Geomorphology of the Sierra Gorda karst, South Spain

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ABSTRACT

The limestone massif of Sierra Gorda is one of the most important karst areas in the Betic Cordillera (southern Spain). In this work, we present a geomorphological map of this area compiled using stereoscopic image analysis and field work. The map covers 300 km², synthesizing karst landforms at a scale of 1:33,000. These landforms have been classified into seven minor and major types (karren, sinkholes and uvalas, poljes, canyons, planation surfaces, springs and travertine formations, and caves). The map is a useful tool for the environmental reassessment of the massif and its possible recognition as a geopark.

ARTICLE HISTORY

Received 24 January 2015
Revised 29 December 2015
Accepted 30 December 2015

KEYWORDS

Geomorphological map; Sierra Gorda; Betic Cordillera; karstic landforms; GIS

1. Introduction

Geomorphological maps play a crucial role in understanding Earth surface processes, geochronology, natural resources, natural hazards, and landscape evolution (Bishop & Shroder, 2004; Blaszczynski, 1997). The main purpose of these graphic inventories (Otto & Smith, 2013) is to record information on the distribution, boundaries, localization, nature, age, and structure of landforms by determining outcrop patterns and indicating them with conventional symbols or by structure-contour lines (U.S. EPA, 2002). The utility of this cartography goes beyond mere geomorphological analysis in-so-much as it can be implemented in land management and geomorphological and geological risk management, and also as a useful tool in other applied sectors of environmental research such as landscape ecology, forestry, and soil science (Cooke & Doorkamp, 1990; Dramis, Guida, & Cestari, 2011; Paron & Claessens, 2011).

Historically, geomorphological mapping has been based upon the integration of multidisciplinary information from the field, remotely sensed data, and cartographic map products (Bishop, James, Shroder, & Walsh, 2012). The appearance of new techniques in geographic information systems (GIS) and high-resolution remote sensing data capture in recent years has led to a renaissance in the methods used and has revolutionized landform analyses (Bishop & Shroder, 2004; Lee, 2001; Otto & Smith, 2013; Paron & Claessens, 2011; Smith, Griffiths, & Paron, 2011).

In geomorphological mapping, karst environments are commonly studied, for example, Sallum and Karmann (2007), Graciotti, Pantaloni, and Foresi (2008), Galve et al. (2009), Huang and Cai (2009), López-Vicente, Navas, and Machín (2009), Siart, Bubenzer, and Eitel (2009), Travassos and Kohler (2009), Fonseca (2011), Gutiérrez et al. (2011), Perego, Zerboni, and Crema (2011), and Amys et al. (2014). Karst relief commonly develops in biogenic, biochemical, and chemical sedimentary rocks, mainly in carbonate rocks such as limestone and dolomite (De Waele, Plan, & Audra, 2009; Groves & Meiman, 2005; Johnson & Stieglitz, 1990). A series of significant practical implications account for the widespread interest in these types of environments: (a) geotechnical hazards of karst for human infrastructure such as houses, streets, etc. (Field, 2010; Gutiérrez, Parise, De Waele, & Jourde, 2014; Vigna, Fiorucci, Banzato, Forti, & De Waele, 2010); (b) frequent leakage problems in reservoirs and other hydraulic infrastructure in karst formations (Bonacci & Roje-Bonacci, 2008; Bonacci, Gottstein, & Roje-Bonacci, 2009; Gutiérrez, Mozafari, Carbonel, Gómez, & Raeisi, 2015); (c) karst areas having significant biodiversity at the surface and underground (Bonacci, Pipan, & Culver, 2009; Culver & Pipan, 2009; Humphreys, 2006); (d) karst aquifers being valuable freshwater resources highly vulnerable to contamination, thus requiring protection (Ravbar & Goldscheider, 2007); (e) deep karst aquifers being valuable geothermal resources (Goldscheider, Madl-Szonyi, Eross, & Schill, 2010); and (f) these relief aspects favour anthropogenic exploitation (Huiziar-Álvez & Oropeza-Orozco, 1989) (e.g. livestock ranching, farming, and mining in the Sierra Gorda karst). These circumstances have therefore awakened considerable scientific interest in karst landscapes (Goepfert, Goldscheider, & Scholz, 2011).

