



## Editorial

## Geomorphological research in Spain

## 1. Introduction

The production of this special issue arose from a successful scientific meeting held in Zaragoza, Spain (September 8–9, 2011), under the theme *Geomorphological Research in Spain*. The main motivation of the event was to recognise and celebrate the outstanding contribution of Prof. Mateo Gutiérrez to the progress of Geomorphology in Spain, on the occasion of his transition to full-time research (Emeritus Professor). Mateo Gutiérrez (b. Burgos, 1941) was the Founding President of the Spanish Society of Geomorphology (1987) and led the organisation of the Sixth International Conference of Geomorphology of the IAG (Zaragoza, 2005). With his enthusiasm and dedication, he has inspired and encouraged numerous geomorphologists, including eleven PhD students, most of them now working as professors or researchers in different universities and research institutions. In his prolific career, he has published more than 200 contributions, including a large number of papers dealing with a wide variety of topics, as well as numerous geological maps. Probably, the most relevant tangible contributions of Mateo Gutiérrez include the editorship of the book *Geomorfología de España* (Gutiérrez, 1994), and the authorship of the books *Climatic Geomorphology* (Gutiérrez, 2001, 2005) and *Geomorfología* (Gutiérrez, 2008). An expanded version of the latter, widely regarded as the reference Geomorphology textbook for Spanish-speakers, will be shortly published in English by Balkema (Gutiérrez, 2013). Since 2011 Mateo has been Emeritus Professor at the University of Zaragoza, Spain.

The meeting *Geomorphological Research in Spain* was attended by around 65 participants, including several geomorphologists from Great Britain (Fig. 1). The opening lecture was presented by Prof. Adrian Harvey, who illustrated Mateo's contributions through some major themes for the Geomorphology of Spain. This stimulating keynote was followed by 40 oral presentations covering a wide geographical and thematic canvas. The second day was devoted to a field trip in Calatayud Graben, Iberian Chain, an area where Mateo has conducted extensive research. Here, we examined a seismogenic Quaternary fault and evidence of evaporite dissolution-induced subsidence, including severe structural damage in Calatayud city. Based on the presentations and the scope of the special issue, selected authors were invited to contribute to this special issue, which includes 18 articles out of the 28 initial submissions. In our opinion, this collection of papers illustrates the great potential of Spanish geomorphology to provide lessons and develop methodologies applicable in other regions of the globe.

## 2. General overview of the Spanish geomorphology

Spain is the southernmost country in Europe and covers an area of 505,990 km<sup>2</sup>, of which 12,465 km<sup>2</sup> corresponds to the Balearic Islands

in the Mediterranean Sea, and the Canary Islands in the Atlantic Ocean. The Spanish territory has a remarkable geomorphological diversity largely due to its geological and climatic variability (Gutiérrez, 1994; Benito-Calvo et al., 2009). Moreover, the pressure on the environment caused by long-sustained human activity makes this country an excellent natural laboratory to investigate anthropogenic impacts on multiple geomorphic processes and landforms (e.g. García-Ruiz and López-Bermúdez, 2009). The wide climatic variability is related to several geographical factors (Font, 1983; IGN, 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. 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. (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 northwestern sector of the peninsula exceeds 1200 mm, whereas there is an extensive sector in the southeast where the yearly rainfall is below 400 mm. The Cabo de Gata, Almería Province, has a mean annual precipitation of ca. 130 mm. (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. 2). 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. For example, the distance between some of the active glaciers in the Pyrenees and playa-lakes with wind-fluted yardangs and evaporite deposition in the semiarid Ebro Depression 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 of mountain ranges and the presence of extensive elevated plateaus (*mesetas*) in central Spain, corresponding to planation surfaces and structural surfaces. These topographic characteristics have a significant influence on climatic features of geomorphological significance. The annual average number of days with temperature below 0 °C exceeds 120 days/yr in most of the mountain areas above 1200 masl in the northern half of Spain, and is typically higher than 60 days/yr in the central *mesetas*. Another important characteristic of the Spanish climate, particularly in the Mediterranean fringe and the mountain regions, is the occurrence of severe rainfall events which may have a dramatic geomorphic effectiveness and are responsible for natural disasters with the highest number of fatalities (e.g. 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



**Fig. 1.** Photograph taken the first day of the meeting “Geomorphological research in Spain” (Zaragoza, September 8–9, 2011) with Mateo Gutiérrez (second line, sixth from the left) and most of the participants.

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. 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. 2A): (1) The Iberian Massif in the western sector, frequently regarded as Variscan 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.

