6 Conglomerate Monoliths and Karst in the Ebro Cenozoic Basin, NE Spain

J. Guerrero, F. Gutiérrez, and M. Gutiérrez

Abstract

The sedimentary fill of the Ebro Cenozoic Basin, NE Spain, includes thick conglomerate successions in the marginal sectors associated with the surrounding Alpine orogens. These commonly cemented alluvial fan and fan delta conglomerates grade rapidly into less resistant fine-grained facies. Differential excavation of the basin fill, together with erosion processes controlled by vertical fractures in the massive and indurated conglomerates, has resulted in the development of monoliths, locally known as mallos, with vertical walls that may reach more than 300 m in height. The cemented and fractured conglomerates in some sectors of the Catalan margin of the basin, mostly composed of calcium carbonate, display features characteristic of well-developed karst terrains, including sinkholes, karst springs, and multilevel cave systems several kilometers long with spelothems.

Keywords

Structural geomorphology • Conglomerate pinnacles • Conglomerate karst • Mallo

6.1 Introduction

The sedimentary fill of foreland basins typically includes significant continental successions (molasse) related to the syntectonic unroofing of the surrounding mountain belts (Allen and Allen 1990). Thick alluvial fan sediments consisting of massive conglomerates and breccias commonly occur along the margins of these basins. Fluvial dissection of the basin fill, together with structurally controlled differential weathering and erosion of these coarse-grained detrital rocks, may result in the development of towers, pinnacles, and fins hundreds of meters high. These structural landforms are widely developed in subhorizontally lying calcareous conglomerates at the margins of the Ebro Cenozoic Basin (Gutiérrez and Peña 1994), where they are usually designated as mallos (meaning thick stick or cudgel; Biarge 2004). The most outstanding examples are located in the following: (1) Tobía-Matute, Anguiano, and Viguera-Islallana in La Rioja, at the boundary with the Iberian Chain; (2) Agüero, Murillo-Riglos, and Salto del Roldán, along the Pyrenean margin of the Ebro Basin in Aragón; and (3) Sant Llorenç de Munt, Montserrat, and L'Espluga de Francolí, in the basin border associated with the Catalan Coastal Chain (Fig. 6.1).

The conglomeratic monoliths may occur as isolated towers with rounded summits and pinnacles (Fig. 6.2), or may form a maze of monoliths and narrow corridors controlled by the fracture pattern (Fig. 6.3). The development of these landscapes is related to the concurrence of a set of lithological, structural, and mechanical factors, within a geomorphic context of fluvial entrenchment and differential erosion (e.g., Benito 1986, 1993; García-Ruiz 2007).

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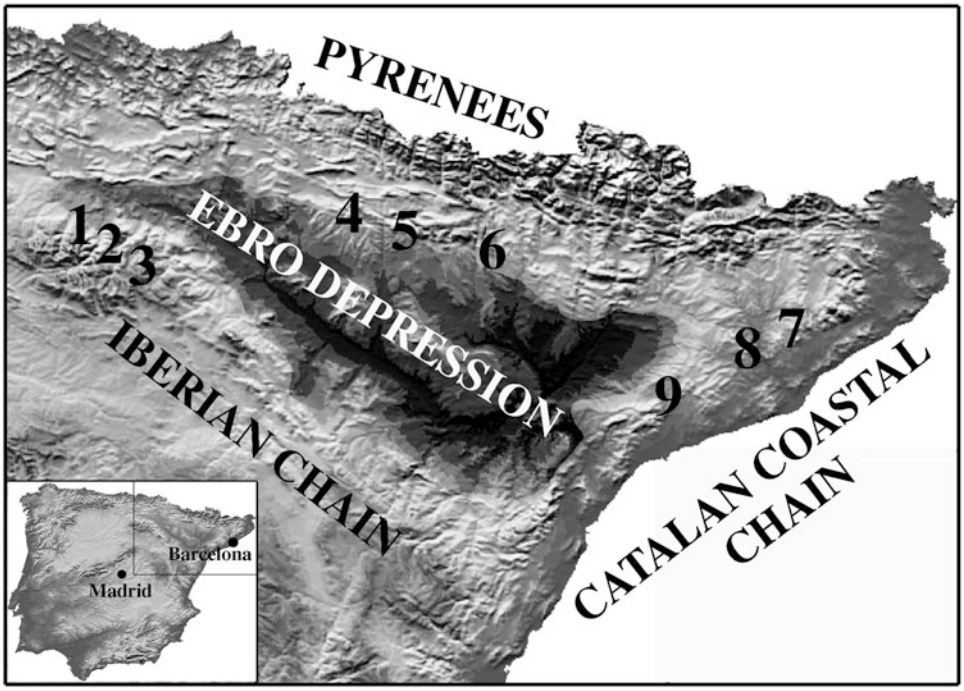

