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SCIENCE

Landforms in the Campo de Calatrava Volcanic Field (Ciudad Real, Central Spain)

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ABSTRACT

A detailed geomorphological map of the Campo de Calatrava Volcanic Field (CCVF) is presented at a scale of 1:50,000. The Campo de Calatrava, located on the south-eastern edge of the Hercynian Massif, is one of the most unusual volcanic areas of the Iberian Peninsula. The volcanic activity develops chronologically from Upper Miocene to Holocene, with a wide range of styles and eruptive dynamics that have created a variety of forms and types of volcanoes, the abundance of maars being outstanding. Thus, this map represents both the landforms of volcanic origin and the interferences that volcanic activity has caused in other processes and forms, offering the reader the key to understanding the origin and fundamental features of the landscape of the territory. Also shown is the crucial role geomorphological mapping can play as a basic tool in the conservation of natural heritage and in territorial planning. The mapping system applied is the French CNRS RCP 77, although various local adaptations have been incorporated. The map legend consists of 80 elements arranged in 10 sections, in which a wide variety of morphostructures, forms and deposits produced under various types of both relict and active morphogenetic systems are identified.

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Mapping; geomorphology; volcanism

1. Introduction

In Spain the production of geomorphological maps is late in comparison with other European countries such as Poland, France (RCP 77), Germany (GMK), the Netherlands (ITC) and particularly Switzerland, whose first maps date back to the early 1950s (Verstapen, 2011). To be more specific, the first geomorphological mapping carried out in Spain was in the late 1970s, and was produced mostly in black and white at a scale of 1:100,000 (Castañón, 1989; Ibañez, 1976; Pellicer, 1984; Peña, 1983). From the late 1980s and early 1990s a new stage in Spanish geomorphological mapping began, with the use of the French mapping system, incorporating colour representation and higher resolution at scales of 1:50,000 to 1:25,000 (Arnaez & García-Ruiz, 1990; Frochoso, 1990; García-Ruiz, 1989; García-Ruiz & Arnaez, 1991; García-Ruiz, Bordonau, Martínez de Pisón, & Vilaplana, 1992; Herrero, 1988). The twenty-first century has seen the beginning of a new trend based on the production of digital, geomorphological mapping, assisted by vector graphics software (CorelDraw, Freehand, etc.), and based on the use of new tools such as high resolution satellite images, global positioning system (GPS) receivers, Digital Elevation Models (DEMs) and geographical information systems (Chueca & Julián, 2008; González, 2007; González, Serrano, & González, 2011; Pellitero, 2009; Rodríguez, 2009; Tanarro, 2002). In

addition, starting in 2004, the Spanish Institute of Geology and Mining (IGME) undertook the development of a national digital geomorphological map, establishing the bases for its production (Martin-Serrano, 2004).

Although Spanish geomorphological mapping is relatively recent, production has been extensive and varied; the mapping of glaciers and periglacial forms of high mountain areas such as the Pyrenees (Chueca, Julián, Peña, & Espinalt, 2000; García-Ruiz & Martí, 2001; Julián & Chueca, 2002), the Baetic Mountains (Gómez Ortiz, 2002) or the Cantabrian Mountains (García de Celis, 1997; González et al., 2011; Pellitero, 2014; Rodríguez, 2009; Ruiz-Fernández, 2011) broadly predominating, but also include polar regions such as the Antarctic (López-Martínez, Martínez de Pisón, Serrano, & Arche, 1995).

As regards the geomorphological mapping of volcanic areas, there has been little development in Europe and even less in Spain; the map by Mallarach (1982) of the volcanic region of La Garrotxa (Girona) stands out for its originality and beautiful execution. Coming within the study area of this paper, the only notable contribution is the geomorphological map of Montes-Campo de Calatrava (García, 1994). This is a synthesis map at 1:200,000, which only covers the western end of the Campo de Calatrava Volcanic Field (CCVF) and in which the representation of the volcanic forms is overly schematic. Although the CCVF is

of great scientific interest as it is home to around 300 volcanoes, with a wide variety of types and shapes which have interfered with other morphogenetic systems, so far a detailed geomorphological map has not been made. Thus, the aims of this paper are to: (1) improve the geomorphological understanding of this volcanic region and (2) provide a geomorphological map that can serve as a basis or tool for making maps of natural hazards and for the conservation of the natural heritage.

