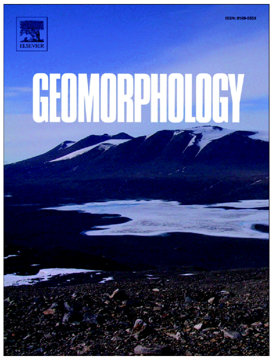

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Geomorphological evolution and chronology of the eruptive activity of the Columba and Cuevas volcanoes (Campo de Calatrava Volcanic Field, Ciudad Real, Central Spain)

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"Declarations of interest: none"

Abstract

In this study we analyze the geomorphological evolution and chronology of the eruptive phases of the Columba and Cuevas volcanoes (Campo de Calatrava Volcanic Field, Central Spain). These are two cinder cones located at the margins of the Jabalón River valley, between the localities of Granátula de Calatrava and Aldea del Rey (Ciudad Real). In order to generate geomorphological map, we conducted fieldwork and photointerpretation of aerial images, in addition to morphometric and volcanostratigraphic analyses aimed at correlating the volcanic deposits and fluvial terraces of the Jabalón River. Finally, we applied OSL (optically stimulated luminescence) dating to obtain the age of fluvial deposits affected by both volcanoes, plus radiocarbon dating to the organic matter of a paleosoil located between the Columba volcano deposits. The results provide a maximum age of 75.16 ± 4.9 ka for the formation of the Cuevas volcano. Moreover, the Columba volcano began its activity with a Strombolian phase around 33.9 ± 2.36 ka BP, followed by a long period of inactivity between 24.9–23.2 ka and 14–13.5 ka BP in which the aforementioned paleosoil formed. Subsequently, the eruptive activity resumed with a phreatomagmatic phase followed by another Strombolian phase, in which a lava flow was emplaced crossing and damming the Jabalón River, thus forcing the deposition of a 9 m thick fluvial terrace above it, at about 6.27 ± 4.28 ka. The Columba volcano is a good example of polycyclic eruptive behavior in a monogenetic volcanic field, whose last eruption occurred between 14 and 6.2 ka ago. The interaction between volcanic and fluvial processes were responsible for the morphological evolution of the area, the study of which has been crucial to determine the evolution of the eruptive activity, its morphological results, and the relative chronologies.

Keywords: Central Spain, Campo de Calatrava Volcanic Field, Geomorphological evolution, Polycyclic volcano, Chronology, Absolute dating

1. Introduction

Volcanoes, as landforms, have traditionally been classified into two types: monogenetic and polygenetic (e.g., Cotton, 1944; Rittmann, 1963; Ollier, 1970; MacDonald, 1972). Monogenetic volcanoes are formed as a result of a single eruption, which lasts for a short period of time that can range from several days to a few years, while polygenetic volcanoes originate from several eruptions separated by relatively long periods of time, so they involve different magmas and complex plumbing systems (Cas and Wright, 1987; Francis, 1993; Walker, 2000; Schmincke, 2004). Monogenetic volcanoes are mainly related to basaltic compositions and low viscosity magmas, and area characterized by Strombolian eruptions with alternating explosive and effusive phases (Vespermann and Schmincke, 2000).

Monogenetic basaltic volcanoes are the most frequent subaerial volcanic forms on Earth (Wood, 1979) and are located in all tectonic setting (e.g., Walker, 2000; Valentine and Gregg, 2008), appearing as isolated forms (e.g., Glazner et al., 1991) or forming clusters in volcanic fields (e.g., Condit et al., 1989; Connor, 1990; Connor and Conway, 2000). From the geomorphological point of view, monogenetic volcanoes are traditionally considered as eruptive cones of small size and volume, between 0.0001–1 km^3 (Vespermann and Schmincke, 2000), with simple forms and structures predominating simple cinder cones, and to a lesser extent, maars, tuff rings, and tuff cones resulting from hydromagmatic explosive eruptions, when the ascending magma comes into contact with water (e.g., Walker, 2000).

However, recent research reveals that some monogenetic volcanoes have a much more complex evolution (Vespermann and Schmincke, 2000; Schmincke, 2004; Brand and Clarke, 2009; De Benedetti et al., 2009), with several eruptive episodes separated by long intervals of rest, for which they have been called polycyclic volcanoes (Németh, 2010; Kereszturi et al., 2010; Németh and Kereszturi, 2015; Brenna et al., 2015; Tchamabé et al., 2016; Smith and Németh, 2017). It should be noted that the first contributions in this regard go back to the 1980s and were carried out in the monogenetic volcanic fields of Cima (California) and Timber Mountain (Nevada), where they identified several cinder cones formed after some episodes of eruptive activity separated by tens to hundreds of thousands of years, which is why they were initially interpreted as polygenetic volcanoes (Turrin et al., 1985; Turrin and Renne, 1987). For a while the terms polygenetic and polycyclic were used synonymously (Bates and Jackson, 1987). Subsequently, the polygenetic term was replaced by polycyclic to refer to such volcanic edifices formed from an intermittent volcanic activity, where the separation time between events exceeds the maximum cooling time calculated for the volume of magma emitted (10^2 to 10^3 years) and in which the amount of magma supplied is also very small (less than 10^5 m^3 a^{-1}) (Renault et al., 1988; Wells et al., 1989; Renault et al., 1990; Perry and Crowe, 1992). In other occasions it has been described how maars may develop over previous cones formed in near-identical locations but separated by considerable time-gaps (Németh et al., 2014), thus offering a particular scenario in which individual short lived eruptions form a landform that then, after a significant time, longer than needed to keep a dyke mobile enough to rejuvenate, is modified by new eruptions occurring nearly at the same place.

In the Campo de Calatrava Volcanic Field (CCVF) numerous investigations have been carried out, mostly concerning its petrology and geochemistry (Ancochea, 1983, 2004; Cebriá, 1992; López Ruiz et al., 1993; Cebriá and López-Ruiz, 1995), structural geophysics (Bergamín, 1986; Granja Bruña et al., 2015), soil science (Raggi, 1983), volcanostratigraphy (Molina, 1975; Gallardo, 2005), and the interactions between volcanic activity and sedimentation (Herrero-Hernández et al., 2012, 2015). Moreover, significant effort has been made in the last decades to characterize the physical volcanology and geomorphology of the CCVF volcanoes (e.g., Poblete, 1994, 2016; González et al., 2007, 2010a, 2010b; Stoppa et al., 2012; Carracedo Sánchez et al., 2012, 2017; Becerra, 2013). Using geomorphological and volcanostratigraphic evidence—such as the presence of paleosoils between the pyroclastic deposits or the staggered arrangement of lava flows from the same volcano at the bottom of the valleys—some of these investigations have shown the polycyclic nature of some volcanoes in this region (Poblete and Ruiz, 2002). Moreover, these studies have also provided a more recent age for some of these volcanoes, specifically between the Lower Pleistocene and the Holocene (Poblete, 1994; Poblete and Ruiz, 2002, 2007) and even the average Middle Holocene for the Columba volcano, according to González et al. (2007, 2010a). A first approach to the analysis of the geomorphological evolution of the Cueva and Columba volcanoes was carried out by Poblete et al. (2014). Despite this, certain aspects concerning eruptive activity, internal structure, and especially the volcanostratigraphic succession of such volcanoes, are still not precisely known.

