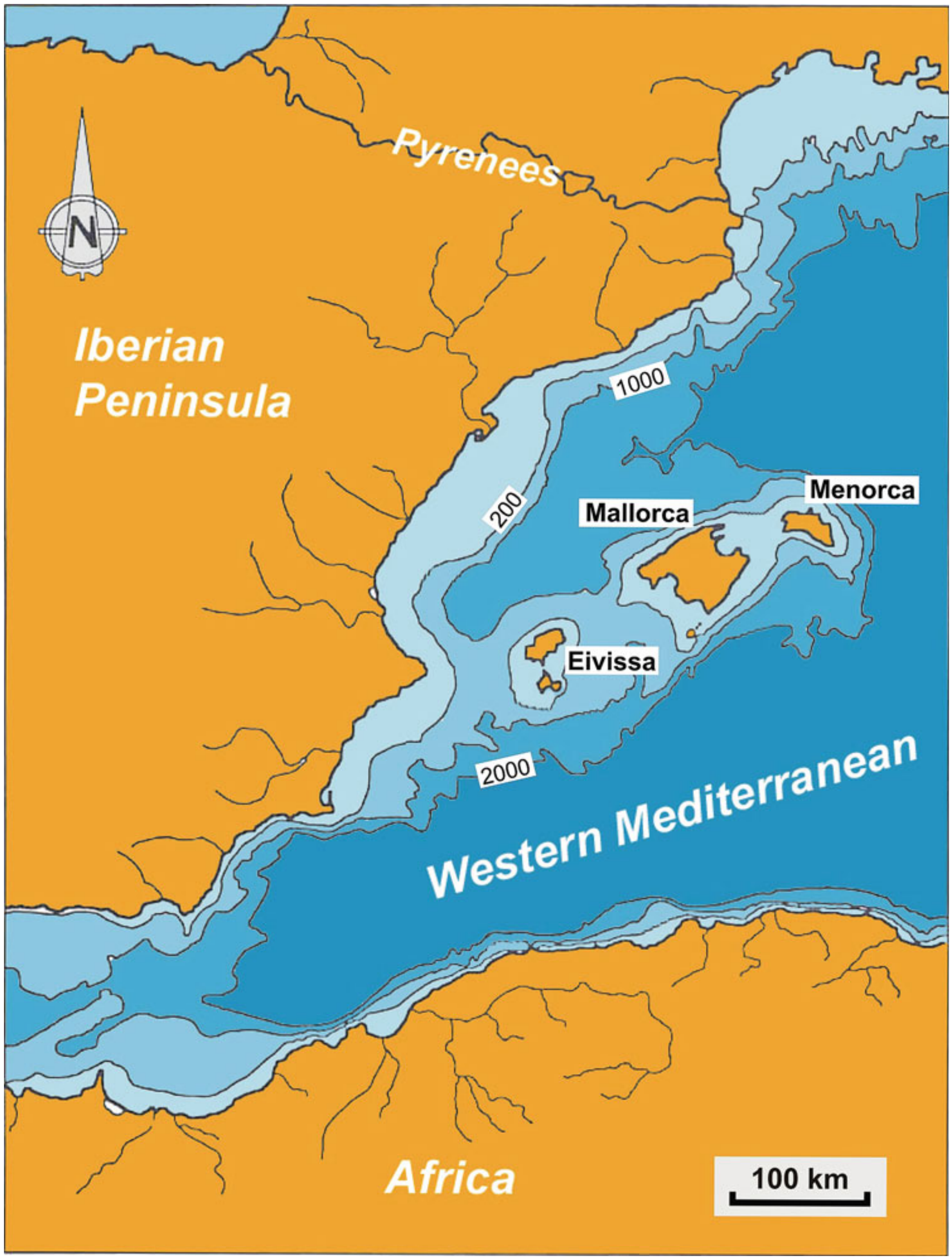

Fig. 7.2 Location of Mallorca Island in the Western Mediterranean basin as a part of the Balearic Promontory, a partially submerged prolongation of the Alpine Betic orogen

with a perimeter of approximately 560 km and a surface area of about 3,650 km^2, is the seventh largest island in the Mediterranean, and together with Menorca, is the most remote with respect to any continental landmass. The island of Mallorca exhibits a rhomboidal shape (96 × 78 km), with its vertices oriented to the four cardinal points. The northernmost point is Cap de Formentor, to the east is Punta de Capdepera, to the south Cap de ses Salines and to the west Sant Elm.