2. Study area

The mapped area is located in the centre of Ciudad Real, in what is known as the CCVF, which is part of the Central Volcanic Region of Spain (CVRS). The CCVF is limited to the north by the southern foothills of the Montes de Toledo and to the south by the Ojailen Valley. It consists of moderately high ranges with altitudes between 700 and 900 m, the Medias Lunas and Calatrava ridges standing out. These ranges alternate with small plains at altitudes around 630–650 m, and drained by the Guadiana River and its tributary the River Jabalon.

From a geological perspective, the CCVF is located on the south-eastern edge of the Central Iberian Zone of the Iberian Massif, near the outer sectors of the Alpine Betic Range, and forms a slight fault trough which was created at the end of the Cenozoic between the Montes de Toledo and the Sierra Morena (Figure 1).

The Paleozoic basement, composed mainly of Armorican quartzites (Lower Ordovician), sandstones (Middle-Upper Ordovician) and slates (Silurian), is articulated around a number of large folded structures oriented from NW–SE to E–W and NE–SW, having been affected by two phases of the Variscan orogeny. This substrate is covered unconformably by siliciclastic fluvial and carbonate lacustrine sediments of Mio-Pliocene age and Quaternary fluvial deposits. The lava flows and volcanoclastic deposits were interbedded with fluvial and lacustrine deposits of the extensional basins (Late Miocene – Quaternary age) that resulted in the formation of a very complete set of sedimentary depositional environments (e.g. Herrero-Hernández, López-Moro, Gómez-Fernández, & Martín-Serrano, 2012, 2015), that occur after the Betic compression of the Serravalian-Tortonian (Figure 2).

The CCVF is characterized by basic monogenic intraplate volcanism (basalts, melilitites and nephelinites). That is to say, with central, simple volcanoes articulated around WNW–ESE primary structural lines and NE–SW to NE–SW secondary ones (Figure 3), following regional order fractures that cut the Hercynian base (Ancochea, 1983; Cebriá, 1992; Herrero-Hernández et al., 2012; Martín-Serrano, Monteserín, Ancochea, Herrero-Hernández, & Rey, 2011). The predominant volcano types are maars, cinder

cones and exogenous domes (Poblete, 1994). The sedimentological analysis of the volcanoclastic deposits led to the identification of facies close to the vents, low-density (dilute) pyroclastic surges, secondary volcanic deposits and typical maar deposits that were outcropped within a monogenetic volcanic field in the CCVF (Herrero-Hernández, López-Moro, Gallardo-Millán, Martín-Serrano, & Gómez-Fernández, 2015).

3. Materials and methods

The materials used in the making of the map were: (1) black and white aerial photographs at a scale of 1:30,000 from the 1980 to 1986 (National Geographic Institute); (2) 0.5 m pixel, colour digital orthophotography from the PNOA (National Program for Aerial Orthophotography) of the National Geographic Institute taken from 2012 onwards and (3) the corresponding 1:50,000 Topographic Map from the Army Geographic Service.

The method used involved the combination of field observations (using GPS to mark trajectories and delineate forms) and remote sensing of aerial photos and digital orthophotographs.

Given the characteristics of the landforms, the processes represented, and size of the area (532 km²), a scale of 1:50,000 was selected as being the most appropriate. Once the scale had been established, the digital base was produced using Esri ArcMap10.1, combining the digital orthophotomaps and the topographic information. Then, the resulting digital base was exported to CorelDraw to design the map and digitize all of the landforms.