Fig. 6.1 Shaded relief model of the NE sector of the Iberian Peninsula indicating the location of the main sites with conglomerate monoliths along the margin of the Ebro Depression. Tobía-Matute (*1*), Anguiano (*2*), Viguera-Islallana (*3*), Agüero (*4*), Murillo-Riglos (*5*), Salto del Roldán (*6*), Sant Llorenç de Munt (*7*), Monserrat (*8*), L'Espluga de Francolí (*9*)

In some sectors (e.g., Riglos, Salto del Roldán), the conglomerate formations are crossed by major transverse drainages coming from the adjacent ranges and flowing along deeply entrenched canyons (Fig. 6.4). These scenic landscapes have attracted human beings from prehistoric times to satisfy their material, spiritual, and recreation needs. In the karstified conglomerates of Cataluña, caves, and rock shelters were used as settlement sites in Upper Paleolithic and Neolithic times (Bergadá et al. 1997). The conglomeratic massif of Montserrat, declared Natural Park, includes the Montserrat Monastery, one of the most popular pilgrimage sites of Cataluña. The archetypal Mallos de Riglos in Aragón is one of the most frequented sites in Spain by rock climbers. It includes several monoliths with vertical walls more than 300 m high and the mythic El Puro (the cigar), a spire first climbed in 1953 after several deadly attempts (Fig. 6.2). An additional feature of the calcareous conglomerates in the SE margin of the basin (Freixes 1987; Bergadá et al. 1997) is the development of cave systems and internal karst hydrology comparable with those characteristic of carbonate and evaporite terrains (e.g., Goeppert et al. 2011). Conglomerate monoliths are also found in other regions of Spain, such as Vadiello, Pyrenees (Rodríguez-Vidal 1986) or Peracense Castle, Iberian Chain (Gutiérrez et al. 2005; Lozano et al. 2007). Outstanding examples of conglomeratic monoliths in other countries include the World Heritage sites of Meteora (Greece), Danxiashan (China), Kata Tjuta (the Olgas, Australia; Twidale 2010), and the Putangirua Pinnacles Scenic Reserve (New Zealand). This chapter reviews the processes and controlling factors involved in the genesis of the conglomeratic monoliths of the Ebro Basin and describes their most important karst features documented in the literature.

6.2 Geological and Geomorphological Setting

The Ebro Cenozoic Basin in NE Spain constitutes the southern foreland basin of the Pyrenees. The development of these two major structural units is related to the convergence and collision of the Iberian and European plates from the end of the Cretaceous to the Miocene (Anadón and Roca 1996). The Ebro Depression, which essentially coincides with the Ebro foreland basin, is a structural and erosional depression drained by the Ebro River and surrounded by Alpine mountain belts, the Pyrenees to the N, the Iberian Chain to the SW and the Catalan Coastal Chain to the SE (Fig. 6.1). During the initial evolutionary stages (Paleocene and Eocene), the Ebro Basin was largely dominated by marine environments, with deposition of thick fan delta and alluvial fan sequences in the eastern sector (Muñoz et al. 2002; Pardo et al. 2004). In late Eocene times, with the Priabonian regression, the basin became a land-locked