The main goal of this study is twofold. On the one hand, we wanted to characterise the geomorphological evolution of the study area and, in particular, the interaction of volcanic activity with fluvial sedimentation, as a major process influencing this morphological evolution. On the other hand, we wanted to deepen into the knowledge of the polycyclic activity in monogenetic volcanism, an aspect that is still poorly known in the geomorphological characterisation of such volcanic fields. This is why we present a detailed geomorphological mapping of two of the main volcanoes of the region, the Columba and Cuevas volcanoes, as well as of the middle section of the Jabalón River valley, where they are located. We also analyze their stratigraphic succession in order to know the interaction between the eruptive activity of these volcanoes and the fluvial dynamics of the Jabalón River. Finally, we identify the eruptive sequence and the age of these two volcanoes, establishing their relative stratigraphy and chronology by using the stratigraphic correlations between volcanic deposits (both lavas and pyroclastics) and terraces and fluvial deposits, as well as absolute dating, and discuss on the basis of these results the age of this volcanism.

2. Geological setting

The Central Spanish Volcanic Region (CSVR), located in the center of the Iberian Peninsula (Ciudad Real Province), is home to around 257 scattered volcanoes over an approximate area of 3,500 km^2, ranging in age from Upper Miocene to Holocene (Poblete, 2016) (Fig. 1). The CSVR together with the Catalan

Volcanic Zone (Martí et al., 1992) form the two main Quaternary alkaline volcanic provinces of Spain belonging to the European Cenozoic Rift System (Wilson and Downes, 1991, 1992; Ziegler, 1992). The CSVR is composed of six volcanic zones: the Montes de Toledo to the North (6 volcanoes); La Mancha (3 volcanoes) to the East; Los Montes de Ciudad Real to the West (20 volcanoes); Ojailén Valley (15 volcanoes) and Alcudia Valley (12 volcanoes) to the South; and finally the Campo de Calatrava (201 volcanoes) in the center (Hernández-Pacheco, 1932; Poblete, 2016). Thus, Campo de Calatrava Volcanic Field (CCVF) is the most important for its extension, diversity of morphologies and number of volcanoes.

The CCVF is located in the southeastern end of the Central-Iberian Zone of the Iberian Massif, near the external sectors of the Alpine Betic Range, forming a slight tectonic depression originated at the end of the Cenozoic (Poblete, 1994). The Paleozoic basement composed mainly of Armorican quartzites (Lower Ordovician), sandstones (Middle-Upper Ordovician) and slates (Silurian), is articulated around a series of large folded structures oriented from NW-SE to E-W and NE-SW, having been affected by two phases of the Variscan orogeny (Ruiz Vegas, 1979). This substrate is covered unconformably by siliciclastic fluvial and carbonate lacustrine sediments of Mio-Pliocene age and Quaternary fluvial deposits. The lava flows and volcaniclastic 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 (Herrero-Hernández et al., 2012, 2015), that occur after the Betic compression of the Serravalian-Tortonian (Fig. 1).

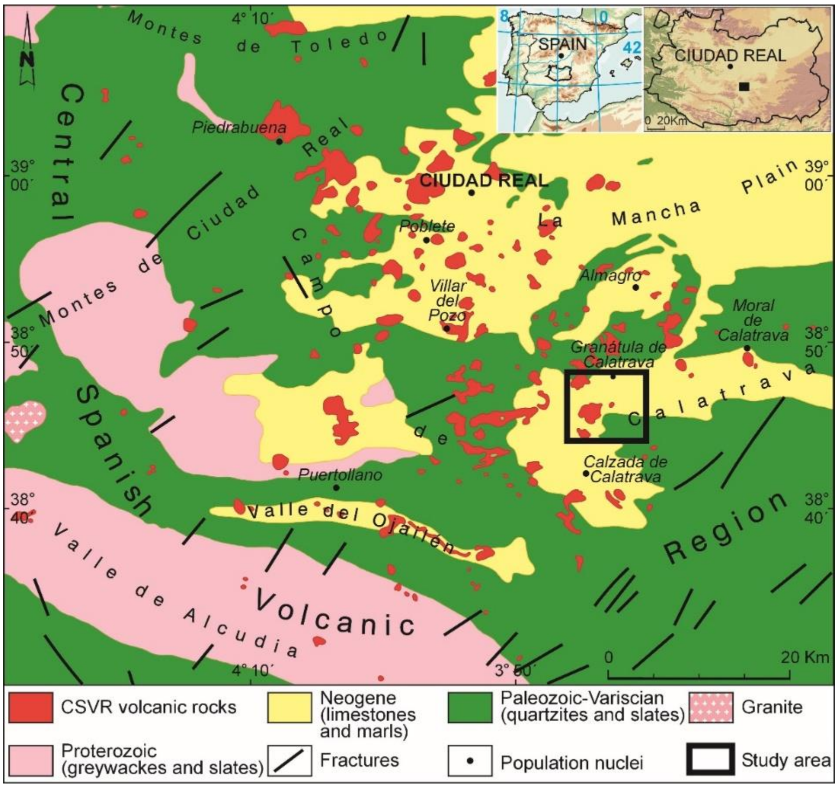

Figure 1. Geological sketch map of CSVR (modified after Vegas, 1971; Ancochea, 1983; Gallardo-Millán and Pérez-González, 2000; Herrero-Hernández et al., 2015) and location of the study area.

The CCVF corresponds to an intraplate volcanism of mafic and ultramafic (olivine basalts, basanites, olivine melilites, olivine leucitites) composition that is mostly represented by maars and cinder cones and lava flows aligned on two main (WNW-ESE and NW-SE) and two secondary (ENE-WSW and NE-SW) structural lineations that affect the Variscan basement (Ancochea and Brändle, 1982; Ancochea, 1983; Cebriá, 1992; López-Ruiz et al., 1993; Cebriá et al., 2011) (Fig. 1). Magmas responsible for this volcanism have been traditionally interpreted to derive from primary, little evolved magmas, formed from different degrees of partial melting of the same enriched and uniform asthenospheric source (Ancochea, 1983;

Cebriá and López-Ruiz, 1995), whose isotopic homogeneity is similar to that of the European asthenospheric mantle (Wilson and Downes, 1991). However, more recent studies point towards the possible carbonatitic nature of the primitive magma of CCVF (Bailey et al., 2005; Humphreys et al., 2010; Stoppa et al., 2012). This volcanism was originally attributed to an extensional tectonic regime or aborted rift (Ancochea, 1983; Doblas et al., 1991; Cebriá and López-Ruiz, 1995). However, other studies point more toward the existence of a baby-plume detached from an active megaplume below the Canary-Azores Islands and the western Mediterranean (Hoernle et al, 1995; Duggen et al., 2005). This is also supported by recent gravity models confirming that the crust shows a quasi-constant thickness (Granja Bruña et al., 2015).