The geomorphological mapping system used is RCP 77 (Recherche Coopérative sur Programme) of the French CNRS (Centre National de la Recherche Scientifique) (Joly, 1997), combined with adaptations of our own.

4. Representation

The geomorphological map of the CCVF is made up of a Main Map and four inset maps: the location mapped area, a regional geological framework, a map of structural lines, and finally, a hypsometric map with the main types of volcanoes. The graphic design and organization have been done to create order, harmony and readability, following the guidelines established by Krygier and Wood (2011) and Otto, Gustavsson, and Geilhausen (2011).

The landforms, processes and deposits have been mapped using 80 symbols grouped into 10 sections, which are explained below in the same order as in the legend.

4.1. Topographic base

This section includes altimetry, planimetry and the current hydrographic network. For the altimetry we

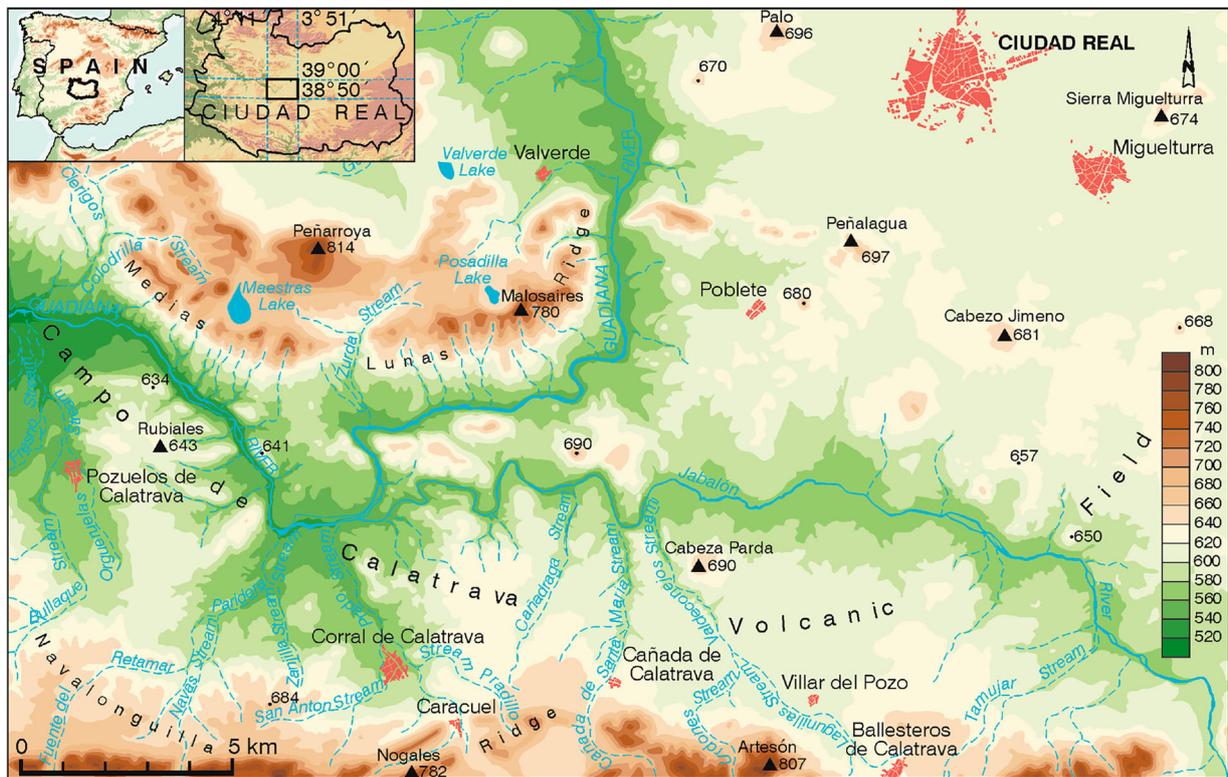


Figure 1. Location map of the study area.

used contours with a 20 m interval, master contour lines at 80% grey and secondary lines at 40%, and also spot heights. Centres of population and trigonometric points are represented within the planimetry. A neutral grey colour was used for both so that they are represented discreetly, and to encourage map reading. Finally, a light blue (Pantone Matching System P306) was used for rivers and streams.