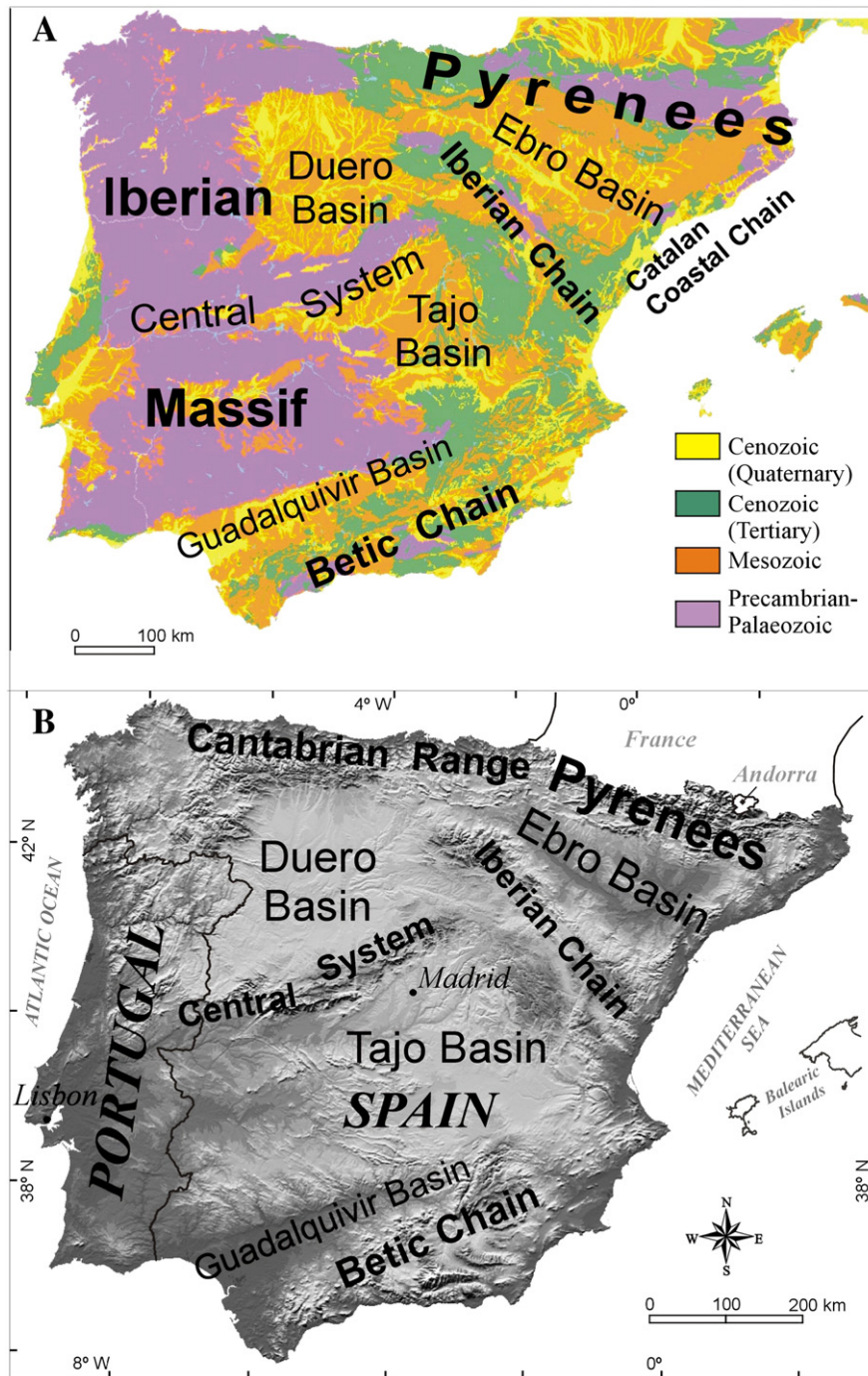
The Iberian Massif is by far the most poorly known area of Spain from the geomorphological perspective. It is the best exposure of the European Variscan orogen, generated by the collision between Laurasia and Gondwana in the late Paleozoic. This structurally complex area mainly consists of Paleozoic metamorphosed sedimentary formations intruded by plutonic rocks, chiefly granitoids. The Mesozoic was a period dominated by erosion which led to the development of extensive peneplains. Compressional Alpine tectonics in this portion of Iberia has been accommodated by the development of intraplate mountain systems and small Cenozoic basins controlled by reverse and strike-slip faults, locally showing evidence of recent activity (e.g. Martín-González, 2009). 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 morpho-structure separates the Duero and Tajo Cenozoic basins in central Spain and reaches 2592 m in elevation. 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 (monadnocks), or occur as concordant flat summits. The mature topography of this relatively stable area has favoured the development and preservation of thick paleoweathering profiles that record past climate conditions and constitute a valuable correlation tool for regional geomorphology (Molina et al., 1997; Martín-Serrano and Molina, 2005). Another characteristic feature of the Iberian Massif is the presence of extensive piedmont alluvial deposits composed of siliceous clasts

with a reddish argillaceous matrix (*raña* surfaces). These thin alluvial mantles situated above the terrace sequences in watershed divide areas and of supposed late Neogene age, record the initial phases of development of the present-day drainage network (Martín-Serrano, 1991; Molina-Ballesteros and Cantano Martín, 2002). 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 Paleozoic rocks with contrasting resistance to erosion (e.g. quartzites and slates) has produced a distinctive Appalachian-type of topography (e.g. Toledo Mountains and Sierra Morena). Some areas of Galicia and the Central System display spectacular examples of granite geomorphology with bornhardts (e.g. La Pedriza de Manzanares), tors, fields of corestones, etch surfaces and tafoni with speleothems (Vidal-Romaní and Twidale, 1998). 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, shaft-dominated caves more than 1.5 km deep, and gorges with impressive walls more than 1 km high. The glaciated areas are restricted to the highest massifs in the central and northern sectors 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., 2012).

The Betic Chain and the Pyrenees are Alpine orogens resulting from the collision of the Iberian microplate with the European and African plates, respectively. 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 3482 m and 3404 masl, respectively. The Pyrenees is essentially a “blocked” plate margin with negligible relative motion, whereas the Betics is currently affected by considerable convergence (4 mm/yr) 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 is the absence of extensive planation surfaces, attributable to rapid deformation in a plate margin context.

The Betics, with a general NE–SW orientation, extend for about 1000 km in the south and southeast of Spain, including the Balearic Islands. 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 allochthonous south-verging structural units made up of Mesozoic and Cenozoic sedimentary sequences