Regarding the age of the volcanic activity, two major stages have been distinguished using of K-Ar radiometric dating in lava flows: the first and least important in terms of morphological repercussions, occurred in the upper Miocene (from 8.7 to 6.4 Ma) and had an ultrapotassium character (Ancochea, 1983); the second and most important in terms of volume and number of volcanic centers and lava flows, had an alkaline and ultra-alkaline composition and extended from the lower Pliocene (4.7 Ma) to the lower Pleistocene (1.75 Ma) (Ancochea and Giuliani, 1979; Ancochea, 1983; Bonnadona and Villa, 1986; Bogalo et al., 1994).

The Columba and Cuevas volcanoes (Fig. 2) are located at the eastern end of the CCVF, specifically, in the sub-basin of Moral - Granátula de Calatrava, which is filled with calcareous and detrital Neogene-Quaternary sediments derived from the middle section of the Jabalón River. Both volcanic edifices are located about 4 km south of the town of Granátula de Calatrava. Specifically, the Columba volcano, located on the left bank of the Jabalón River, consists of a 100 m high cinder cone crowned by a circular crater of 200 m in diameter, from which several very fluid lava flows (flow lengths up to 1,500 m) of basaltic composition were emitted, crossing and blocking the course of the Jabalón River. On the other hand, the Cuevas volcano is a smaller cinder cone, without a crater, that barely rises more than 40 m on the right bank of the Jabalón River (Fig. 2).

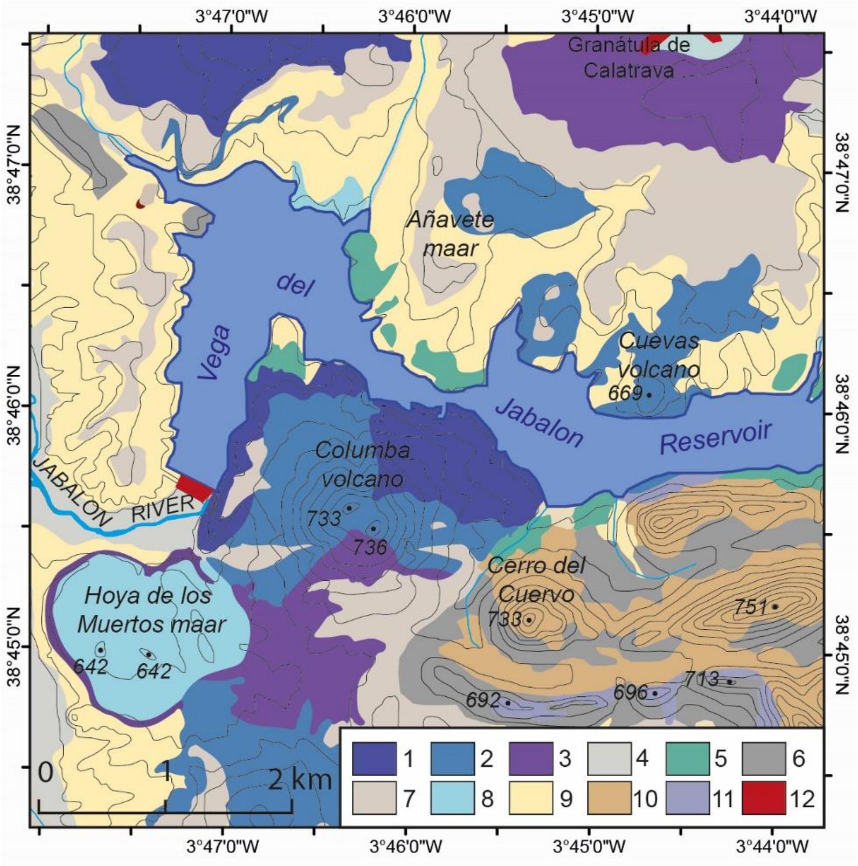

Figure 2. Geological map of the study area modified from Montes et al. (2004). 1. Basalts and basanites (lava flows, Upper Miocene-Lower Pleistocene). 2. Nephelinites and melilitites (pyroclastic fall deposits, Upper Miocene-Lower Pleistocene). 3. Hydromagmatic deposits (Upper Miocene-Lower Pleistocene). 4. Alluvial valley floor (Holocene). 5.

Pebbles and cobbles of quartzite (fluvial terrace, Upper Pleistocene). 6. Pebbles and cobbles of quartzite (colluvial glacis, Lower Pleistocene). 7. Laminar calcretes (main erosion surface of the La Mancha Plain, Lower Pleistocene). 8. Limestones and marls (Upper Pliocene). 9. Sands, pebbles, and clays (Lower Pliocene). 10. Quartzites, sandstones, and slates (Middle Ordovician). 11. Slates (Middle Ordovician) 12. Dam.

3. Material and methods

The research is supported by photointerpretation of aerial images, geomorphological cartography, volcano-stratigraphic and morphometric analysis, as well as various geochronological dating techniques.