4.2. Lithology

This section includes 11 rock formations present in the study area, listed in chronological order on the map legend. Three major lithological units can be distinguished. First, the Paleozoic rocks formed by quartzite microconglomerates, then the Armorican quartzites of the Lower Ordovician, and finally the shales and sandstones of the Silurian–Middle Ordovician. The Paleozoic rocks are represented by light crimson (P224 to 50%, 60% and 40%, respectively, according to their hardness) used for the metamorphic rocks of the Paleozoic base (Joly, 1997), with an overprint of dots and dashes in negative. The second lithological set is formed by sedimentary materials of the Pliocene, namely, sand, marl and limestone, which, because they belong to a cenozoic sedimentary basin, are represented with a light brown colour (P472 to 40%, 60% and 80% on the basis of their hardness); sands with an overprint of reddish spots (P471), and marls and limestones with a pattern of dashes and bricks, respectively, in negative. Third, the volcanic basaltic

lithology of the Pliocene-Pleistocene is represented using different Greek letters.

4.3. Tectonics

Tectonic events are represented in this section, especially fractures that skew the Paleozoic basement and the dips that are presented by limestones as a result of explosive hydromagmatic activity. The colour used to represent these deformations is black.

4.4. Structural landforms

We distinguish three types of structural forms. First, the horizontal or tablelands defined by the Neogene sedimentary series present at the southern tip of the map. Next, the pseudo-Appalachians folded forms linked to the Paleozoic quartzite rocks. Such forms are represented by a striped pattern and a group of linear symbols in dark brown, a strong, neutral colour (P470) (Joly, 1997). Finally, the karst surface forms, limited to a small number of dolines, are drawn using a bluish-green colour (P569) for the outline, while the surfaces are not coloured.

4.5. Volcanic landforms and deposits

A total of 36 volcanoes have been inventoried. From a morphological perspective they correspond to exogenous domes and cinder cones (Figure 4). Seventeen different types of volcanic shapes and deposits have