**Fig. 2.** Geological map (A) and shaded relief model (B) of mainland Spain (produced by Alfonso Benito).

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 is clearly the best region in Spain to investigate the impact of active tectonics on landscape development. The Eastern Betics displays excellent examples of fault-controlled mountain fronts and alluvial fan systems (e.g. Silva et al., 2003), whose development may be affected by multiple factors: tectonic activity, climate variability and base level changes (Silva et al., 1992; Harvey et al., 1999). 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). In the Betic Chain, the evolution of the drainage network, largely guided by the postorogenic basins, has been the focus of pioneering studies addressing issues like the impact of capture-induced base-level changes (Harvey and Wells, 1987; Goy et al., 1994; Mather, 2000; Maher et al., 2007; Whitfield 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 morpho-stratigraphic 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. Limestone karst is well-developed in numerous regions, mostly of the Outer Betics, with magnificent examples of poljes controlled by active faults (e.g. Zafarraya Polje; Lhenaff, 1986; Reicherter et al., 2003), karren fields (Torcal de Antequera, Tramuntana Range) and cave systems, some of them with significant economic (Nerja show cave), engineering (Hundidero Gato Cave and the failed Montejaque Dam project) and paleoanthropological (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 (Calaforra and Pulido-Bosch, 2003). Evidence of Quaternary glaciation is restricted to Sierra Nevada, which is the southernmost glaciated area in Europe. Here, valley glaciers reached around 3 km in length during their maximum extent, 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 (Gelabert et al., 2003; Azañón et al., 2005; Delgado et al., 2011) and, unlike in the Pyrenees, debuttressing related to deglaciation has had 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. 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, constitutes 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 Paleogene sequences deposited in former foreland basins incorporated into the orogene. The topography shows a general decrease in elevation from the axial zone, with peaks above 3000 m, towards the southern margin of the orogenic wedge. The regional geomorphology is dominated by differential erosion processes controlled by the E–W structure, and N–S glacial–fluvial transverse valleys coherent with the general topographic trend. Differential erosion of erodible sediments, mostly Paleogene argillaceous formations and Triassic clays and evaporites, has generated broad E–W trending erosional depressions which display the best developed pediment and terrace sequences. The transverse drainages have carved deep and narrow valleys with local widenings associated with less resistant lithologies. In the greater part of the Pyrenees, the headwaters of the catchments were occupied by valley glaciers in the late Pleistocene, which reached the maximum extent well-before the global Last Glacial Maximum (García-Ruiz et al., 2003; Jiménez-Sánchez et al., 2012). In the central Pyrenees, the valley glaciers, in some cases more than 500 m thick and 30 km long, reached elevations below 900 masl. In the more humid Cantabrian Mountains the front of some paleoglaciers was situated below 500 masl. 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 morpho-stratigraphical relationships and geochronological data (Lewis et al., 2009; Jiménez-Sánchez et al., 2012). At the present time, there are about 20 cirque glaciers restricted to massifs higher than 3000 masl in the central Pyrenees. 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). Periglacial activity is represented by both active and relict talus slopes, rock glaciers (Serrano et al., 2010) and patterned ground. Landslides

in the Pyrenees constitute a major morphogenetic process and, together with flooding, is 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). In glaciated valleys with unstable lithologies, deep-seated landslides related to the debuttressing of oversteepened slopes may display very high spatial frequencies (Guerrero et al., 2012a). The development of most of the large landslides is favoured by litho-structural factors, like the presence of thick halite bearing evaporites (Gutiérrez et al., 2012), or the favourable attitude of the strata (Pinyol et al., 2012). In addition to glacial debuttressing, 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) 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<sup>2</sup> in area and 1200 m in relief (White et al., 1997; Gutiérrez et al., 1998). 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, poljes frequently with vague structural control, deep canyons, ponors and springs, as well as caves with large vertical development (Arañonera Cave, 1350 m). 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). Moreover, numerous dam projects have been severely affected by karst-related water leakage problems (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. During the Neogene, extensional tectonics generated horst and graben morphostructures superimposed on the previous contractional structures. The Neogene grabens in the Iberian Chain are filled with alluvial and lacustrine sediments, whereas those of the Catalan Coastal Chain may 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 200 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). One of the most outstanding geomorphological characteristics of these orogens, especially the Iberian Chain, is the presence of extensive pplanation surfaces cut across deformed pre-Neogene rocks, chiefly Mesozoic carbonate rocks (Gutiérrez and Peña, 1994). This general plateau-like topography is locally interrupted by monadnocks, frequently underlain by more resistant Paleozoic rocks, neotectonic grabens, erosional depressions and fluvial valleys. The flat topography developed on carbonate rocks has favoured the development of doline fields (Gutiérrez and Peña, 1979), karren and poljes, generally controlled by faults (e.g. Gracia et al., 2003). Pleistocene glaciers were restricted to cirques carved in the hard-rock massifs higher than 2000 m located in the northern and central sector of the Iberian Chain. In the high country, active and relict periglacial features are relatively abundant, including nivation cirques,

protales ramparts, rock glaciers, patterned ground, grèzes litées, and remarkable block streams (e.g. Gutiérrez and Peña, 1977). 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 with frequent tufa accumulations (Vázquez-Urbez et al., 2011). Both, the Iberian Chain and the Catalan Coastal Chain have good examples of tectonic landforms associated with active normal faults, like mountain fronts, triangular facets and disrupted drainages (Perea et al., 2012; Zarroca et al., 2012). In the northern sector of the Catalan Coastal Chain there are basaltic volcanic fields controlled by post-orogenic normal faults. The Garrotxa area includes more than 40 nicely preserved Late Pleistocene cones developed by strombolian and phreatomagmatic eruptions (Martí et al., 2011). Also in the northern sector of this chain there are extensive inliers of Variscan basement with good examples of landforms related to surface and subsurface granite weathering (Roqué et al., 2011). The Catalan Coastal Chain, forming a topographic barrier adjacent to the Mediterranean Sea, is one of the most prone areas in Spain to the occurrence of flash floods and rainfall-triggered landslides (e.g. Vilaplana, 2008; Llasat et al., 2010).

Spain has four large Cenozoic basins that cover around one third of the country area. These morphostructural depressions control the path of the main fluvial systems, from which they receive their names; Ebro, Duero, Tajo and Guadalquivir basins. The formation and development of these sedimentary basins have been mainly controlled by the tectonic evolution of the surrounding Alpine orogens and, in the case of the Ebro, Duero and Tajo basins, by the capture of the depressions and the progressive change from endorheic-aggradational to exorheic-incisional conditions. The Ebro and Guadalquivir depressions are foreland basins of the Pyrenees and Betic Chain, respectively. The Duero and the Tajo depressions are essentially intracratonic structures bounded by Alpine contractional structures. The ENE–WSW Guadalquivir Basin has been open to the sea during its entire evolution and the Miocene–Quaternary fill mainly consists of marine sediments. The southern half of the basin is dominated by olistostromes made up of chaotic Mesozoic and Cenozoic rocks, whereas the northern half is mainly underlain by autochthonous soft marly sediments. The upper and middle reach of the Guadalquivir valley, currently abutting the rectilinear northern margin of the basin, displays an extensive terrace sequence on the southern margin (Díaz del Olmo et al., 1989; Baena and Díaz del Olmo, 1997). In the lower reach, the river splits into several anastomosed channels flowing through an extensive marshland separated from the sea by a long spit bar with a large superimposed dune field (Doñana National Park). The growth of the spit bar has induced the rapid siltation of the marshland after the Flandrian transgression and the shifting of the river channel to the SE (Zazo et al., 1999). The Ebro, Duero and Tajo basins have relatively similar sedimentary and geomorphic evolutions. Most of the outcropping sediments in these depressions are Oligo-Miocene continental formations with subhorizontal structure deposited under endorheic conditions. These sediments typically display a roughly concentric facies distribution, with conglomerates at the margins that grade distally to fine-grained alluvial fan facies, and lacustrine evaporites and carbonates in the depocentral sectors. The end of the endorheic fill is commonly recorded by Miocene limestone units which may connect, physically or altitudinally, with planation surfaces at the basin margins (e.g. Benito-Calvo and Pérez-González, 2007). These endorheic basins were captured in the Miocene by the external drainage network. The new exorheic conditions led to the development of the present-day drainage network responsible for the dissection of the sedimentary fill and the development of stepped pediment and terrace sequences. The oldest