3. 1. Field work

Fieldwork campaigns undertaken between 2015–2018 included extensive geomorphology and stratigraphy along and around the two volcanoes, and the lateral extent of cones, lava flows, and pyroclastic deposits were mapped, as well as the various levels of fluvial terraces, glacis (an erosional or depositional landform, with little slope), and other significant or representative geomorphological forms. The position of each measurement station was recorded with portable GPSMAP® 60CSx devices, with an accuracy of <10 meters 95% typical, and subsequently corrected by digital elevation model (DEM) and GIS. The sedimentological and lithological characteristics of each deposit were carefully annotated and when possible samples suitable for further luminescence and radiocarbon dating were collected. The mapping elaborated in the field work was contrasted with the information obtained through the photointerpretation of the aerial images of the National Flight of Spain from 1980–1986 and of the digital orthophotos of the PNOA of 2015, with pixel size 50 cm, mosaic RGB, and in the Enhanced Compression Wavelet (ECW) format. As a result, a detailed geomorphological map was produced at a scale of 1:25,000. This allowed us to understand the interactions between eruptive processes and other processes of modeling dynamics, especially the fluvial ones, and to identify the most significant geomorphological forms. All the collected information was incorporated into a georeferenced database and processed through a Geographical Information System managed by the ArcGIS 10.1 software (© ESRI). The geomorphological mapping system used (nomenclature, symbology, etc.) was the RCP 77 of the French CNRS (Center National de la Recherche Scientifique) (Joly, 1997), combined with adaptations of our own. The digital cartographic base map used in the preparation of the geomorphological map was produced using ArcMap 10.1 (© ESRI). The coordinate projection system used was the ETRS89 DATUM and UTM 30, with geographic coordinates expressed in latitude and longitude. The digitization of the different landforms and the final design was exported and carried out using CorelDRAW GS X7. Volcanostratigraphic analyses, including thickness and extent of the deposits and lavas, lithology and sedimentology of volcanic and fluvial deposits, and stratigraphic correlations between all these materials, were carried out in the Columba and Cuevas volcanoes. According to previous studies (Poblete and Ruiz, 2002, 2007; González et al., 2010a; Becerra, 2013; Poblete et al., 2016) these volcanoes were the ones that present a major stratigraphic and morphological complexity, and the new data collected permitted to establish the succession of erupted products, as well as the morphological evolution of the cones. This information was used to reconstruct the eruptive phases and styles that occurred in the construction of these volcanoes (e.g., Fisher and Schmincke, 1984; Manville et al., 2009; Martí et al., 2018; Németh and Palmer, 2018), as well as to determine the interactions that took place between the eruptive activity of each volcano with the fluvial dynamics of the Jabalón River. This was done by establishing precise stratigraphic correlations between the volcanic deposits (lava flows and pyroclastic deposits) and the fluvial terraces deposited by the Jabalón River in the vicinity of both volcanoes.

3.2.- Geochronology

Datings of the fluvial terraces of the Jabalón River that were either covered by the volcanic deposits or affected by the eruptive phases of the Columba and Las Cuevas volcanoes, were carried out using optically stimulated luminescence (OSL). Four samples of fluvial deposits of the Jabalón River were dated, two on the terrace located at 20 m above the current river level (covered by pyroclastic deposits from Las Cuevas volcano), one on that located 15 m above the current river level (related volcanostratigraphically with the first lava flow of the Columba volcano), and another on the terrace found at 9 m above the current river level, which covers the last lava flow emitted by the Columba volcano. The OSL dating (Murray and Wintle, 2000; Murray and Olley, 2002) allows us to estimate the age of the last time the sediments were exposed to sunlight, thus providing the age of deposition and burial of the sediment within the alluvial sequence. The age range of this method covers from 100 to 350,000 years BP, with an uncertainty of typically 5-10% of the age of the sample (Murray and Olley, 2002). The protocol followed was: first the profile of the deposit was covered with a dark cloth and the surface material of the outcrop was cleaned to eliminate the grains exposed to sunlight. In taking samples, precautions were taken to avoid areas with signals of water circulation or sediments that were bioturbated, always choosing well-stratified sediments to avoid problems with partial replacement of the luminescence signal during transport (Wallinga, 2002; Rittenour, 2008). The samples were extracted by opaque PVC tubes about 25 cm long and 4 cm in diameter. The sediments were processed and measured in the Dating and Radiochemistry Laboratory of the Autonomous University of Madrid (Spain). All the samples were stored in the dark for a period of 600 hours and then subjected to an abnormal decay test, in which it was found that the signal losses were less than 1%. Based on these results, we evaluated the paleodose or, failing that, the equivalent dose by applying the additive dose protocol using the fine-grained technique, specifically, the fraction between 2 and 10 microns (Zimmerman, 1971). The calculation of the annual dose was made by combining two types of measurements: on the one hand, the beta radioactivity from the K-40 present in the samples and, on the other hand, the alpha radioactivity derived from their Uranium and Thorium (Nambi and Aitken, 1986). A TL-DA-10 luminescence reader was used for the measurements.

Four samples of organic matter were also collected from the paleosoil located between the “aa” lava flow and the PDC deposit on the edge of the SE flank of the Columba volcano, exactly in the trench of the kilometer point 16 + 500 of the CM- 413 that links the towns of Aldea del Rey and Granátula de Calatrava. Here, field evidence shows that the PDC deposit acted as a vegetation base in time the aa lava flow covered it. The samples were collected at different depths of the paleosoil with a clean spatula, placed in aluminum foil and stored in sealed plastic bags. The samples were sent to the Radiocarbon Laboratory (Poland) to carry out radiocarbon dating through AMS method using the standard procedures of this lab (https://radiocarbon.pl/en/description-of-procedures/). The ages obtained were calibrated with OxCal software v4.1.7 (Ramsey, 2010).

4. Results

4.1. Las Cuevas volcano

Las Cuevas volcano is located 3 km south of Granátula de Calatrava and rises about 40 m on the right bank of the Jabalón River (Fig. 2). It is a small cinder cone formed from three eruptive phases that generated pyroclastic deposits and lava flows. The pyroclastic deposits that form this volcano can be studied in a distal outcrop located 800 m to the NNE of the volcano (38°46’24.6” N / 3°44’28.4” W), where a 3.5 m thick succession includes from base to top: a) a 2.53 m thick, dark pyroclastic fall deposit, rich in scoria lapilli, which shows an incipient horizontal stratification and normal grading; b) a thinly laminated, dilute PDC deposit of 55 cm thick, composed of beds of fine ash alternating with coarser beds rich in lithic fragments; c) a denser PDC deposit of about 44 cm thick that rests in erosive unconformity on the previous deposit. It is a massive deposit, of a light color, rich in lithic fragments from Paleozoic rocks (Fig. 3). This variation on the nature of the deposits indicates a change from Strombolian to phreatomagmatic activity during the construction of Las Cuevas volcano.

Figure 3. Stratigraphy of the volcanic deposits at Hormigoneras quarry. A) Pyroclastic fall deposits. B) dilute PDC deposit. C) dense PDC deposit. Contacts between formations are marked by black and white lines. Note the person for scale (height, 1.80 m) and the hammer, 33 cm. The inset aerial photograph shows a sector of the Jabalón River and the location of this observation point.

At the southern slope of the cone it is observed the interaction of the volcanic deposits with the fluvial sediments (Fig. 4). In particular, the base of the slope is formed by the Strombolian fallout deposit, here showing a thickness greater than 10 m, with a marked oblique stratification. A very compact and lithified fluvial deposit, 1–2 m thick, formed of small gravels and rounded sands cemented by an abundant carbonated matrix, rests on this pyroclastic fall deposit. The two OSL dates of this fluvial terrace located at 20 m above the current river bed provide an age between 75.24 ± 4.8 and 75.08 ± 5.17 ka (Table 1). The fluvial deposit is overlaid by 1 m of the dilute PDC deposit, which incorporated fragments of the cemented fluvial deposit, thus showing how the explosion, at least partially, truncated the roof of the river deposit. Lastly, the dry PDC deposit is covered by a 4 m thick “aa” lava flow that contains a large number of block size fragments of the cemented fluvial terrace and the PDC deposits.