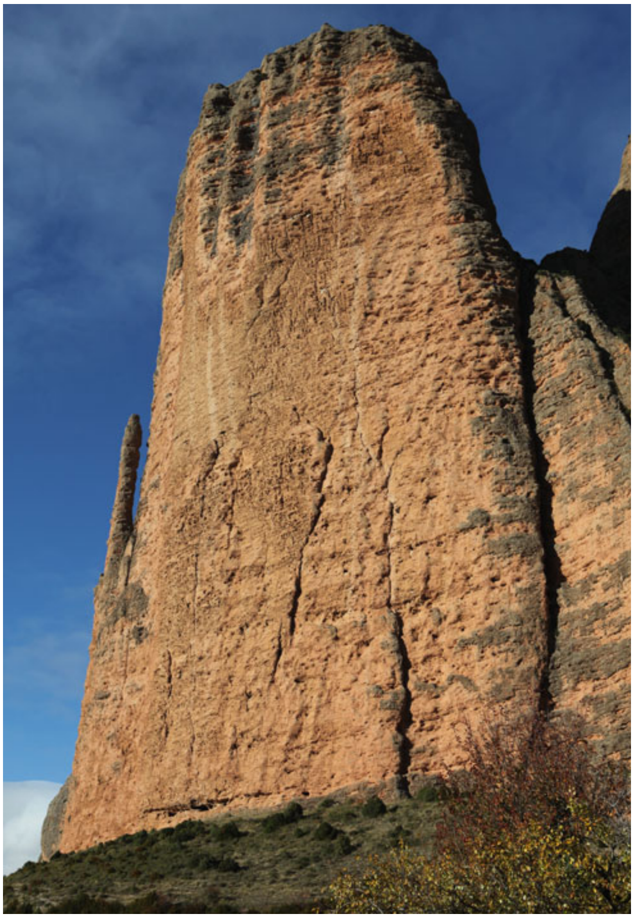

Fig. 6.2 The Pisón Mallo (Riglos, Pyrenean margin), a conglomerate monolith with vertical walls more than 300 m high. The pinnacle attached to the cliff is called El Puro (the cigar), a classical challenge for rock climbers (Photograph taken by F. Gutiérrez)

depression with continental sedimentation (Riba et al. 1983). The paleogeography during this endorheic stage essentially comprised alluvial fans in the marginal areas of the basin grading into evaporite and carbonate lakes in the most subsiding sectors. The distribution of the main evaporite and carbonate lacustrine formations records a progressive southward migration of the depositional axis of the basin related to the propagation of the Pyrenean orogenic wedge and the forebulge (Riba et al. 1983; Ortí 1997). The marginal conglomerates, mainly deposited by sheet floods and debris flows (Blair and McPherson 1994), typically display a sharp lateral facies change into less resistant sandstones and argillaceous rocks. In Middle–Late Miocene times, the basin was captured by a proto-Ebro River and opened toward the Mediterranean Sea (Vázquez-Urbez et al. 2002; García-Castellanos et al. 2003; Pérez-Rivarés et al. 2004; Arche et al. 2010). During this stage, a new drainage network developed and dissected the basin fill by headward expansion, generating stepped sequences of mantled pediments and terraces. The topography within the Ebro Depression is mainly controlled by differential erosion related to the distribution of lithofacies. The central lacustrine successions, commonly capped by limestone units, and the marginal conglomerates form prominent reliefs, while erosional depressions with extensive mantled pediment sequences occur in the areas dominated by argillaceous sediments.

6.3 Controlling Factors and Origin

The development of conglomerate monoliths requires the concurrence of a number of litho-structural and geomorphic factors (e.g., Benito 1986, 1993; García-Ruiz 2007; Fig. 6.5).

- The existence of a thick succession of massive conglomerates with a sharp lateral change into more erodible fine-grained detrital facies, as is commonly the case in alluvial fan environments. This lithological change favors the formation of conglomerate escarpments by differential erosion (Fig. 6.2). Massive or poorly bedded conglomerates are more suitable for the development of monoliths. The towers and pinnacles developed on relatively well-bedded conglomerates, including fine-grained beds, tend to reach lower heights and display more irregular scarps with ledges and notches related to stratigraphically controlled differential recession (e.g., Mallos de Agüero; Fig. 6.6).
- High degree of induration of the conglomerates related to carbonate cementation. This feature grants cohesion and compressive strength values high enough to withstand towers several hundred meters high (Young et al. 2009) and favors surface and subsurface dissolution processes, especially when the clasts are mainly composed of limestone. García-Ruiz (2007) compares the landforms developed on indurated calcareous conglomerates versus low cohesion siliceous conglomerates along the Iberian Chain margin in La Rioja. The distribution of these lithofacies is controlled by the rocks exposed in the drainage basins (Muñoz-Jiménez 1992) that used to feed the alluvial fans in which they were deposited. The cemented conglomerates form excellent examples of monoliths with vertical walls (Tobía-Matute, Anguiano, and Viguera-Islallana), whereas gully systems and deep-seated landslides are the main erosional landforms developed in the loose siliceous conglomerates.
- A critical predisposing factor is related to the attitude, spacing, and orientation of the facture system. Subvertical fractures are required for the development of high- and steep-walled monoliths (Fig. 6.7). Fractures whose dip show a slight deviation for a vertical attitude limit the