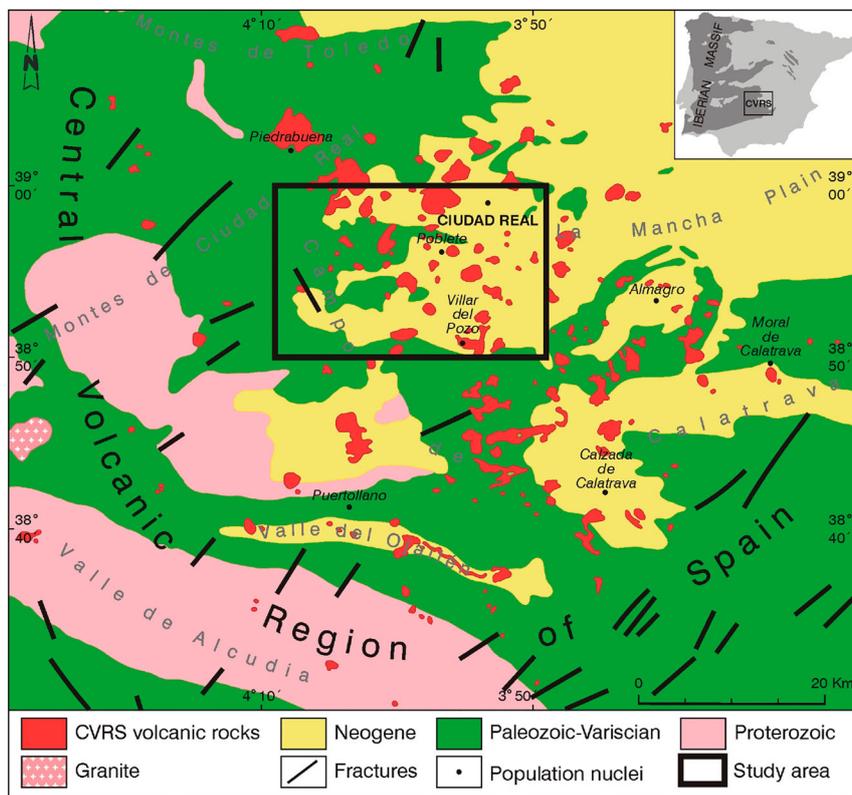


Figure 2. Geological schematic map of the CVRS (modified after Ancochea, 1983; Gallardo-Millán & Pérez-González, 2000; Herrero-Hernández et al., 2015; Vegas, 1971).

been mapped. The forms and deposits of volcanic origin are represented in orange (P021). However, the texture of the pyroclastic material and the scoriaceous lava flows are symbolised with an overlay of positive points

and chaotic lines of a reddish hue (P1495 and P1795), respectively. Also shown by means of reddish linear symbols (P1795) are the scarps of the fronts of the lava flows, from less than 5 m to over 20 m.

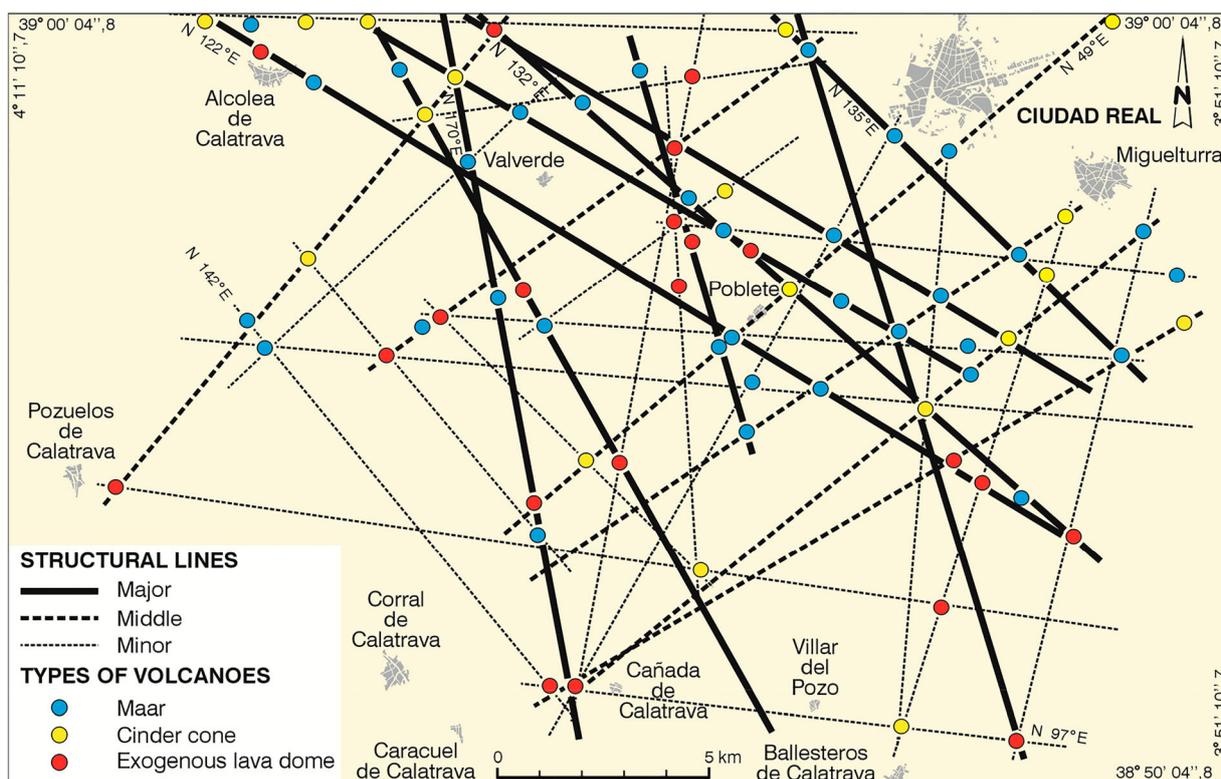


Figure 3. Structural map of the CCVF.