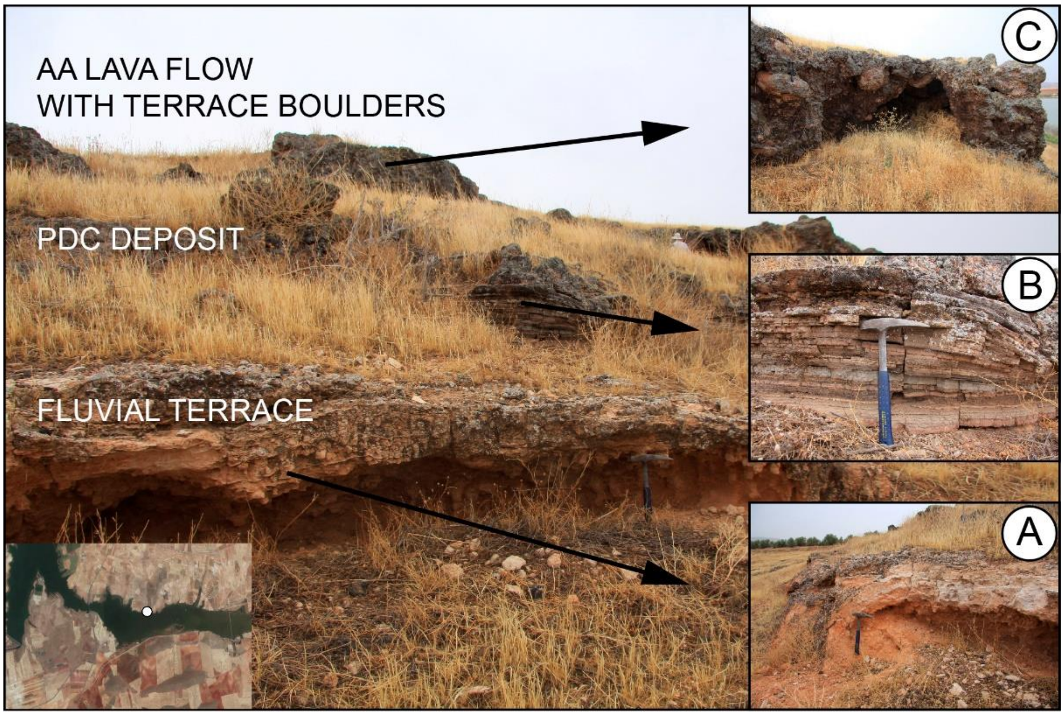

Fig. 4. Volcanostratigraphic succession of the southern slope of Las Cuevas volcano (right bank of the Jabalón River). A. Fluvial deposits with an abundant carbonate matrix. B. Dilute PDC deposit. C. “Aa” lava flow front with abundant fragments of the fluvial terrace and of PDC deposits. The inset aerial photograph shows a sector of the Jabalón River and the location of this observation point

4.2. Columba volcano

The Columba volcano is located on the left bank of the Jabalón River, 2.3 km to the WSW of Las Cuevas volcano and 4.5 km to the SW of the town of

Granátula de Calatrava (Fig. 2). It consists of a pyroclastic cone 100 m high with 1 km of basal diameter, quite symmetrical, crowned by a circular crater of 200 m in diameter. A characteristic feature of the Columba volcano is the abundance of basaltic lava flows of basaltic nature that extend mainly towards the W and N of the cone, covering the fluvial terraces located 15 and 5 m above the Jabalón River. The widest lava flow (up to 250 m wide) comes from the base of the cone and at present it remains uncovered due to the construction of the dam of the Vega del Jabalón in 1992, forming a lava front of up to 30 m that displays spectacular columnar jointing. Two more lava flows with "pahoehoe" morphologies flowed in a north and northeast direction, advancing perpendicular to the Jabalón River, crossing it and obstructing the water flow. Thus, such lava flows acted as natural barriers (a natural dam) that twice repressed the Jabalón River, causing its flooding and forcing the deposition of the materials dragged by runoff water. The first of these lava emissions occurred when the base level of the Jabalón River was located at 15 m higher, since it is stratigraphically correlated with the fluvial terrace level located at that height. The age of this terrace obtained by OSL of the quartz sands is of 33.9 ± 2.36 ka, which allows dating the beginning of the eruptive activity of the Columba volcano in the Upper Pleistocene. The second of the lava emissions descended towards the N and E and crossed the river valley when its bed was located 5 m above the current position, damming the water flow and forcing the deposition of fluvial sediments 9 m above it. Nowadays, only one meter of lava is exposed, since the rest is covered by the Vega del Jabalón reservoir water. This lava flow is characterized by a marked spheroidal disjunction and covered by the fluvio-lacustrine terrace level (Fig. 5). This fluvio-lacustrine deposit has a thickness of 2 meters and is composed of two levels: a lower one, composed of 1 m thick small ridges and rounded gravels of quartzite and basalt, and an upper one mainly constituted of clays and silts, together with some volcanic bombs. The OSL dating of the quartz sands of the lower level provide an age of 6,271 ± 428 yr BP (Table 1).

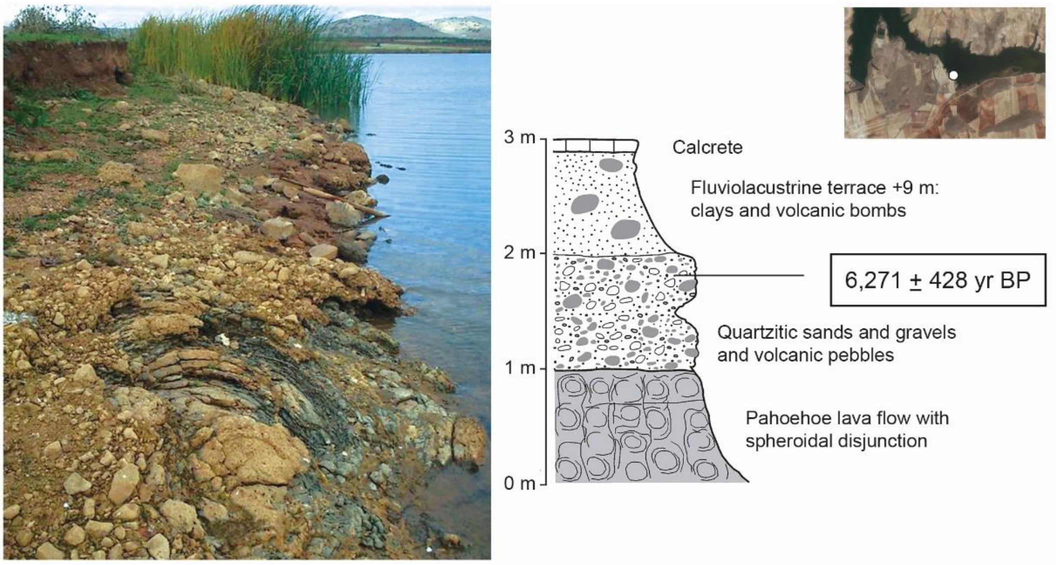

Fig. 5. The pahoehoe lava flow of the Columba volcano (left margin of Jabalón River) covered by the fluviolacustrine terrace of the Jabalón River. The inset aerial photograph shows a sector of the Jabalón River and the location of this observation point.