exorheic morpho-sedimentary units typically correspond to extensive and prominent mantled pediments (e.g. *rañas*) that record unconfined alluvial–fluvial systems developed before the entrenchment of the fluvial systems and the formation of staircased terraces (e.g. Martín-Serrano, 1991; Lucha et al., 2012). The landscape within these Cenozoic basins is largely influenced by the distribution of lithofacies. The marginal conglomerates form elevated areas and locally stunning monoliths more than 300 m high with precipitous cliffs controlled by vertical fractures (e.g. Riglos and Montserrat in the Ebro basin). Erosional depressions with extensive mantled pediments and badland landscapes occur in the areas dominated by argillaceous facies. The limestone units cap buttes, mesas and structural platforms with fields of shallow solution sinkholes. The reliefs formed by relatively thin limestone caprocks underlain by erodable sediments are frequently surrounded by sequences of talus flatirons (Gutiérrez-Elorza et al., 2010). The Ebro and Tajo basins have thick halite- and glauberite-bearing evaporitic units. In these areas the alluvial deposits are locally thickened recording dissolution-induced synsedimentary subsidence (Benito et al., 2010; Guerrero et al., 2012b; Silva et al., 2012). In these areas, sinkholes may show a high activity in the most densely populated lower alluvial levels, resulting in high risk scenarios (Galve et al., 2009). Eolian activity has a significant geomorphic imprint in the southern sector of the Duero basin, where the bedrock is dominated by friable arkosic sandstones and the fluvial systems are mainly nourished by sands. Here, there are extensive sand sheets, dune fields (Bateman and Díez, 1999; García-Hidalgo et al., 2007; Bernat-Rebollal and Pérez-González, 2008), and abundant deflation basins; pans and blowouts (Gutiérrez-Elorza et al., 2005). In the Ebro Basin, where there is very limited availability of sands, eolian accumulations are very scarce, but the strong wind has carved yardangs in gypsiferous rocks and unconsolidated lake deposits in the leeward margin of playa-lakes (Gutiérrez-Elorza et al., 2002). Another common feature of the Cenozoic basins is the occurrence of endorheic areas that may host ephemeral saline lakes. Subsurface evaporite dissolution and eolian deflation are generally the main processes involved in their genesis.

An additional geological unit in Spain is the Canarian Archipelago, a chain of hot-spot related volcanic islands that extends for around 500 km across the eastern Atlantic. These islands have grown upon the slow moving Jurassic oceanic lithosphere next to the passive margin of the African plate. The Cenozoic volcanic sequences, dominated by basaltic rocks, record a long period (>20 Ma) of eruptive activity, from the early building up of submarine sea mounts to the polyphasic development of volcanic edifices, eventually affected by giant landslides (Carracedo et al., 2002). The islands constitute steep piles of volcanic rocks rising several kilometres above the abyssal plain, with less than 10% of the volume emerged above the sea. The Teide stratovolcano in Tenerife is the highest peak in Spain (3.718 masl), with more than 7 km in relief with respect to the adjacent abyssal plain. Long-sustained subaerial volcanism has produced large volcanoes with subcircular bases, or elongated ridges where the emission of magma is controlled by persistent rift systems and active volcanic underplating. The age of these hot-spot-related islands shows a general decrease to the west. All the islands have significant Miocene volcanic sequences, whereas La Palma and El Hierro developed in the Plio-Quaternary times. A total of 18 historical eruptions have been documented over the last 500 years. The penultimate event was the 1971 Teneguía volcano eruption in La Palma, and the most recent event the 2011 submarine eruption of El Hierro (Pérez-Torrado et al., 2012). The 1730–1736 eruption of Timanfaya, Lanzarote, is the second largest basaltic fissure eruption documented in historical time. It lasted for more than 2000 days and eruptive activity from a 14 km long fissure produced more than 30 cones and lava flows covering around 200 km<sup>2</sup>; over 20% of the island (Carracedo et al., 1992). The areas affected by recent volcanic activity are dominated by poorly dissected lava fields and cones (Rodríguez-González et al., 2012).



Lava tubes and sinkholes resulting from the collapse of their roofs, locally designated as *jameos*, are relatively frequent in some sectors. The 17 km long Viento-Sobrado Cave, Icod de los Vinos, Tenerife, is the largest lava tube in Europe. The old massifs are characterised by a deeply entrenched drainage network and isostatic uplift induced by erosional unloading (Menéndez et al., 2008) and landforms related to differential erosion like volcanic necks and protruding dykes. A striking feature in the Canaries is the giant landslides related to the gravitational collapse of volcanoes, favoured by the continuous growth of the edifices, the presence and injection of dykes, and pressurised fluids (Cendrero and Dramis, 1996; Masson et al., 2002; Hürlimann et al., 2004). These mass movements, with an estimated frequency of 125–170 ka, are expressed as huge arcuate escarpments and chaotic landslide deposits, mostly accumulated on the sea floor, which may exceed 1000 km in length (Urgelés et al., 1997). The development of these structural collapses may cause dramatic changes in the magma feeding system and influence the subsequent volcanic and geomorphic evolution of eruptive complexes (Boulestex et al., 2012).