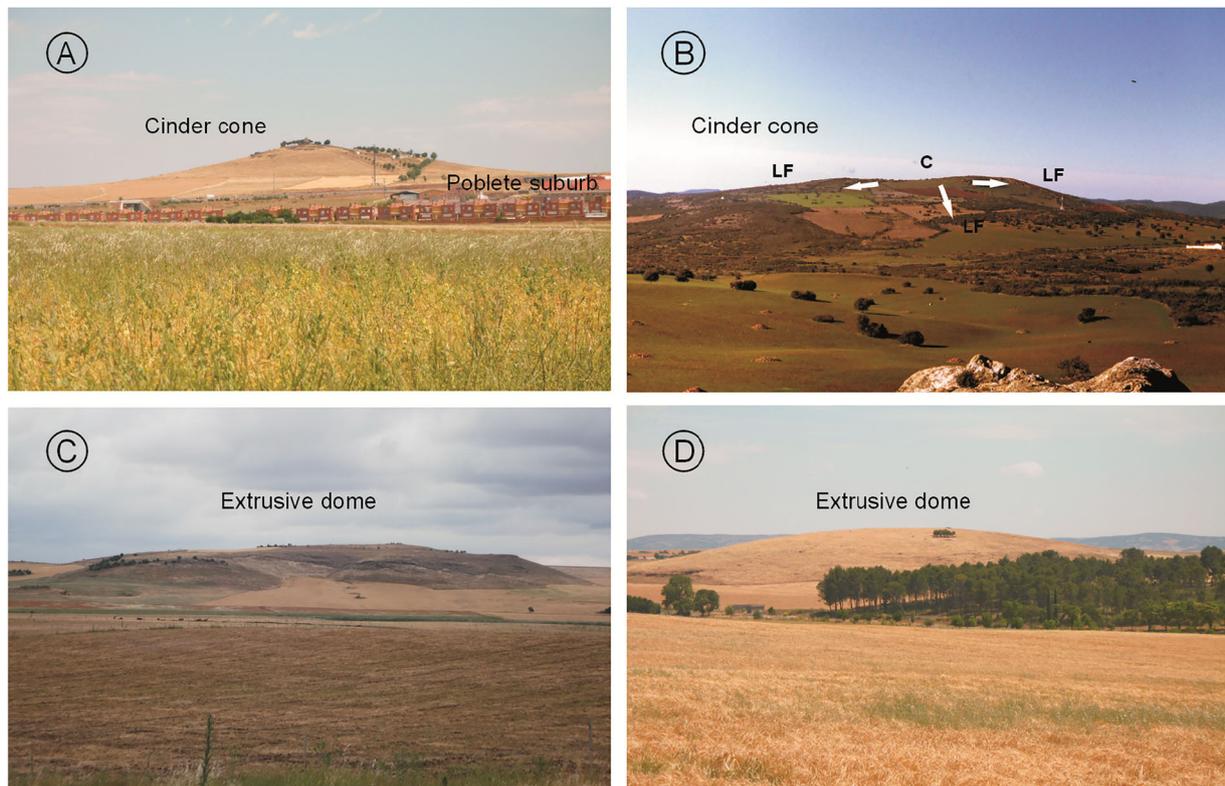


Figure 4. Types of magmatic volcanoes. (a) Cinder cone without crater (Cabezo del Rey volcano), (b) Cinder cone with summit crater (Peñarroya volcano), LF (lava flow), C (crater). The arrows indicate the direction of the lava. (c) Las Moreras extrusive dome. (d) Cabezo de los Pescadores extrusive dome.