In the Betic Cordillera (southern Spain), many karst areas have been studied and mapped (Burillo, 1998; Calaforra, 2004; Calaforra & Berrocal, 2008; Delannoy, 1998; Delannoy, Guendou, Quinif, & Rairon, 1993;
Durán, 1996; Durán, Andreo, Carrasco, & López, 2005; Durán & López, 2008; García-Rossell & Pezzi, 1975; Gualda, 1988; López, 1974, 1987; Marco, 2006; Marco, Matarredona, Padilla, & Diez, 2000; Pulido-Bosch, 1986, 1993; Thauvin, 1981; Vera, Ruiz-Ortiz, García-Hernández, & Molina, 1988). However, other karst regions, despite their extent, lack a systematic geomorphological survey. Such is the case of the Sierra Gorda limestone massif, which has been the subject of geological and hydrogeological studies (Cherif, Pulido-Bosch, López-Chicano, Morell, & Gámez, 1995; Delgado, 1973; Delgado, Hidalgo, Fernández, & del Valle, 1974; García-Hernández, Lupiani, & Vera, 1986–1987; Jiménez de Cisneros, Mas, & Vera, 1990; Lhénaff, 1998; López-Chicano, 1992; López-Chicano, Calvache, Martín-Rosales, & Gisbert, 2002; Mudarra & Andreo, 2011, 2015; Pístre, López-Chicano, Pulido-Bosch, & Drogue, 1999; Sanz de Galdeano, 2013), but until now has lacked detailed and updated geomorphological mapping. The only overview of its karst landforms was carried out by Pezzi (1975b, 1977a, 1977b), with others studying its fracturing, karstification, and recent geodynamic evolution (López-Chicano, 1995; López-Chicano & Pulido-Bosch, 1994).

This work addresses this gap with an updated geomorphological map of the karst complex of Sierra Gorda at a scale of 1:33,000 (Main Map). This map has the potential to be an extremely useful tool for the protection and management of the massif’s valuable natural heritage. The information collected must be taken into account in view of the possible inclusion of Sierra Gorda karst in the Network of Protected Natural Areas of Andalusia and is also an essential step towards recognizing this site as a geopark.

2. Study area
Sierra Gorda lies in the southernmost Iberian Peninsula, in the province of Granada (Spain). It has a surface area of 300 km² and reaches a maximum elevation of 1669 masl (Figure 1). It is limestone-dolomitic and Jurassic to Cretaceous in age (Cherif et al., 1995; Jiménez de Cisneros et al., 1990; Sanz de Galdeano, 2013), belonging to the internal Subbetic sector of the External Zones of the Betic Cordillera (Vera, 2004). Its karstic landscape is the result of a long geomorphological evolution, especially impacted by geological and climatic events during the last 11 million years (López-Chicano, 1995). The karstification of the massif has continued since then, with periods of varying intensity, although it appears that, at present, there is some deceleration in karst processes (Lupiani & Soria, 1988) related with the loss of vegetation cover in the massif due to cold (Pezzi, 1977a) or anthropogenic pressure (Díaz del Olmo & Delannoy, 1989).

Its extensive doline fields and large border poljes make it a true holokarst, hosting one of the largest carbonate aquifers in southern Spain (López-Chicano, 1992). At its southernmost end is the Zafarraya polje, one of the most significant functional karst depressions on the Iberian Peninsula, with an area of 22 km², a maximum length of 10 km from west to east, and a width of 3.5 km from north to south (Durán, López, & Vallejo, 1998; Lhénaff, 1998; López-Chicano et al., 2002; Sanz de Galdeano, 2013).