Laboratory ref.	Landform/deposit	Material	Tecnique	Age	
				C^{14} BP	Cal^{2} BP 2σ
Poz-52166	Paleosol (Columba)	Organic material	AMS	11980±110	14113-13577
Poz-52167	Paleosol (Columba)	Organic material	AMS	11950±90	14031-13580
Poz-56641	Paleosol (Columba)	Organic material	AMS	15290±220	18902-17980
Poz-56642	Paleosol (Columba)	Organic material	AMS	20090±320	24912-23281

UA-24799[1]	Paleosol (Columba)	Charcoal/humus	AMS	6560±130	5724-5297
UA-33366[1]	Plant molds (Columba)	Charcoal	AMS	6590±200	5900-5202
MAD-6210BIN	T+9 m (Jabalón)	Sands	OSL	6271±428	
MAD-6205rBIN	T+15 m (Jabalón)	Sands	OSL	33952±2367	
MAD-6314rBIN	T+20 m (Jabalón)	Sands	OSL	75082±5177	
MAD-6313rBIN	T+20 m (Jabalón)	Sands	OSL	75241±4803	

1. González et al. 2007. 2. Calibration was made with the software OxCal v4.1.7 (Ramsey, 2010).

Table 1. Summary of radiocarbon and OSL ages obtained from the Columba and Las Cuevas volcanoes.

Another relevant aspect to understand the eruptive behavior and the geomorphological evolution of the Columba volcano is the presence of a paleosoil observable at the southern base of the cone 400 m from the crater, which is interbedded with the succession of its deposits (Fig. 6). From base to top, this is composed of a) a lava flow of “aa” morphology whose thickness oscillates between 0.5 m and 5 m; b) a 40 cm thick, light brown color paleosoil, with a polyhedral structure, developed in a scoria lapilli fallout deposit formed on top of the lava flow; c) a dry, dilute PDC deposit of 4 m thick, with marked horizontal bedding, overlying the paleosoil; and d) a massive deposit containing a large amount of spheroidal bombs and scoria in an abundant clay-like matrix. This last deposit was interpreted as a lahar deposit (González et al., 2007, 2010a) but it resembles more the basaltic ignimbrites described by Martí et al. (2017) for the La Garrotxa volcanic field, as it shares with them similar lithological and sedimentological characteristics, including an abundant ash matrix, internally massive structure, a basal planar contact, and the presence of a thin ash rich layer at the base.

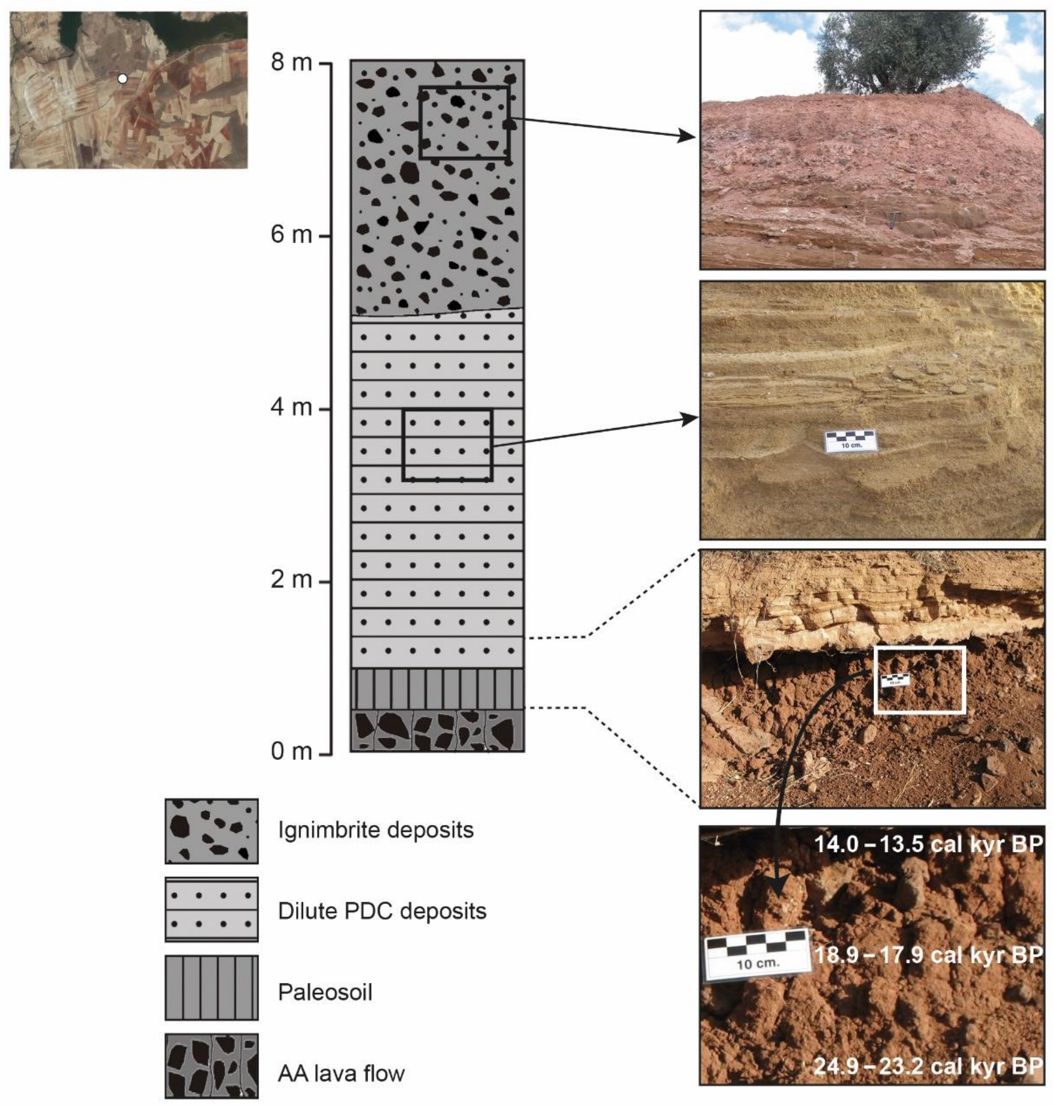

Fig. 6. Succession of deposits from the trench located at km 16+50 m on the road CM-413 from Aldea del Rey to Granátula de Calatrava (southern side of the base of the Columba cone). The inset aerial photograph shows a sector of the Jabalón River and the location of this observation point.