An outstanding asset of the Spanish geomorphology is the extent and diversity of the coastal environments, with ca. 8000 km of coastline surrounding mainland Spain, as well as the islands of the Canarian and Balearic archipelagos. The main factors that control the geomorphology and Quaternary geology of the Spanish coasts include (Goy and Zazo, 2005): (1) Eustatic changes; in the last glacial cycle, at ca. 18 ka, the sea level dropped more than 100 m below the present-day position, favouring the development of extensive eolian accumulations (Sanjaume and Gracia, 2011); (2) Litho-structural factors, including substantial differential uplift and neotectonic deformation in numerous sectors, especially in the Betic Cordillera (Zazo et al., 1993, 1999); (3) Geographic location between the European and African continents and the Atlantic and Mediterranean basins, both connected from the Early Pliocene through the Strait of Gibraltar; (4) Tidal range; (5) Relative orientation of prevailing winds and the coastline; and (6) Human activity, chiefly the construction of coastal structures and dams in the drainage basins that have modified sedimentation and erosion patterns. A remarkable feature of the Spanish coasts is the presence of good sequences of raised marine terraces and alluvial fans associated with areas affected by neotectonic uplift, which constitute excellent records of sea level change and valuable markers to identify and assess recent tectonic deformation (e.g. Zazo et al., 2003, 2012; Rodríguez-Vidal et al., 2004). The geomorphology of the coasts in the Mediterranean, including the Balearic Archipelago, is largely determined by the distribution of areas affected by positive and negative vertical tectonics and the microtidal regime (range below 50 cm). The subsiding areas are characterised by the development of lakes and lagoons associated with spit bars and dune systems related to the Flandrian transgression (ca. 6.5 ka), as well as beach-ridge progradational complexes (Goy et al., 2003). The uplifting sectors are dominated by Plio-Quaternary sequences of alluvial fans and marine terraces, as well as rock cliffs. These coasts also include deltas related to the progradation of fluvial systems after the Flandrian transgression, largely influenced by human activity in recent centuries (e.g. Lario et al., 1995). The geomorphic features of the Atlantic coast in the Gulf of Cadiz are largely controlled by the distribution of the different geological units and the presence of active faults with different orientations with respect to the coastline. In the Cenozoic Guadalquivir Basin, the low relief coast has extensive estuaries and marshes associated with the lower reach of the main rivers, partially closed by spit bars up to 30 km long and large dune fields (Borja et al., 1999; Zazo et al., 1999). The Atlantic coast developed in the Straits of Gibraltar has a strong structural control and displays good sequences of raised marine terraces and cliffs interrupted by small bays and coves. The most notable landforms in the Atlantic coast of northern Spain are the Galician *rías* (deep fluvial valleys partially submerged by the sea; Pagés-Valcarlos, 2000), estuaries (Flor and Flor-Blanco, 2006), rock cliffs and stepped sequences of

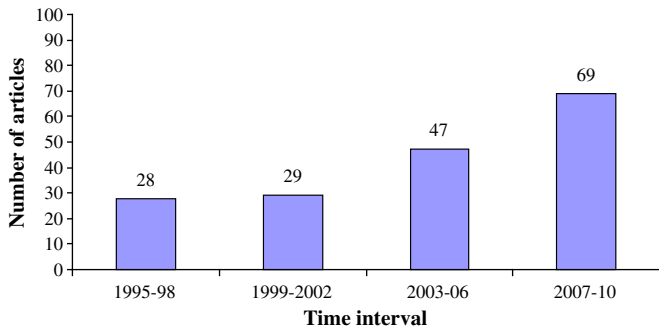
*rasas* (Álvarez-Marrón et al., 2008). The latter, interpreted as wave-cut platforms, correspond to flat surfaces cut across bedrock, perched up to several hundred metres above the sea level and locally covered by a thin veneer of deposits.

### 3. Geomorphological investigations in Spain through the journal *Geomorphology*

In order to analyse some aspects of the geomorphological research in Spain with international projection over the last two decades, we have identified all the papers dealing with this country published in the journal *Geomorphology*, since the release of the first issue in 1987. *Geomorphology*, which is the most referenced international journal on the subject, may be considered as a good source of information to infer some of the main patterns of the geomorphological research carried out in Spain. We have compiled a list of 241 papers, including the 18 articles of this special issue and those available online as in press (see online Supplementary Material). These contributions deal with geomorphological investigations carried out in Spain regardless of the nationality and affiliation of the authors. They represent 5.5% of the papers published in *Geomorphology* (4385 in October 2012). Around 64% of the papers are authored by 1 to 4 people. Regarding the affiliation of the senior authors, 78.4% and 10.4% of the papers were led by geomorphologists based in Spain and in the UK, respectively. Around half of the latter (13 papers) are related to the prolific research activity developed by Adrian Harvey and his former students (see Mather and Stokes, 2003; Plater and Lang, 2008). Belgium and The Netherlands, with 6 papers each, represent separately 2.5% of the total, and other countries have four or fewer papers.

The first paper dealing with Spain published in the journal *Geomorphology* dates back to 1994; i.e. 8 years after the first issue was released. Fig. 3 shows the number of papers related to Spain published from 1995 to 2010, grouped into 4-year-long periods. The number of papers shows a rapid increase in the last decade, from 28 to 29 papers published in 1995–98 and in 1999–2002, respectively, to 69 articles produced in 2007–10. A similar trend was observed by García-Ruiz (1999) for the number of papers published by Spanish authors in the main international geomorphological journals during the 1990s. This rise in productivity may be attributed to several factors: (1) An increase in the number of people working on geomorphological topics and in the amount of economic resources devoted to such research. Fortunately, the perception of *Geomorphology* as a subject instrumental in understanding and solving multiple environmental problems is increasing. Moreover, there are a growing number of geologists who are reorienting their investigations from the study of old geological features to more practical active surface processes and recent geological records. (2) The evaluation of scientific production in Spain, based on the number of papers published in international journals included in the Journal Citation Reports of the ISI Web of Knowledge. (3) The publication of a collection of 14 widely quoted papers in the special issue of *Geomorphology*, *Long-term landscape development in Southern Spain*, edited by Mather and Stokes (2003). Unfortunately, the current cuts in the government budget devoted to research and development (4%, 7% and 25.5% in 2010, 2011 and 2012, respectively) will have a negative impact on geomorphological production in Spain. In fact, the progress achieved over recent decades, including the creation of research groups and the training of ground-breaking researchers, has recently stalled and could undergo serious set-backs within a few years (Moro-Martín, 2012; Pain, 2012).