Fig. 6.3 Gently dipping conglomerates in the vicinity of Matute village (Iberian Chain margin), deeply dissected by a fluvial canyon (Manzanar Creek) and fracture-controlled corridors (Photograph taken by F. Gutiérrez)

Fig. 6.4 Conglomerates at the northern margin of the Ebro Basin dissected by the transverse Flumen River canyon (Salto del Roldán, Guara Natural Park). Image of the Amán Mallo taken from San Miguel Mallo. To the left, Mesozoic and Paleogene formations of the Pyrenees overthrusting the subhorizontally lying Tertiary conglomerates (Photograph taken by F. Gutiérrez)

Fig. 6.5 Sequence of block diagrams illustrating the development of monoliths on thick and massive conglomerate successions affected by widely spaced orthogonal fractures (Illustration produced by Santiago Alberto-Moralejo)

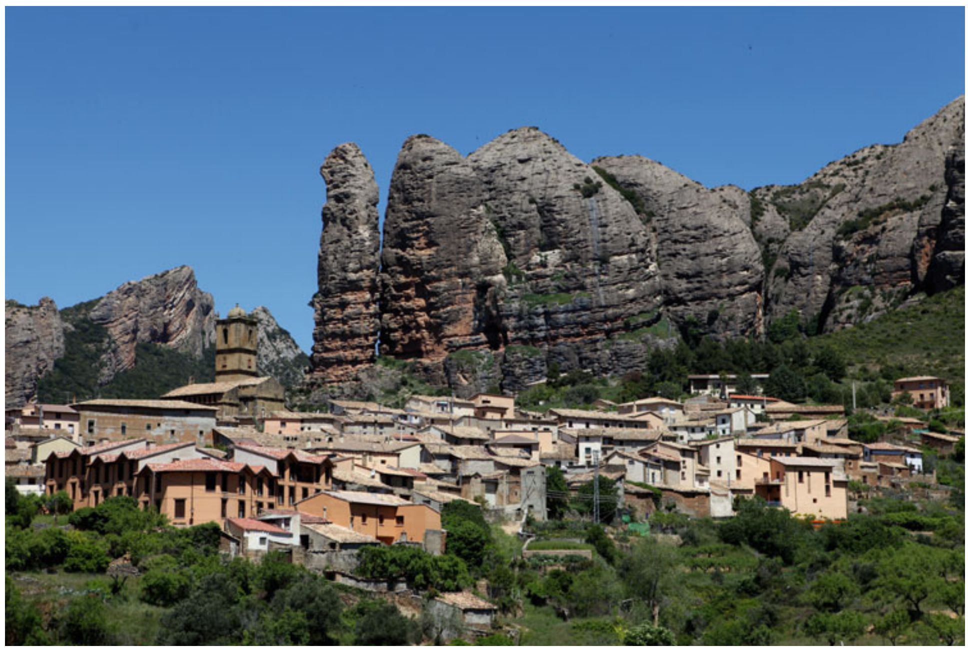

Fig. 6.6 The Mallos de Agüero (Huesca Province) carved on relatively well-bedded cemented conglomerates affected by a widely spaced network of vertical fractures. These Tertiary sediments where deposited on the proximal sector of alluvial fans developed at the Pyrenean margin of the Ebro Basin. Agüero village at the foot of the cliffs (Photograph taken by F. Gutiérrez)