The paleosoil is rich in organic matter and molds of small herbaceous plants. This allowed obtaining four radiocarbon dates from different depths in the deposit that provided ages between 24.9–23.2 ka, 18.9–17.9 ka and finally 14.0–13.5 ka.

4.3. Geomorphological mapping

The new field data presented above were used to revise and update the geomorphological map of the study area elaborated by Poblete and Ruiz (2002), which covers a wider area that the one occupied by the Columba and Las Cuevas volcanoes, so we extended our field mapping to cover the full area. We used 40 symbols to distinguish the different stratigraphic units, and geomorphological and structural features (Fig. 7). A total of 6 volcanic edifices were mapped: the cinder cones of Columba, Las Cuevas, La Cornudilla, and Cabezuelos, and the maars of Añavete and Hoya de los Muertos.

The maar of the Hoya de los Muertos is the oldest volcano in the study area, formed in the Pliocene following a phreatomagmatic explosion and later subsidence of the diatreme that produced the periclinal and convergent tilting of the Ruscinian limestones of the border of the depression (Poblete and Ruiz, 2002). At 1 km to the SSE of this maar, the Cabezuelo volcano (Fig. 7) adopts the shape of a small cinder cone of 694 m a.s.l. crowned by a rather short lava flow that emplaced towards the north. The age of the Cabezuelo volcano according to K/Ar dating is around 2.8 Ma (Ancochea, 1983).

For the cinder cone of the Cornudilla (Fig. 7), we can only see the extensive, very fluid lava flow that, after being channeled through the bottom of the valley of the Cañada Honda, opens up in the form of a fan or lava delta upon reaching the Jabalón valley. In fact, it is a wide “pahoehoe” lava under whose base lies a detritic or accumulation glacis hanging above 30–40 m with respect to the Jabalón River bed; we therefore estimate that its age may correspond to the Middle-Upper Pleistocene (Fig. 7).

The maar of Añavete, located 2 km SW of Granátula de Calatrava, is a depression or hollow with a half-moon shape surrounded by a tuff-ring, not showing any evidence of volcanotectonic subsidence, as it occurs with others that are typical of Pliocene maars. It is probable then, that this phreatomagmatic eruption occurred during the Quaternary, although we cannot estimate the age due to the lack of good volcanostratigraphic profiles.

Finally, the Columba and Las Cuevas volcanoes, located on both banks of the Jabalón River, interfere with some of the seven levels of fluvial terraces on the map. Specifically, on the geomorphological map we see that the lava flows which moved towards the northwest were emitted from the base of the Columba cone and covered the levels of terraces located above 15 and 5–6 m of the current river bed, while those emitted from the crater descended the slope of the cone and crossed the river channel perpendicularly, blocking the water flow and thus damming it. Also on the map we observe that Las Cuevas volcano is built on a fluvial terrace located at 20 m above the bed of the Jabalón River.

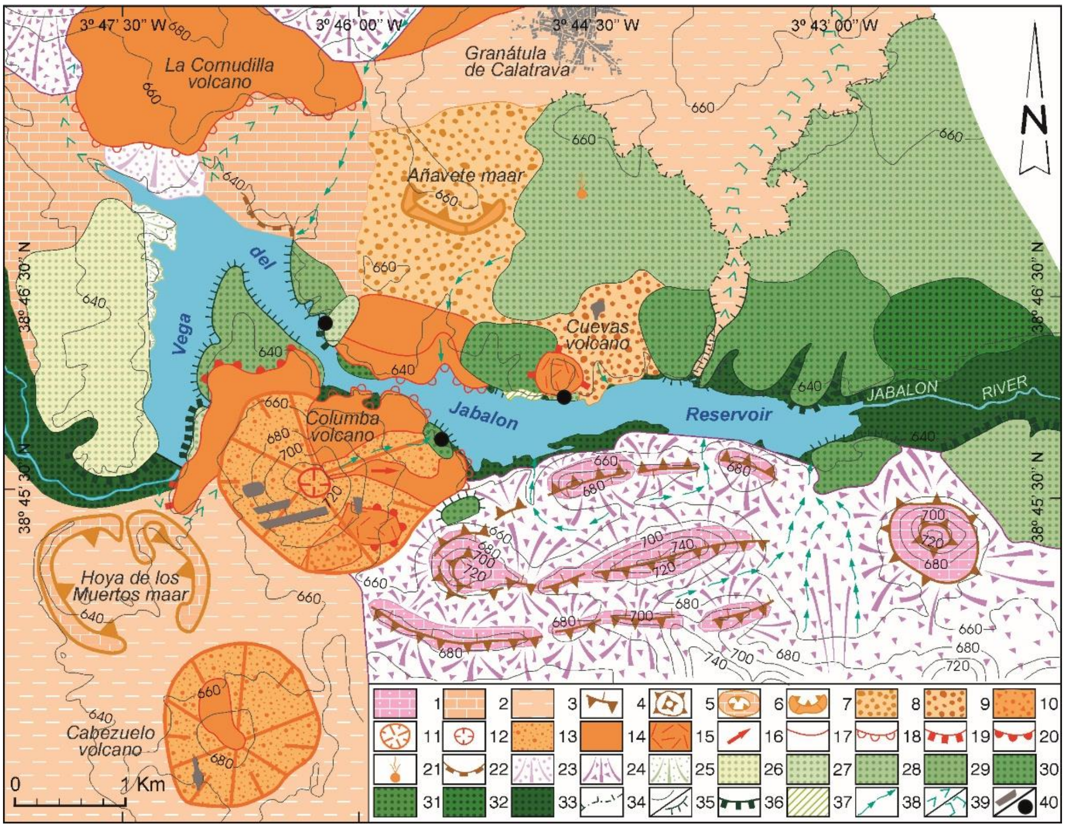

Figure 7. Geomorphological map of the study area. 1. Armorican quartzites. 2. Limestones of the Pliocene. 3. Marls of the Pliocene. 4. Pseudo-Appalachian crest. 5. Upstanding syncline. 6. Maar with volcanotectonic subsidence. 7. Maar with ring. 8. Dilute pyroclastic surge deposits. 9. Dense pyroclastic surge deposits. 10. Ignimbrite deposits. 11. Cone. 12. Crater. 13. Pyroclastic fall deposits. 14. Pahoehoe lava flow. 15. Aa lava flow. 16. Lava flow trend. 17. Very gentle lava flow front. 18. Gentle lava flow front. 19. Abrupt lava flow front. 20. Very abrupt lava flow front. 21. Extinct pseudogeyser. 22. Cornice. 23. Accumulation glacis. 24. Colluvial glacis. 25. Sheet-flood glacis. 26. +30–40 m. 27. +15 m fluvial terrace. 28. +20 m fluviolacustrine terrace. 29. +5–6 m fluvial terrace. 30. +9 m fluviolacustrine terrace. 31. +5 m fluvial terrace. 32. Level of fluvial accumulation. 33. Alluvial valley floor. 34. Dismantled terrace edge. 35. Gentle and steep terrace edge. 36. Abrupt terrace edge. 37. Lacustrine calcretes. 38. Gullies. 39. V-shaped valley and flat-