Generally, the karstic landforms identified in Sierra Gorda have been impacted, first, by the structural control of the Alpine orogeny on the massif and, second, by karstic dissolution processes. The flatter areas of Sierra Gorda have the most developed and diversified exokarst, whereas the steeper slopes at the edges of the massif have underdeveloped, very simple karst landforms (López-Chicano, 1995).

According to Pezzi (1977a, 1977b), Díaz del Olmo and Delannoy (1989), López-Chicano and Pulido-Bosch (1994), and López-Chicano (1995), the main causes for this exceptional karst are: (a) The uniformity, enormous thickness (1000 m), great purity, and massive nature due to folding of the consolidated white limestones (oolitic, pisolith, and very fossil-rich) that characterize most of the massif. (b) Its morphology in the form of a domed anticline with a gentle dip in most of the central massif. (c) High fracturing and fissuring that have defined the dissolution and controlled karstification. (d) Heavy rainfall on the massif (for its regional context), with average annual values of around 1000 mm/year in the peak areas. (e) Colder Pleistocene climate conditions, which favoured a periglacial morphogenetic system.

In contrast to the factors favouring karst solution, current rhexistasy conditions are limiting it: the lack of vegetation and the scarce soil development (Pezzi, 1977a, 1977b) as a result of intense, long-term deforestation and livestock ranching. These conditions have turned the study area into a sparsely populated land.

3. Material and methods
The geomorphological map is based on 1:50,000 geological maps (IGME, 1986, Geological and Mining Institute of Spain, maps 1.024, 1.025, 1.039, 1.040) and 1:25,000 topographical maps (IGN, 2000–2011, National Geographic Institute of Spain, maps 1.024 II-IV, 1.025 I-III, 1.039 II, 1.040 I), integrated within a GIS.

The mapping involved two main work phases: (a) Mapping the most visible karstification using stereoscopic image analysis of three aerial photograph series (from 1956, scale of 1:33,000; 1977, scale of 1:5000; and from 2011, scale of 1:10,000), available on REDIAM (Environmental Information Network of Andalusia). (b) Georeferencing small landforms by field work (caves, polygonal depressions, residual hills, small dolines, swallets, and resurgences).
The karst elements are shown in different colours in order to provide a better understanding of the relief, and have been classified into structural, karst, and slope landforms according to the key used by the IGME (Martín-Serrano, Salazar, Nozal, & Suárez, 2008), and using terminology from the U.S. EPA (2002) in certain cases. Other relevant works have been considered to support the key, such as Tricart (1972), Verstappen and Van Zuidan (1991), and Peña (1997).

4. Karst landforms: map and description

4.1. Minor karst landforms

The intense microfracturing and microfissuring of the Sierra Gorda limestone has led to a multitude of minor karst forms grouped under the generic name of karren in karstic landscapes. In some cases, the origin is structural (tectonic control) or a consequence of hydrodynamics due to erosion and dissolution by rainwater (López-Chicano, 1995).

The geomorphological map contains four basic types of karren: (a) Karren in blocks (clints), deep vertical fissures (grikes) and trenches, that formed in joints and fractures, is the most extensive limestone pavement type. (b) Large-scale karren appearing primarily in sloped areas, allowing soil to be cleared away by run-off and giving rise to large landforms. (c) Ruiniform relief of karren (Figure 2) corresponding to boulder fields or isolated crests, similar to those typical of a dolomitic landscape. (d) And, depending on the extent of cover, covered karren (crypto-karren), semi-covered karren, and bare karren.

4.2. Large-scale karst landforms

Dolines and uvalas

Dolines are one of the most characteristic elements of the Sierra Gorda karst. In our opinion, the existing high degree of fissuring, related to tectonic processes (López-Chicano & Pulido-Bosch, 1994), is the main determining factor in the formation of most of the dolines. Furthermore, their distribution in the massif appears to be related to a double pattern that causes the inner central area (the highest) to have the greatest number of dolines: its relatively flat topography and the higher rainfall of this sector compared to the slopes and basal areas are factors that undoubtedly favour greater karstification and reduce runoff.