height of the monoliths and favor the development of upward-tapering pinnacles and spires. The density and spacing of the fractures should reach values within a range adequate to compartmentalize upright parallelepipedic rock masses that may evolve into stable monoliths. A high density of fractures leads to a rapid erosion of the conglomerate massif (Fig. 6.8), whereas massive reliefs and mesas tend to develop on conglomerates with a low density of joints. Benito (1986, 1993), comparing the spatial distribution of conglomerate landforms in Aguero-Riglos area and the fracture density, infers that in that sector of the Pyrenean margin, the mallo landform is best developed with fractures densities of around 75 fractures/km^2. Fracture orientation also plays a significant role in the development and geometry of the monoliths. Orthogonal fracture systems control the formation of towers and pinnacles, whereas conglomerates affected by a more penetrative set of parallel fractures promote the formation of elongated monoliths (fins), like in Montserrat (Figs. 6.8, 6.9) and Sant Llorenç de Munt.

- Relatively rapid entrenchment of the fluvial network favors (1) the differential erosion of the more distal fine-grained alluvial fan facies and the development of conglomerate escarpments; (2) the headward expansion and incision of gully systems, which contributes to the preferential erosion of conglomerates along fracture-controlled drainages and the evacuation of sediments accumulated at the foot of the scarps. In fact, some of the best examples of monoliths occur associated with major fluvial systems, whose incision has led to a continuous rejuvenation of the topographic gradient (e.g., Riglos, Salto del Roldán, Viguera-Islallana; Figs. 6.4, 6.7). In the Ebro Basin, this long process of base-level lowering and differential erosion started in Miocene times, when the basin was captured by the external drainage network and changed to exorheic conditions.

Figure 6.5 illustrates the development of conglomerate monoliths. In an initial phase, the entrenchment of the drainage network in the basin and differential erosion of fine-grained alluvial fan facies result in the development of

Fig. 6.7 The Mallo Firé in Riglos, an association of elongated monoliths controlled by *vertical fractures*. The Gállego River valley with well-developed terraces in the *bottom*, and the conglomerates of Murillo de Gállego on the *upper-right corner*. The saddle situated to the *right* of the Mallo Firé corresponds to the thrust that defines the contact between the Ebro Basin (conglomerates) and the Pyrenees (folded carbonate rocks) (Photograph taken by F. Gutiérrez)

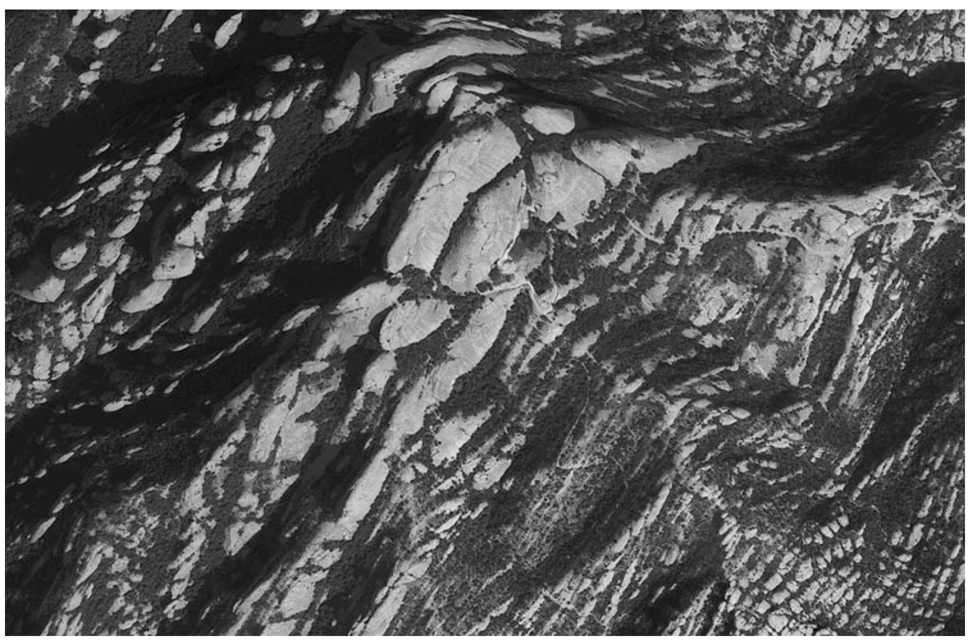

Fig. 6.8 Oblique aerial view of the conglomerates in Montserrat affected by a dominant NNE–SSW fracture set with variable spacing, controlling the development of fin-like elongated monoliths. The monoliths with higher relief are associated with the areas where the fracture spacing is wider