The 241 papers have been grouped into the following general subjects: Regional geomorphology, Neotectonics, Karst, Volcanism, Weathering and soils, Soil erosion, Slopes and landslides, Fluvial–alluvial, Coastal–marine, Lakes, Eolian, Glacial, Periglacial, and Environmental geomorphology (Fig. 4A). Just two themes, Fluvial–alluvial (53 papers) and Soil erosion (46 papers), account for 41% of the contributions. The categories Slopes and landslides (34 papers) and Coastal–marine



**Fig. 3.** Histogram showing the number of papers dealing with the geomorphology of Spain published in *Geomorphology* between 1995 and 2010, grouped into 4-year-long periods.

(26 papers) represent 14% and 11%, respectively. Other frequently addressed topics include Neotectonics (17 papers, 7%), Karst (15 papers, 6%) and Weathering and soils (14 papers, 6%). A striking feature regarding the karst papers is that more than half of them are related to evaporite karst; outcrops of these rock types cover around 7% of the area of the country. *García-Ruiz (1999)* reached similar findings analysing the geomorphological scientific production in Spain up to 1998 considering a large number of local and international publications. The most outstanding discrepancy is that in that bibliometric analysis, which included national publications, Glacial geomorphology was the third topic with the largest number of articles, whereas in the journal *Geomorphology* it only represents 4%.

To analyse the geographical distribution of the contributions related to Spain, the papers have been grouped considering the following main geological units (*Fig. 4B*): the Iberian Massif in the western Iberian Peninsula, the volcanic Canary Islands, the main Cenozoic basins (Ebro Basin, Duero Basin and Tajo Basin), and the Alpine orogens, including the Pyrenees, the Catalan Coastal Ranges, the Iberian Chain, the Central System and the Betics. The latter zone incorporates the Guadalquivir Basin because some investigations overlap both regions. The Pyrenees embraces all the ranges related to the Alpine orogeny in northern Spain, including the eastern Cantabrian Mountains. An additional category corresponds to Spain, ascribed to papers dealing with the whole country or several geological units. By far, the area where the highest proportion of investigations published in *Geomorphology* has been developed corresponds to the Betics, with 101 papers (42%). Around half of these papers correspond to the Fluvial-alluvial and Soil erosion thematic groups. Well behind are the Pyrenees (31 papers) and the Ebro Basin (28 papers). The most frequent topics in the Pyrenees are Slopes and landslides, Soil erosion and Fluvial-alluvial, whereas in the Ebro Basin the Fluvial-alluvial and Karst thematic groups prevail. The rest of the articles of each area represent less than 10%.

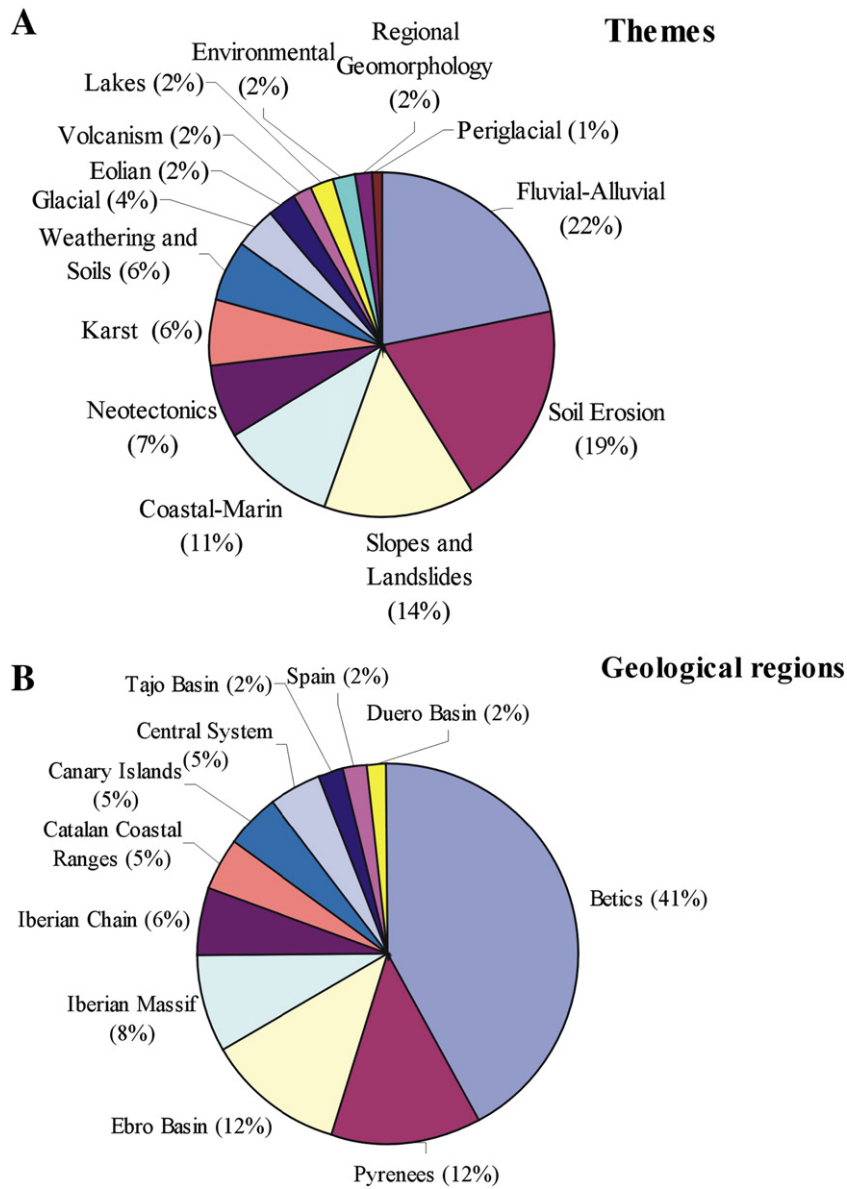
#### 4. The papers in this special issue

The eighteen papers of this special issue cover a wide breadth of topics and regions in Spain. The first two articles provide valuable reviews on the geomorphology of the Iberian continental margin and the Quaternary history of sea level change in Spain. *Maestro et al.* present an overview of the geomorphology of the continental margin and the abyssal plains around the Iberian Peninsula. The studied area, covering approximately 2.3 million km<sup>2</sup> of the seafloor, has a great diversity of morphologies, largely related to the complex geology of the Iberian Peninsula and its location between the Atlantic Ocean and the Mediterranean Sea. It includes striking features like various morpho-structures related to salt flowage, mud volcanoes, pockmarks, volcanic seamounts, contourite drifts, moats and channels, submarine canyons and channels up to 400 km long, turbidite systems as much

as 350 km across, debris flows 100 km long. The distribution of the geomorphic features, classified into structural (tectonic and volcanic), depositional and erosional, is analysed in relation to morphotectonic and oceanographic factors. The paper is accompanied by a groundbreaking “Geomorphological Map of the Iberian Continental Margin at 1:2,000,000 scale” downloadable as supplementary material. *Zazo et al.* review the morpho-stratigraphic record of Quaternary sea level changes in the Mediterranean and Atlantic coast of Spain, including the Canary Islands. The coastal geomorphic responses to sea-level changes with different temporal frequencies are illustrated through the best preserved and most complete morpho-stratigraphic sequences, covering a wide range of geodynamic contexts (tectonically active and stable) and integrating the spatial relationships between marine and terrestrial records.