There are 1692 dolines of significant size (i.e. mappable at a scale of 1:33,000) identified in the Sierra Gorda (Pezzi, 1977b, which is equivalent to a density of 7.9 dolines/km$^2$. However, according to López-Chicano (1995), the number of small dolines is much larger, with some areas having up to 40 dolines/km$^2$ (e.g. Santa Lucía peak). In these cases, representation on the map is inadvisable at the scale considered. The most characteristic feature of these dolines is undoubtedly their structure, for example, the common alignments or fields of dolines (Figure 3). There are trough-shaped and funnel-shaped dolines, circular and ellipsoidal dolines, with either a flat bottom covered in terra rossa or an uneven, rocky bottom. As the geomorphological map reveals, there are also many irregularly shaped dolines.

In the specific case of the uvalas, they are formed due to the coalescence of several dolines, although some located in the top third of the massif maybe related at least in part with periglacial modelling processes, as Ćalić (2011) has demonstrated in the area of Dinaric karst. This theory is reinforced by the periglacial modelling evidence dating from the Riss glacial maximum identified by Pezzi (1975a) in a nearby massif at similar elevations (Torcal de Antequera).

Poljes

These lower karstic planation surfaces are located between 900 and 1100 m in areas where the flat
topography has allowed the complete karstification of limestone and the formation of depressions lined by red clays.

There are at least six karst depressions that can be considered poljes, the three internal poljes (Majada del Charco Negro, Majada del Quejigo, and Casa de los Muertos) and the poljes on the boundary of the main limestone mass of the Sierra Gorda (Las Pilas, Llanos de la Dona, and Zafarraya). All are open depressions with difficult exorheic drainage with the exception of the Zafarraya polje (López-Chicano, 1995), which is closed and has an endorheic regime (Figure 4) due to the special hydrological and hydrogeological conditions of the depression (Lhénaff, 1986). At 22 km², it is the largest depression in the Betic Cordillera. It is a tectonic polje with an irregular shape, some 12 km long by 3.5 km wide, primarily at an altitude of 900 m. The polje drains a catchment area of 150 km² in which the Madre creek is the main drainage for surface runoff. The creek disappears in a group of sinkholes (swallets) that are not always enough to prevent flooding in the endorheic depression. Five significant floods were identified over the last 100 years by López-Chicano et al. (2002). There are four noteworthy residual hills in the floor of the depression, with the largest occupied by the village of Zafarraya.

Less-defined depressions occur south of this area: Llanos de Júrtiga, which drains the Dona polje, and the depression between the Mina peak (1203 m) and
the Morillos Peak (1045 m), which drains the Zafarraya polje.

**Upper karstic planation surfaces**
The southern part of the massif has up to three karstic planation surfaces, which are the result of intense karstification of limestone in areas of lower gradient (∼4–12%) located in the south-central massif around the highest part, at elevations of 1000–1400 m (López-Chicano, 1995; Pezzi, 1977b). The lower surface is at 1000–1050 m, including part of the divide between the Dona and Pilas poljes. The intermediate (and most extensive) level is divided into extensive portions between 1200 and 1300 m, with some dolines and numerous residual hills of low elevation (traditionally known as ‘hums’) such as the Cerro de la Torrecilla (1321 m) (Figure 4), Cazadores (1321 m), and Gavilanes (1456 m). The upper surface, between 1300 and 1400 m, is south-west of the mountain chain and is a highly karstified area of gentle gradient.

**Fluvial-karst canyons**
A set of faults has favoured the entrenchment of the surface network in the Liassic limestone and in the Pliocene calcareous breccias and limestones, especially on the borders of the Sierra Gorda massif, where the main external drainage flows. Of noteworthy size are the fluvial-karst canyons of the Salar creek, incised for a length of 2 km east of the massif, and those of the Barrancón creek (Frio River) to the west, with an incised meander.

In much of the rest of the massif, its relatively flat morphology (a consequence of the massive character of the limestone outcrops) and the absence of large faults prevent the formation of relevant fluvial-karst canyons.