a conglomeratic massif bounded by an escarpment. A conjugate system of widely spaced vertical fractures controls focused weathering and erosion processes resulting in steep-sided gullies, locally hanging, and corridors that individualize rock prisms. Rock falls are the dominant processes acting on the competent calcareous conglomerate walls, promoted by mechanical (e.g., frost shattering), chemical (e.g., dissolution), and biological (e.g., root wedging) weathering. Fluvial erosion, mostly related to severe storm events in the gully bottoms, contributes to the evacuation of the deposits supplied from the hillslopes. Long-sustained base-level lowering related to fluvial entrenchment leads to the development of progressively higher monoliths with vertical walls and rounded summits.

6.4 Karst in Conglomerate Monoliths

Fractured conglomerates consisting of limestone clasts with a cemented calcareous matrix are suitable formations for the development of karst features. Subsurface water circulation through fractures and interstitial pores causes the

Fig. 6.9 Les Agulles, Montserrat, elongated monoliths controlled by a penetrative system of parallel and vertical fractures (Photograph taken by C. Miñarro)

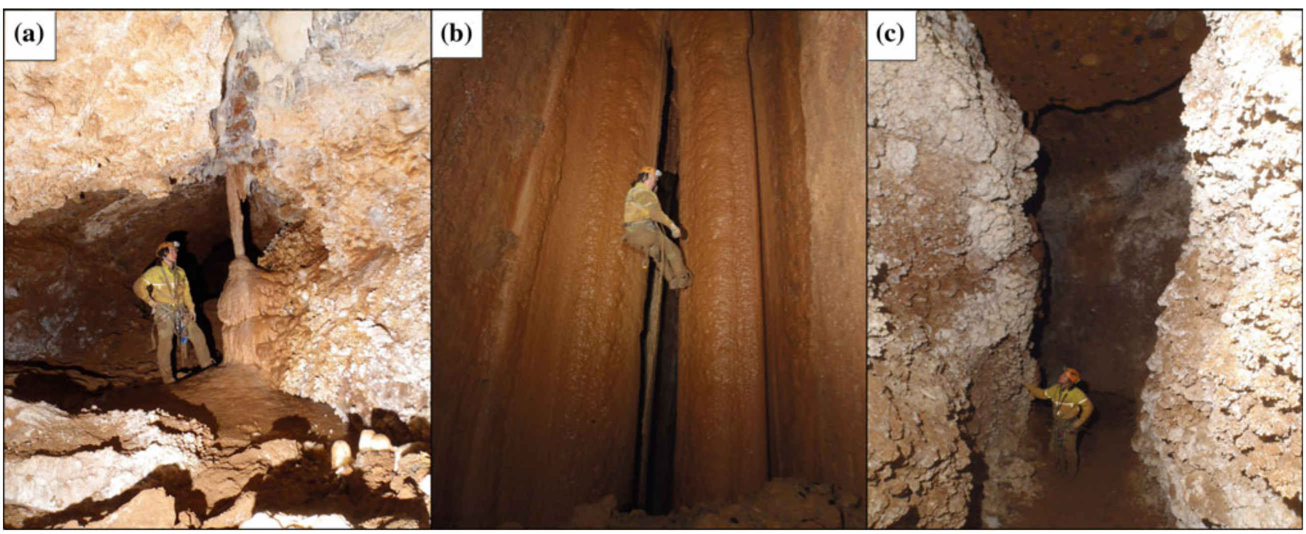

Fig. 6.10 Images of Cuberes cave. **a** Column. **b** Flowstone. **c** Canyon-like subhorizontal passage (courtesy of L. Almela)

progressive enlargement of discontinuity planes and the dissolution of the cement, matrix, and limestone clasts, resulting in a permeability increase. This is a self-accelerating process that fosters higher flow and karstification. Over time, a mature karst may develop in conglomerates, displaying many of the surface and underground landforms and hydrogeological characteristics of carbonate and evaporite karst systems (e.g., Goeppert et al. 2011).