Regarding the geomorphology and tectonics, three main morphostructural units can be differentiated: the Tramuntana Range, Es Pla depression and the Llevant Ranges (Fig. 7.1b). They are related to a complex NE–SW horst and graben structure superimposed on previous compressional structures. The mountain ranges correspond to horsts: Tramuntana Range, Llevant ranges, as well as some ridges in the central sector of the island. The central Es Pla depression, dominated by a flat topography, corresponds to an overall graben structure, including several sub-basins at Palma, Sa Pobla and Campos. The NE–SW-trending Tramuntana Range, 90 km long and 15 km in average width, constitutes the north-western mountainous portion of the island. Here, several peaks reach more than 1,000 m a.s.l. (e.g. Puig Major 1,445 m).

The Tramuntana Range, stretching from Andratx area (Sant Elm and Dragonera islet) to Cap de Formentor, is the most prominent mountain system in the Balearic Archipelago. Its structure is characterized by a series of NE-SW folds, thrusts and faults developed during the orogenic and post-orogenic phases of the Alpine orogeny. One of the most remarkable morphological features of the Tramuntana Range is the asymmetry between the rugged and steep NW-facing coastal flank, and the more gentle SE side. Such contrast is controlled by the NW vergence of the structure (general SE dip of the strata) and the maturity of the relief. While the coastal side displays a juvenile relief, affected by intense erosion including frequent rockslides, the south-eastern sector shows a more subdued landscape related to a long-sustained erosion history since the Late Neogene.

The stratigraphy of Mallorca, and that of the Tramuntana Range, includes formations ranging in age from Carboniferous to Quaternary, with an important hiatus at the base of the Tertiary. The sedimentary successions record a wide variety of depositional environments. The approximate aggregate thickness of the exposed stratigraphic sequence is 3,000 m, in which clastic sediments are scarce and carbonate rocks constitute the dominant lithology.

The Mesozoic succession in Mallorca is over 1,500 m thick. Triassic, Jurassic, and to a lesser extent Cretaceous rocks constitute the vast majority of the outcrops in the Tramuntana Range, the Llevant ranges and in some of the small hills in the central Es Pla depression. The Triassic sequence mainly consists of continental Buntsandstein red mudstones and sandstones, the shallow marine limestones and dolomites of the Muschelkalk facies, and the Keuper, which represents a regressive phase characterized by red and yellowish argillaceous sediments, halite-bearing evaporites and volcanic rocks. Rhaetian dolomites, deposited during the end of the Triassic, point the beginning of a long period of marine sedimentation that continued throughout the rest of the Mesozoic. The Lower Jurassic rocks (Lias) mainly consist of shallow platform massive micritic limestones ca. 400 m thick. These limestones form the bulk of the intensely karstified summits at the Tramuntana Range. The variegated Middle Jurassic (Dogger) and Upper Jurassic (Malm) rocks record a progressive transition towards hemipelagic and pelagic environments. The pelagic sedimentation commenced during the Upper Jurassic, and water depth increased during the Lower Cretaceous with deposition of marls and white marly limestones. The Cretaceous rocks are scarce in Mallorca, although they can reach 150 m in thickness.

The Cenozoic successions exceed 1,500 m in thickness. The Palaeocene and Lower Eocene in the Balearics correspond to a long erosional hiatus related to the emersion of the area, which accounts for the absence of rocks of these ages, as well as for the erosion of Upper Cretaceous formations. The oldest Palaeogene sediments, a few tens of metres thick, crop out in the Llevant ranges and are of Middle and Upper Eocene age. They are formed chiefly by calcarenites and marls rich in nummulites. The Oligocene rocks are more abundant, consisting of polygenic conglomerates, siltstones and limestones with algal concretions. Later, sediments including limestone conglomerate Burdigalian in age, accumulated in Lower-Middle Miocene times, and are affected by folding and thrusting. The synorogenic Lower-Middle Miocene sequences found in Mallorca comprise lacustrine and pyroclastic rocks (earliest Miocene), turbidites (during Burdigalian to Langhian tectonic pulsations), as well as lacustrine and alluvial fan deposits accumulated in terrestrial fault-bounded basins related to the final Late Miocene compressional episodes. The post-orogenic Upper Miocene rocks form a tabular area (called Migjorn) that surrounds the mountain ranges and underlie the coastal platform at the south and east of the island (see Fig. 7.1b); but without significant outcrops in the Tramuntana Range.