The next three papers deal with the spatial and temporal evolution of glaciers in different mountain regions of northern and central Spain. The presented geochronological data strongly support that glaciation in the last cycle peaked much earlier than the global Last Glacial Maximum of MIS2. *Jiménez-Sánchez et al.* review the history of glacial research in the mountains of northern Spain (Pyrenees and Cantabrian-Galician mountains) and analyse the available information on the timing and extent of Pleistocene glaciations, with special focus on the last local glacial maximum. The numerical ages obtained in diverse settings and by means of multiple techniques demonstrate that, in northern Spain, the maximum extent of the ice in the last glacial cycle occurred well before the global LGM of MIS 2 (18–21 ka). The more abundant geochronological data from the Pyrenees indicate a local glacial maximum between 50 and 70 ka in MIS 4. Moreover, they report morphostratigraphic evidence and numerical ages (OSL, cosmogenic surface exposure) recording previous glacial cycles during MIS6 and MIS8, in which glaciers covered more extensive areas than in the last maximum ice extent. *Serrano et al.* present a novel reconstruction of the late Quaternary glacial evolution in the central Cantabrian Mountains (N Spain) based on geomorphological mapping, paleo-ELA estimations and numerical dating. They identify four main glacial stages in these Atlantic mountains, characterised by markedly different precipitation between the northern side (ocean-facing) and the southern one (precipitation shadow). Glaciers reached the maximum extent before the global LGM. The second stage, also older than the LGM, is tentatively situated in the MIS3 to MIS2 transition or in MIS2. The third stage is ascribed to the Tardiglacial (14–15 ka). The most recent one, corresponding to the Little Ice Age and restricted to the highest massifs, is documented by historical records. *Carrasco et al.* present a 3D reconstruction of the ice mass during its maximum extent in the Bejar Range, Central System, based on detailed geomorphological mapping and physical models. At this stage, dated at ca. 27 ka by <sup>10</sup>Be, the planated summit of the range was capped by a plateau glacier up to 120 m thick, linked to radiating outlet glaciers that reached a minimum elevation of 1220 masl. During the deglaciation, the dome-shaped icecap evolved into an icefield eventually disconnected from the valley glaciers. This piece of work provides valuable data on the Late Pleistocene evolution of a highly sensitive paleoglacier located in a low latitude Mediterranean area with both Atlantic and continental influence.

An innovative concept on the development of tafoni on granitoids is proposed by *Roqué et al.* in the Catalan Coastal Chain. These authors infer subsurface metre-sized spheroidal pockets of weathered granite, as revealed by low resistivity anomalies in electrical resistivity tomography (ERT) profiles and hyperbolic diffractions in radargrams acquired by ground penetrating radar (GPR). The spatial association of these underground features with tafoni of similar sizes and geometries at the surface leads the authors to propose a new genetic model for these controversial landforms. Tafoni development may be initiated in the subsurface by preferential weathering related to groundwater flows controlled by fractures. Erosion enhances groundwater flow by unloading the rock mass and dilating fractures and eventually



**Fig. 4.** Percentage of papers dealing with Spain published in the journal *Geomorphology* according to their thematic (A) and geographical ascription (B). The geographical zones correspond to the main geological units of Spain.

leads to the exposure of the weathering pockets evolving into tafoni. Whitfield et al. analyse the impact of Quaternary environmental change on the evolution of the Bergantes River, Iberian Chain, recorded by a sequence of six terrace levels. The stratigraphy and sedimentology of the terrace deposits, together with geochronological data, allow the differentiation of two periods with contrasting fluvial behaviour. The two oldest Pleistocene terraces, ascribed to glacial conditions, record major aggradation phases with significant sediment supply from tributary drainages and hillslopes. The four youngest terraces represent small and short-duration cut and fill cycles characterised by limited sediment supply, mostly related to the trunk river. These cycles are attributed to stadial (aggradation) and interstadial (incision) phases that have occurred over the last 25 ka. The inferred evolution reveals that in high sensitivity fluvial systems, like the Bergantes River catchment in semiarid Spain, incision and aggradation patterns may be controlled by both orbital- and suborbital-scale climate changes, which determine variations in vegetation and sediment supply. Ortega et al. analyse the evolution of the Las Torcas multilevel cave system in the Atapuerca Range (Iberian Chain), which hosts the most important hominid-bearing archeo-paleontological sites in Europe. Detailed mapping of the subhorizontal

passages and geomorphic markers of paleobase levels allows the authors to establish a correlation between the three cave levels and Early–Middle Pleistocene terraces of the Arlanzón River. Fluvial incision, erosional lowering and eventually collapse sinkhole development, resulted in the formation of cave entrances, allowing human occupation from ca. 1.22 Myr until the caves and associated sinkholes became filled by the end of the Middle Pleistocene.