The scientific literature dealing with karst features developed in conglomerates is rather limited. Conglomerate karst has been reported in Kuruköprü Basin, Turkey (Degirmenci and Günay 1993), southern France (Bès 1994), the northern foreland basin of the Alps, Germany (Scholz and Strohmenger 1999), Russia (Filippov 2004), northern Italy (Ferrarese and Sauro 2005), Slovenia (Gabrovsek 2005; Lipar and Ferk 2011 and references therein), Jura Mountains, NW Switzerland (Lapaire et al. 2006), the northern Alps, Austria-Germany (Goeppert et al. 2011). Ferrarese and Sauro (2005) mapped more than 2,000 sinkholes and blind valleys in the Miocene Montello Conglomerate in Italy. Bol'shaya Cave, Russia, with more than 47 km of surveyed passages, is the longest conglomerate cave in the world (Filippov 2004).

In Spain, karst features developed on carbonate-rich conglomerates have been documented in a number of areas (e.g., Martín-Algarra et al. 1989; Durán and López-Martínez 1999; Antón 1992). However, the most outstanding examples are found in conglomerates associated with the Catalan margin of the Ebro Basin. Karst landforms have been described in calcareous Paleogene conglomerates at Sant Llorenç del Munt, Sant Miguel Montclar, L'Espluga de Francolí, Montserrat Massif, Montsen, Serradell, and Sant Llorenç de Morunys (Freixes 1989). Surface karst landforms are typically restricted to solutionally enlarged fractures, swallow holes, and microkarren developed on large limestone boulders. The main dissolution-related features correspond to well-developed caves and the characteristic subsurface karst hydrology (Bergadá et al. 1997). The Terrasa Excursionist Center has inventoried around 600 caves in Sant Llorenç del Munt, some of them with archaeological and paleontological sites (Jorquera 1970; Nebot and Hernández 2007). The 12.8-km-long Cuberes Cave in L'Espluga de Francolí is one of the longest conglomerate caves in the world (Freixes 1989; Fig. 6.10).

According to Bergadá et al. (1997), the cave systems developed in the calcareous conglomerates of the Catalan margin of the Ebro Basin consist of short and vertical conduits that connect with subhorizontal passages that may reach several hundred meters long. Vertical conduits result from dissolution along vertical joints, while the horizontal galleries are often associated with more fractured conglomerates or impervious beds. These passages, commonly developed at different levels, display circular or ellipsoidal sections modified by basal incisions (keyhole section) and lateral notches, recording an initial phreatic phase and subsequent vadose entrenchment related to the episodic entrenchment of the drainage network. Freixes (1987, 1989) studied a number of temporal and permanent springs in the Sant Llorenç del Munt conglomerate massif. He found retarded downward vadose circulation before reaching a primary flow pathway. He classified these peculiar karst aquifers as diffuse flow hydrogeological systems with relative long water residence time. Precipitation from oversaturated water results in the formation of spelothems in the caves (Fig. 6.10) and tufa deposits in some springs.

6.5 Conclusions

The development of monoliths (mallos) in the calcareous conglomerates along the margins of the Ebro Basin results from the concurrence of several factors, related to the sedimentary, diagenetic, and erosional history of the sediments. These are: (1) Deposition of thick calcareous conglomerates in alluvial fans and fan deltas developed at the tectonically active margins of the basin; (2) Sharp lateral change between the conglomerates and more distal fine-grained facies; (3) Significant induration of the deposits by cementation processes; (4) Development of a network of vertical fractures with adequate spacing; (5) Progressive entrenchment of the drainage network after the capture of the basin and differential erosion of the fine-grained facies; (6) Preferential weathering and erosion processes acting on the fractures, leading to the compartmentalization and individualization of monoliths and in some cases the formation of mazes of corridors. These calcareous conglomerates cemented by calcium carbonate and affected by fractures, constitute a suitable terrain for the development of geomorphic and hydrological karst systems, like those reported in the Catalan margin of the basin. These conglomerate massifs display grikes, swallow holes, and well-integrated cave systems consisting of vertical fracture-controlled conduits and different levels of subhorizontal passages formed under phreatic conditions.

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