Mallorca is the most extensive emerged portion of the so-called Balearic Promontory (Fig. 7.2). This is part of the Betic orogen, a fold and thrust belt resulting from the continental collision between the African and Iberian plates, which occurred from the Upper Cretaceous to the Middle Miocene (ca. 84–15 Ma). The main compressional structures were developed during the Alpine orogeny and consist of NW-verging thrust sheets. The thrust planes are generally associated with Triassic marls and evaporites (Keuper facies) that behave as detachment horizons. The amount of shortening achieved by the thrust structure has been estimated at 44 %. Late Miocene extensional tectonics during the post-orogenic phase generated a horst and graben structure. Differential vertical displacement of tectonic blocks is evidenced by uplifted Pleistocene shorelines and subsidence basins like Palma, Inca-Sa Pobla and Campos.

Summing up, the present-day geological architecture of Mallorca is the result of a complex evolution comprising three main phases: (1) Mesozoic sedimentary phase; (2) Alpine compressional tectonics; and (3) Post-orogenic extensional neotectonics (Late Neogene to Quaternary). The latter phase produced the main morphostructural units, namely the Tramuntana Range, Es Pla depression and Llevant ranges (Rose et al. 1978; Ginés et al. 2012).

7.3 General Landforms

Mallorca exhibits an almost unparalleled variety of landforms within a relatively small territory: steep mountains, deep ravines, precipitous cliffs, broad fertile plains, sandy bays and charming coves (Rose et al. 1978). The topography of Mallorca is mainly determined by late Cenozoic

Fig. 7.3 The impressive gorges of Sa Fosca and Torrent de Pareis are surrounded by vast and almost impassable karrenfields, characterized by an extremely jagged terrain, comprising sharp ridges and pinnacles separated by deep clefts (*Photo* J. Ginés)

extensional tectonics, responsible for the gentle hills of the central plains, as well as the rugged mountains of the Tramuntana Range and Llevant ranges. The rest of the island is characterized by subdued rolling terrains surrounded by a platform of horizontally lying Upper Miocene carbonates, covered locally by Pliocene to Pleistocene sediments. No perennial watercourses are found in Mallorca. Run-off is drained by flash ephemeral streams locally designated as "torrents".

In the Tramuntana Range, the fold and thrust structure is transversally dissected by discordant streams flowing through spectacular narrow gorges that cut across the massive limestone successions. The most distinctive geomorphic features of the Tramuntana Range are closely related to lithology. The alternation of soft rocks (marls, clays, volcanics) and resistant limestones determine many of the landforms observed in the landscape. Since about 65 % of the Tramuntana Range corresponds to limestone outcrops, karst landforms are the most outstanding ones (Ginés 1998). Polje-like depressions, dolines, extensive karrenfields and karstic gorges are widely distributed over the entire mountain range (Bär 1989; Ginés et al. 1989; Ginés and Ginés 1995, 2009). The impressive gorge of Torrent de Pareis, with walls 300 m high, is a remarkable example of such a rugged terrain (Fig. 7.3). Generally, the current landscape of the Tramuntana Range is a particular mixture of karstic wilderness and anthropogenic features such as terraces, cultivated areas and farmhouses, whose economical upkeep is nowadays uncertain (Ginés 1999).

The vast majority of the karst landforms in the Tramuntana Range occur on Lower Jurassic micritic limestones, which are by far the most common outcropping lithology in the mountain range. Large karrenfields, dolines, pinnacles, caves and shafts are ubiquitous features on these rocks, characterized by their remarkable purity and high strength. Minor outcrops of Rhaetian dolomites and Lower Miocene (Burdigalian) limestone conglomerates also show good examples of karst landforms in the Tramuntana Range: deep shafts and karren pinnacles, respectively.