4.6. Phreatomagmatic landforms and deposits

A total of 34 maars of hydromagmatic origin have been mapped, of which 6 are Pliocene and present a volcano-tectonic collapse. The Pliocene maars are characterized morphologically by constituting circular or semi-circular crater depressions bordered around their perimeter by tilted Pliocene limestones, with periclinal dips converging towards the interior of the depression. However, they lack the typical tuffaceous rings characteristic of Pleistocene maars, which consist of an annular lip formed by deposits of pyroclastic waves that surround the crater depression (Figure 5).

Given that their origin is due to hydromagmatic explosions, that is, those resulting from contact between magma and water confined in aquifers, we have replaced the orange (P021) that is used in the RPC 77 system to represent shapes and hydrovolcanic deposits, with a milder tone, pastel orange colour (P155 and P156). To distinguish them chronologically, the Pliocene phreatomagmatic maars and deposits are represented with a brightness of 85% (P155), whilst those of the Pleistocene are expressed with a brightness of 78% (P156).

4.7. Attenuated periglacial landforms

In the study area periglacial forms are limited to the presence of debris cones, scree slopes, scree and

accumulation glaciais located around the quartzite ridges of Medias Lunas and Calatrava, where they attain their highest altitudes. Magenta (P252) has been used for the outline of the scree slopes and the debris slope, with the same colour but at 80% for the fill (Joly, 1997). Four levels of accumulation glaciais have been distinguished, with ages corresponding to the upper, middle, lower-middle and lower Pleistocene. These have been represented by the colour magenta (P252) at 100%, 80%, 60% and 40%, respectively. Thus, the approach taken to express the greatest age or the age of the forms is to decrease the percentage of the pure colour (i.e. increase its brightness). All the periglacial forms in this region are inherited and have formed under the heavily attenuated cold conditions that prevailed during the Quaternary.

4.8. Fluvial and lacustrine landforms

Fourteen different forms and fluvial deposits have been mapped. Cyan green has been used to represent linear symbols (P339), except for glaciais-terraces and alluvial fans, where a more luminous green (P383) has been used. A total of three levels of river terraces have been identified. A dark spring green colour (P350) has been used to plot the contour of the river terraces, whilst for the polka dot pattern a dark yellow colour (P378) has been used, with different intensities depending on their age.



Figure 5. Types of hydromagmatic volcanoes. (a) La Posadilla maar on quartzitic monoclinial crest. (b) Los Corchuelos maar on quartzitic anticline. (c) El Mortero maar on cenozoic sediments. (d) Las Higuieruelas maar on Pliocene limestones with volcano-tectonic subsidence.

4.9. Mediterranean and semi-arid domain

This section includes, first, the piedmont alluvial glacis located at the southern tip of the map, at the foot of Navalanguilla Ridge, between the towns of Corral and Pozuelos de Calatrava. There are also small isolated patches that are distributed around the volcanoes of Cabeza Parda and Las Higueras. Notably, the piedmont alluvial glacis are relatively dismantled as a result of the incision of the Prado, of the Bullaque and of the Paridera streams that drain into the River Guadiana. The alluvial piedmont glacis are made up of a heterometric fanconglomerate of extremely worn and rounded quartzites in a clay-sandy matrix of yellowish-reddish hue (Munsell Color 7.5YR 6/8). Its origin is associated with alluvial fans in high energy regimes (torrential) under a semi-arid or arid climate environment (Casco, 1990). Because of this, we have resorted to the use of neon yellow colour (P123) to represent the outline, as well as the symbol and the spot pattern. Moreover, the sheet-flood glacis formed from the

dismantling of the alluvial piedmont glacis have been mapped using for plotting their outline, symbol and the spot pattern, the olive green colour (P583), since they came about as a result of a rill wash (Joly, 1997).