**Caves, shafts, and caverns**
The Sierra Gorda has a fossil endokarstic network mainly controlled by its structure. This network is poorly known (Durán & López, 1999), and although there are over 100 penetrable cavities, with a total gallery length of around 3000 m, and an average duct length of only 30 m (López-Chicano, 1995; López-Chicano & Pulido-Bosch, 1994), the known underground karstic network is not significant. There is a clear predominance of subvertical cavities, and a maximum depth of 149 m in the Sima de los Machos (Durán & López, 2008; López-Chicano, 1995). Karstification at depth is only possible through discontinuities able to contain and transmit water (e.g. stratification surfaces, doline discharge areas and, above all, fractures of tectonic origin such as fault lines and joints), which favour the formation of cave passages and other small, poorly penetrable cavities due to the extreme scattering of rainwater infiltration points and filling by calcite (López-Chicano & Pulido-Bosch, 1994; Marín, Torices, & Calvo, 1983). Generally, therefore, only cavities draining surface runoff are penetrable (López-Chicano, 1995).

**Karst springs and travertine formations**
The Sierra Gorda is a permeable massif that absorbs water through numerous infiltration points, largely fissures originating in fractured tectonics, to form a free karst aquifer with resources estimated at around 120 hm³/year (López-Chicano & Pulido-Bosch, 2002). The various discharge points are located in the foothills of the Sierra Gorda, mainly where the limestone is in

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**Figure 4.** Zafarraya polje viewed from the west. On the horizon in the centre, the ‘hum’ of Cerro de la Torrecilla. Photo credit: José Antonio Olmedo-Cobo.
contact with more impermeable materials such as Pliocene-Quaternary silts, sands, and conglomerates at the north end, and with Betic clays, arenites, and marls at the south end. The main springs have peak volumes of flow of 700–1000 L/s (Frío River), 1700 L/s (Manzanil), and 300 L/s (Piscina Yola). In some cases, the volumes of flow in certain springs can show very large variations from 0 to 2000 L/s (Beas, 1990).

Most karst springs have significant associated tufa deposits, most of them as travertine formations. Particularly noteworthy are those north of Sierra Gorda in the natural entrenched riverbed of the Genil River (‘Loja’s Hell’) (Figure 5) at the sources of the Frontil and Manzanil creeks.

5. Conclusions

This research presents a detailed and updated geomorphological map of one of the most important karst relief areas in the Betic Cordillera (southern Spain). This map of the Sierra Gorda karst identifies a series of minor exokarst landforms, such as different types of karren, and large-scale landforms such as closed depressions (dolines, uvalas, and poljes), fluvial-karst canyons, and different planation surfaces. In addition, we have mapped the main endokarst landforms comprising different underground cavities (caves, shafts, caverns, etc.) and the springs and travertine formations associated with the underground hydrographic network.

In addition to updating available information on the Sierra Gorda through the geomorphological mapping of the karst, the main practical application of the map is its role as a useful tool to re-examine the natural heritage of the Sierra Gorda in view of its possible inclusion in the Network of Protected Natural Areas of Andalusia. Currently, this site is part of the Natura 2000 network as a Site of Community Interest and a Special Area of Conservation, with one of the conservation priorities being the massif’s karst landform system.

Upcoming research should focus on detailed mapping of less-studied karst landforms such as the distinct types of closed depressions, open poljes, and karren, and an in-depth knowledge of the endokarst landforms. It is also important to examine the origin and functioning of uvalas in relation to new scientific theories on the topic. Finally, the possible periglacial modeling of the upper part of the karst needs to be studied carefully. The information gathered and future results will be essential to raising appreciation of this site to achieve its recognition as a geopark.

Software

The stereoscopic image analysis, digitalization, and composition of the geomorphological map were undertaken using Esri ArcGIS 10.2.1.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by research project [CSO2009–06845-E] of the Ministry of Science and Innovation of Spain Government. We would like to acknowledge the economic support of the Regional Development Institute of the University of Granada for financing the translation of the manuscript, done by Christine Laurin, to whom we are also deeply grateful.

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