7.4 Karst Geomorphology

Karst landforms are common in the Tramuntana mountains. Large karst depressions with flat floors up to 2 km across, resembling poljes but generally smaller or drained by surface drainage can be found, especially in the northern part of the range (Ginés and Ginés 1995). Some of them are not closed depressions because they have been captured by streams or karst gorges. Their elongated shape is in most cases controlled by the geological structure (Fig. 7.4), especially thrust faults that place in contact impervious marly rocks against karstifiable limestones.

Dolines only show a relatively high density in some intensively karstified sectors in the central part of the mountain range (Escorca municipality), although they have a lower imprint on the landscape than karren landforms. Dolines typically show a subcircular or ellipsoidal perimeter

Fig. 7.4 Water collected into Coma de Son Torrella feeds the Font des Verger cave-spring, located in the nearby transversal valley of Biniaraix. This elongated polje-like depression (1.5 km long and 250 m wide) shows a structurally controlled NE-SW trend (*Photo* J. Ginés)

Fig. 7.5 Typical doline of the central sector of the Tramuntana Range belonging to a cluster of four dolines called Es Clots Carbons. The flat floor of the doline shows a particular fire-controlled plant community dominated by heather; *Erica arborea* (*Photo* A. Ginés)

(Fig. 7.5), and their area ranges from 200 to 15,000 m^2 (major axial lengths between 20–150 m) (Ginés et al. 1989). They tend to form clusters, and their flat bottom is typically underlain by silty soils. Nonetheless, the total area covered by dolines is negligible compared with that of the surrounding karrenfields.

Karren are widespread on large limestone outcrops devoid of soil cover, forming extensive karrenfields. These highly corroded bedrock exposures, up to several km^2 in area, behave as groundwater input areas with no surface drainage. Well-developed karrenfields constitute an almost impassable terrain, with sharp ridges, clefts and spectacular

Fig. 7.6 Typical karst landscape of the Tramuntana Range (Lluc, Escorca municipality). This characteristic karren assemblage is a combination of rillenkarren, trittkarren and rinnenkarren features, sculpturing the sides of pinnacles which emerge over a cleared holm-oak (*Quercus ilex*) forest. Elevation of this site is 550 m a.s.l., and average annual rainfall values exceed 1,000 mm (*Photo* A. Ginés)

pinnacles resembling some tropical karren landscapes. The most impressive karrenfields are located on the NW slopes of the northern sector of the range, between Sóller and Pollença (Fig. 7.6), at rather moderate elevations. Here, the occurrence of karren precludes any kind of cultivation.

Observation of karren features throughout the Tramuntana Range allows recognition of several distinctive karren assemblages, whose distribution shows a clear correlation with the altitudinal gradient. For example, solutional forms present in the highest summits of the range are very different from those located at the lowest elevations, with semi-arid climate (Ginés and Ginés 1995; Ginés 1998). Likewise, the best-developed karrenfields in Mallorca are found in quite specific environmental conditions, characterized by precipitation >800 mm/year, mean annual temperature >15 °C, and elevation between 200 and 700 m a.s.l.

Karrenfields are vast bare rock areas dominated by small-scale karren sculpturing (Ginés 2004, 2009). Straight solutional shapes are typically the most conspicuous and abundant features in most karrenfields, namely rillenkarren (Fig. 7.7) and rinnenkarren (Fig. 7.8). Both karren types, which differ significantly in size and genesis, have given a characteristic furrowed appearance to rock outcrops. Rinnenkarren are remarkably wider runnels and result from solution on rock slopes by channel-collected waters, whereas straight rillenkarren flutes rarely exceed 2 cm in width and are generated by direct-rainfall impact processes. Some morphological and evolutionary features of rillenkarren have been intensively investigated at the Lluc site (Lozano 1884; Bär et al. 1986; Ginés 1998), in the central sector of the Tramuntana Range (520 m a.s.l.; mean annual precipitation >1,000 mm). Recent investigations reveal that the morphometric characteristics of rillenkarren are related to the environmental conditions, reflecting altitude-controlled climatic gradients and increasing rainfall and decreasing temperature with elevation (Ginés and Ginés 2009; Lundberg and Ginés 2009). An additional interesting aspect of rillenkarren is the contribution of biokarstic processes to the development of these elementary forms. Fiol et al. (1996) demonstrate that the mechanical removal of small limestone particles, detached by the impact of raindrops, is an efficient process involved in rillenkarren growth. This detachment of particles is greatly favoured by the presence of endolithic algae that have previously corroded the rock surface, with the subsequent weakening of its crystalline structure.