Finally, the presence of calcretes and ferromanganese crusts is very common in the study area. In the first case, there are calcretes barely a few centimetres thick that lie scattered about on the surface of the river terraces. However, in the NE end of the study area the calcretes are several meters thick and generate an extensive tabular accumulation surface. In both cases an oblique striped olive green pattern (P583) has been used, but with a greater density for the tabular surface, and a lower density for the laminar calcretes.

The ferromanganese crusts affect both alluvial piedmont glacis and accumulation glacis, colluvial glacis (Figure 6), and even fluvial terraces. In no case is there any presence of aluminium minerals, and their morphogenesis is linked to an intense hydrothermal activity (Figure 7) and Mediterranean paleoclimatic conditions (Poblete, 1994, 2003). Such crusts are

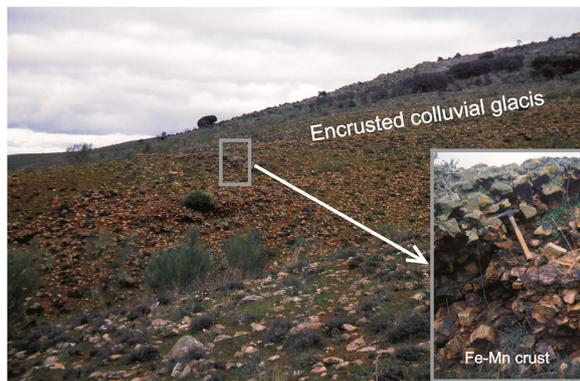


Figure 6. El Chorrillo's colluvial glacia encrusted by ferromanganese cement. A detail of the ferromanganese crusts can be seen at the lower right corner of the photo.



Figure 7. Ferruginous hot spring (Villar del Pozo's old bath house). (a) Carbonic dioxide escapes as bubbles as pressure decreases. (b) Precipitation of the ferruginous solutes dissolved in the water after degassing.

Quaternary, and have been represented by an olive green coloured (P583), oblique mesh-like pattern (Joly, 1997).

4.10. Anthropogenic landforms

In this section only opencast pits excavated mainly on cinder cones in order to extract the pyroclastic materials for the manufacture of pozzolanic cements are included. The opencast pits have been represented by a point symbol in black.

5. Conclusions

This article presents a geomorphological map at a scale of 1:50,000 of the volcanic area of Campo de Calatrava (Ciudad Real, Central Spain). The large number of landforms and geomorphological processes represented evidence the rich geodiversity of the study area.

The map legend includes 80 symbols organized in 10 sections covering the topographic base, lithology, tectonics, structural landforms, volcanic landforms, phreatomagmatic landforms, attenuated periglacial landforms, fluvial and lacustrine landforms,

Mediterranean and semi-arid domain, and anthropogenic landforms.

The main advantages of the mapping system used are:

- (1) This is a well-structured and mature cartographic method, particularly suitable for making large and medium scale maps (1:25,000–1:250,000).
- (2) It is notable for its simplicity and expressiveness, on subordinating the lithology to the landforms and surface formations.
- (3) Another feature of note is that the morphostructural domains and the morphogenetic systems are easily differentiated through the use of specific colours characterized by their harmony and visual legibility.
- (4) It is also a flexible and open approach that allows the adaptation of symbols or colours to the representation of specific morphological aspects of specific areas.

Despite its uniqueness, the volcanic area of Campo de Calatrava continues to be subject to intense mining activity, which threatens the conservation of its geomorphological heritage. Because of this, this geomorphological map can be a useful tool for effective management and planning. In addition, such a map can serve as a basis for derived maps with various applications: maps of natural risks, planning maps, and landscape protection maps, etc.

Software

The digital cartographic base map used in the preparation of geomorphological map was produced using Esri ArcMap10.1, while the digitization of the different landforms and the final design was carried out using CorelDraw GS X7.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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