The following four papers deal with several geomorphological aspects related to highly soluble Tertiary evaporite formations in the Tajo and Ebro basins. Silva et al. unravel the morpho-stratigraphic position of the Arriaga Paleolithic sites located within complex Middle–Late Pleistocene thickened terrace deposits of the Manzanares River (Tajo Basin). These fossil-rich fluvial sequences record syndepositional subsidence related to evaporite dissolution. The paper illustrates the need to integrate geomorphological, stratigraphic, pedological and geochronological data to infer the evolution recorded by time-transgressive morpho-stratigraphic fluvial units governed by the spatial migration of subsidence phenomena. In a stretch of the Ebro Valley, Guerrero et al. (2012b) document kilometre-scale subsidence depressions, thickened terrace and pediment deposits (>50 m) and intense gravitational



deformation mainly related to interstratal glauberite and halite dissolution. The splendid exposures of dissolution-induced deformation affecting the evaporitic bedrock, including collapse breccias with a complete textural gradation from crackle packbreccias to chaotic floatbreccias, and karstic residues, may constitute a valuable surface analogue for prolific hydrocarbon reservoirs, as well as mineralisation associated with paleokarst formations. This work demonstrates for the first time subsidence phenomena related to dissolution of an exceptional glauberite unit, in which glauberite beds, up to 30 m thick, reach a cumulative thickness of 100 m. Gutiérrez et al. investigate the origin and morpho-stratigraphic evolution of a playa-lake system developed on gypsiferous bedrock in the Ebro Basin. This area has been the focus of numerous paleolimnological investigations, probably lacking a good understanding of the geomorphic context. The authors, based on detailed geomorphological mapping, document a sequence of three lacustrine terraces and wind-fluted yardangs in the leeward sector. Radiocarbon dating of the intermediate terrace indicates an aggradation phase between 3.9 ka and ca. 2 ka, followed by an excavation phase related to wind erosion ascribable to dry conditions. The estimated lowering rate by deflation of around 3 mm/yr is comparable with those reported for paleolake basins in several arid regions of the world. The integration of morpho-stratigraphic and geophysical data supports a mixed karstic and eolian origin for the lake basin and allows ruling out previous interpretations involving the collapse of large bedrock cavities. Artieda analyses peculiar weathering landforms frequently found in the gypsum outcrops in the Ebro Tertiary Basin, including domes up to 1.1 m across (also designated as gypsum tumuli) and decimetre-scale blisters. These features are related to the volume increase and swelling of the most surficial weathered bedrock due to in situ dissolution and crystallisation of gypsum in pores under a semiarid climate. The paper presents a thorough characterisation integrating field observations and a comprehensive microscopic analysis, providing robust supporting evidence for a genetic model.

The last six papers deal with different geomorphic processes with significant environmental implications and temporal changes in morphogenetic and sedimentary processes strongly influenced over the last decades by human activity. Díez-Herrero et al. present the main results of dendrogeomorphological studies applied to flood risk analysis in the Central System. The paper illustrates how data on the chronology and magnitude (paleostage) of paleofloods derived from the analysis tree-rings may be incorporated in risk analysis and the management process, contributing to a reduction in the uncertainty of magnitude and frequency relationships and helping to identify the most cost-effective mitigation measures. García-Ruiz et al. investigate debris flows triggered by a short-lasting and high intensity rainstorm event on steep slopes underlain by colluvium affected by a wildfire three weeks before. Indirect estimates of rainfall intensity reveal that the removal of the plant cover by burning involved a significant reduction in the rainfall threshold for initiating debris flows. This work illustrates how the elimination of the vegetation by fire may dramatically increase the sensitivity of slopes, so that ordinary rainfall events may lead to extraordinary erosion processes and geomorphic effects. Navas et al. assess rates and patterns of soil redistribution over the past 45 years in an internally drained karst catchment (ca. 80 ha) in the Pyrenees using fallout  $^{137}\text{Cs}$  derived from nuclear testing. Areas of sediment gain and loss are defined by the geostatistical interpolation of  $^{137}\text{Cs}$ -derived soil redistribution point data (100×100 m grid). The authors, using a GIS and a detailed DEM estimate spatially distributed erosion and deposition rates for the whole catchment, covering around 80 ha. The comparison of these data with detailed geomorphological maps provides clues on the main factors controlling soil redistribution (e.g. cultivation) and reveals a clear linkage between erosion and depositional landforms. Gallart et al. analyse sediment dynamics in a humid mountain basin of the Eastern Pyrenees where badlands are the main sediment source and rainfall shows a high interannual variability. Erosion rates are obtained by different methods covering

variable spatial and temporal scales; plot-scale measurements (up to 3 years long), monitoring of water discharge and suspended sediment loads in gauging stations (15 years), simulation of badland erosion with the KINEROS2 event model for 15 years. The comparison of the results and the assessment of the uncertainty and representativeness of the measurements, taking into account their temporal variability, indicate that sediment dynamics is mainly controlled by erosion processes in the badlands, unless infrequent severe events occur, which may activate sediment stores and other sediment sources. Moreover, they conclude that the long-term sediment production in these basins may be simulated with acceptable results if long records accounting for the high temporal variability are available. Del Río et al. analyse quantitatively the shoreline changes that have occurred over the period 1956–2008 in 58 sandy beaches in the micro-mesotidal and low energy south Atlantic Spanish coast comparing orthorectified aerial photographs. Additionally, in selected areas the evolution of beach profiles is studied by topographic monitoring (2000–2006). The observed spatial-temporal change patterns reveal that sediment supply, largely reduced in some sectors due to dam construction, is the main controlling factor. Other significant factors include nearshore bathymetry, as it influences wave action, and human alterations such as construction of transverse structures obstructing longshore drift and back beach development. A morphological and evolutionary classification of sandy beaches is proposed, which may be used for managing retreating beaches, a resource of great environmental and economic importance in the area. Bruschi et al., using sediment cores from eight estuaries in northern Spain and dated by  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$ , document a general increase in the sedimentation rate during the last century. No relationship between this trend and rainfall data has been found, but a good correspondence with several indicators of the human activities that contribute to modify the land surface (e.g. construction of new houses, GDP, cement consumption). The similarity in the temporal trends supports the hypothesis proposed by the authors and already tested in other regions, whereby the activity of certain geomorphic processes has increased worldwide during the “Anthropocene”, mainly due to the impact caused by human activity on the ground surface and the consequent changes in the sensitivity and thresholds of geomorphic systems (i.e. global geomorphic change).

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.geomorph.2012.12.014>.

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Francisco Gutiérrez  
*University of Zaragoza, Spain*  
Corresponding author.  
E-mail address: [fgutier@unizar.es](mailto:fgutier@unizar.es).

Adrian Harvey  
*University of Liverpool, UK*

José María García-Ruiz  
*Pyrenean Institute of Ecology (CSIC), Spain*

Pablo Silva  
*University of Salamanca, Spain*

Antonio Cendrero  
*University of Cantabria, Spain*