The spectacular karren assemblages dominated by pinnacles show clear evidence of subsoil dissolution during the first stages of evolution of these karrenfields (Ginés 1995). Such subcutaneous inheritance is evident from the rounded geometry of the pinnacle ridges and the rather smooth appearance of most of the rundkarren runnels. The inherited subsoil features are in many cases obliterated by typical bare karren types (rainpits, kamenitzas, rillenkarren, sharp wandkarren), as described by Smart and Whitaker (1996) and Ginés et al. (2010). It is worth to mention the high density of pinnacles (more than 10 pinnacles per hectare), the substantial proportion of surface area occupied by small pinnacles, as well as by larger residual rocky hills with sharp pointed forms. More than 10 % of the pinnacles are more than 10 m high, and their slopes predominantly show

Fig. 7.7 Straight rillenkarren (solution flutes), a typical feature in the Tramuntana Range. The average width of the flutes is around 1.6 cm (*Photo* A. Ginés)

Fig. 7.8 Vertical rinnenkarren (solution runnels) wider than 20 cm, commonly furrowing the flanks of pinnacles that were formed by subsoil dissolution (*Photo* J. Ginés)

gradients exceeding 45°, which contributes to make these karst landscapes extremely rough and wild.

Caves and shafts are quite abundant in the rugged and deeply entrenched karst areas of Mallorca (Ginés and Ginés 2011), with over one thousand of subterranean cavities inventoried up to date. Most of the caves are less than 1 km in long; only two caverns are more than 300 m deep. The dominant features are vadose shafts, which often include vertical pits more than 100 m deep (Fig. 7.9). Some small shafts located in the high country seem to be genetically related to corrosion favoured by snow accumulation. A small number of sub-horizontal hydrologically active

Fig. 7.9 The impressive Avenc de Femenia shaft, a single pit 120 m deep (*Photo* J. Ginés)

passages (water-table caves) are occasionally found. On the other hand, most of the sub-horizontal caves are composed of presumably old collapse chambers. As a general trend, the main speleogenetic phases must be pre-Quaternary, as the Pliocene endemic vertebrate remains found in some cave sediments indicate (Ginés et al. 2012). It seems that apart from intense speleothem growth, the majority of the caves have undergone limited morphological modifications during the Middle and Late Pleistocene.

7.5 Conclusions

The Tramuntana Range in Mallorca Island is a representative area for the study of karst landforms and processes in a mountainous Mediterranean environment. Jurassic and Lower Miocene limestones, affected by folding and thrusting during the Alpine orogeny, show evidence of intense karstification, including large karst depressions, deep gorges, dolines and extensive karrenfields with a remarkable diversity of solutional micro- and meso-forms. Abundant shafts and caves also characterize the karst landforms of these mountains.

The distribution and morphometry of the different karren assemblages are controlled by the climatic gradients, mainly determined by the elevation, ranging from sea level to 1,445 m. Biokarst processes have a significant contribution in karren development, especially in some specific ecological situations, like the semi-arid peripheral sectors of the range and the north-facing slopes of the highest summits. Some spectacular karren-pinnacle landscapes, characteristic of the central part of the range, have evolved from subsoil karren exhumed by various soil-loss processes.

The Tramuntana Range is an excellent natural laboratory for karst studies and particularly for karren investigation in mid-latitudes, owing to the great variety of environmental conditions, as well as to the significant human impact on the area over the last five millennia.

References

Bär WF (1989) Atlas Internacional del Karst. Hoja 5: Lluc/Sierra Norte (Mallorca). Endins 14–15:27–42

Bär WF, Fuchs F, Nagel G (1986) Lluc/Sierra Norte (Mallorca)—Karst einer mediterranen Insel mit alpidischer Struktur (UIS International Atlas of Karst Phenomena, sheet 5). Zeitschrift für Geomorphologie N.F., Suppl. Bd. 59:27–48 + 1 map

Fiol LA, Fornós JJ, Ginés A (1996) Effects of biokarstic processes on the development of solutional rillenkarren in limestone rocks. Earth Surf Proc Land 21:447–452

Ginés A (1995) Deforestation and karren development in Mallorca, Spain. In: Bárány-Kevei I (ed) Environmental effects on karst terrains. Special issue of Acta Geographica Szegediensis. Homage to László Jakucs, Szeged, pp 25–32

Ginés A (1998) L'exocarst de la serra de Tramuntana de Mallorca. In: Fornós JJ (ed) Aspectes geològics de les Balears. Universitat de les Illes Balears, Palma de Mallorca, pp 361–389

Ginés A (1999) Agriculture, grazing and land use changes at the Serra de Tramuntana karstic mountains. Int J Speleol 28 B (1/4):5–14

Ginés A (2004) Karren. In: Gunn J (ed) Encyclopaedia of caves and karst science. Fitzroy Dearborn, New York, pp 470–473

Ginés A (2009) Karrenfield landscapes and karren landforms. In: Ginés A, Knez M, Slabe T, Dreybrodt W (eds) Karst rock features, Karren sculpturing. Zalozba ZRC, Ljubljana, pp 13–24

Ginés A, Ginés J (1995) Les formes exocàrstiques de l'illa de Mallorca/The exokarstic landforms of Mallorca island. In: Ginés A, Ginés J (eds) El carst i les coves de Mallorca/Karst and caves in Mallorca. Endins, 20/Mon. Soc. Hist. Nat. Balears 3, Palma de Mallorca, pp 59–70

Ginés A, Fiol LA, Pol A, Rosselló JA (1989) Morfologia i vegetació d'un grup de dolines de la Serra de Tramuntana (Mallorca). Endins 14–15:43–52

Ginés A, Ginés J, Miralles PM (2010) Anàlisi morfomètrica del carst de pinacles mediterrani de sa Mitjania (Escorca, Mallorca). Endins 34:109–124

Ginés A, Ginés J, Fornós JJ, Bover P, Gómez-Pujol L, Gràcia F, Merino A, Vicens D (2012) An introduction to the Quaternary of Mallorca. In: Ginés A, Ginés J, Gómez-Pujol L, Onac BP, Fornós JJ (eds) Mallorca: a Mediterranean benchmark for Quaternary studies. Mon. Soc. Hist. Nat. Balears 18, Palma de Mallorca, pp 13–53

Ginés J, Ginés A (2009) Mid-mountain karrenfields at Serra de Tramuntana in Mallorca Island. In: Ginés A, Knez M, Slabe T, Dreybrodt W (eds) Karst rock features, Karren sculpturing. Zalozba ZRC, Ljubljana, pp 375–390

Ginés J, Ginés A (2011) Classificació morfogenètica de les cavitats càrstiques de les Illes Balears. In: Gràcia F, Ginés J, Pons GX, Ginard A, Vicens D (eds) El carst: patrimoni natural de les Illes Balears. Endins, 35/Mon. Soc. Hist. Nat. Balears 17, Palma de Mallorca, pp 85–102

Lozano R (1884) Anotaciones físicas y geológicas de la isla de Mallorca. Excma. Diputación Provincial de Baleares. Imprenta de la Casa de Misericordia. Palma de Mallorca

Lundberg J, Ginés A (2009) Rillenkarren. In: Ginés A, Knez M, Slabe T, Dreybrodt W (eds) Karst rock features, Karren sculpturing. Zalozba ZRC, Ljubljana, pp. 185-210

Rose J, Crabtree K, Cuerda J, Osmaston AH (1978) The Quaternary of Mallorca. Quaternary Research Association, Bedfordshire

Smart PL, Whitaker FF (1996) Development of karren landform assemblages—a case study from Son Marc, Mallorca. In: Fornós JJ, Ginés A (eds) Karren landforms. Universitat de les Illes Balears, Palma de Mallorca, pp 111–122