floored valley. 40. Opencast pit and sampling sites for dating (modified after Poblete et al., 2014).

5. Discussion

We focus the discussion on three main aspects of the volcanism studied in this work: the evolution of the eruptive activity in the volcanoes Columba and Las Cuevas, the occurrence of the Jabalón River damping episodes, and the age of this volcanism.

The construction of the cinder cone of Las Cuevas begins with an explosive Strombolian phase that only generated pyroclastic materials, which accumulated close to the vent forming a cone-shaped, small volcanic edifice (Fig. 8.1). This Strombolian phase was followed by a brief period of rest during which the Jabalón River deposited a terrace level 20 m above the current river bed on one side of the cone. Subsequently, the eruptive activity resumed with a phreatomagmatic explosive phase probably caused by the presence of water in the alluvium of the river. This explosion generated a dilute PDC that expanded radially from the vent, forming a deposit with the classical characteristics of the dry pyroclastic surge type deposits (e.g., Fisher and Schmincke, 1984; Cas and Wright, 1987; Németh, 2010). Although the fluvial terrace is located at 20 m above the current Jabalón's channel, it should be noted that its upper part was partially dismantled by the multiple and periodic explosions linked to the phreatomagmatic phase. So it is logical to think that its thickness was originally greater. Finally, the fact that the dry PDC deposit is covered by a 4 m thick lava flow that contains lithic fragments from the cemented fluvial terrace and the PDC deposit, it indicates that the eruptive activity returned to magmatic after the highly explosive phreatomagmatic episode. If we take into account that the fluvial terrace has an age of around 75 ka and that it was deposited at the end of the initial Strombolian phase and was later covered by the dry PDC deposit, it follows that the Strombolian phase has an age older than that of the fluvial terrace. Accordingly, the phreatomagmatic episode and the subsequent emplacement of the lava flow occurred after the deposition of the fluvial terrace, so younger than this OSL age, which represents a certain interruption in the eruptive activity of the Las Cuevas volcano (Fig. 8).

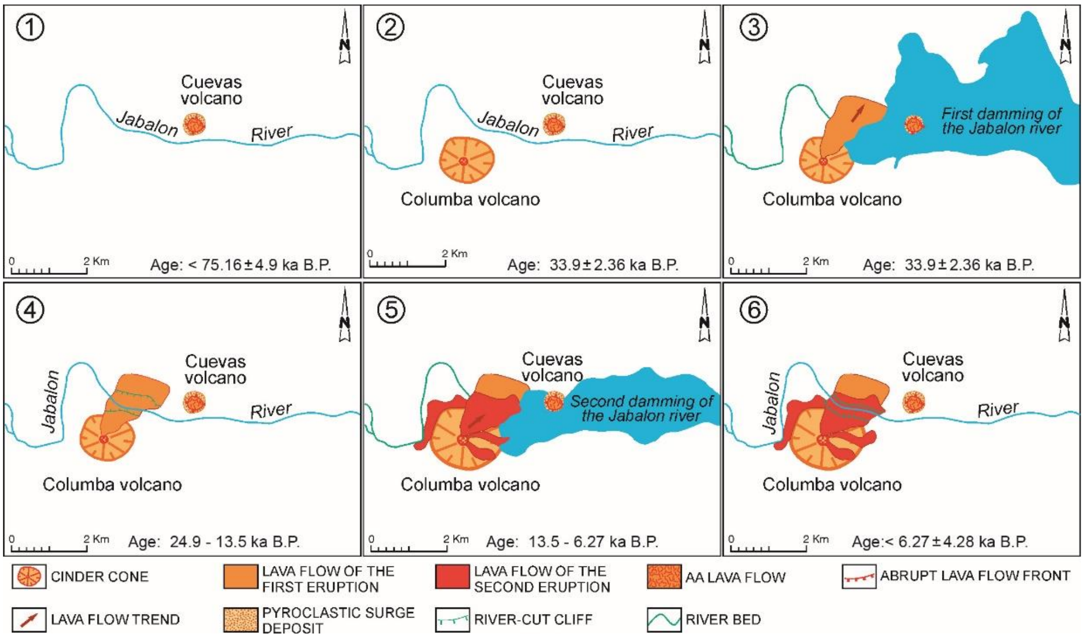

Fig. 8. Geomorphological and hydrodynamic evolution of the mid sector of the Jabalón River (see main text for explanation)

With regard to the Columba volcano, the obtained results suggest that it had prolonged volcanic activity that began around 33.9 ± 2.36 ka, with a Strombolian dynamism that generated the construction of the cone mainly by accumulation of scoria lapilli (Fig. 8.2) and a wide lava flow from the base of the cone that blocked the Jabalón River (Figs. 3 and 8.3). This allowed the formation of the fluvial terrace that was placed 15 m above the current river channel. This first episode was followed by a long period of rest (Fig. 8.4) in which a paleosoil developed on the Strombolian deposits and the lava flow from 24.9–23.2 ka to 14–13.5 ka, which indicates that the edaphogenesis of the paleosoil took place after a long period of inactivity or rest that lasted for about 10,000 years. Subsequently, eruptive activity reactivated with a brief phreatomagmatic phase followed by a second Strombolian phase that emitted lava flows from the crater, which also blocked the Jabalón River again giving rise to the formation of the fluvio-lacustrine terrace 9 m above the current river channel at about 6,271 ± 428 yr BP (Fig. 8.5).

Therefore, the Columba and Las Cuevas volcanoes (Fig. 8.6), despite their modest dimensions and morphological simplicity, are polycyclic edifices that originated from several eruptive phases separated by non-eruptive episodes. These edifices were constructed during two to three eruptive cycles each one separated by sufficient time to allow dyke solidification, thus freezing the plumbing system. This generated two (or three) overlapping volcano, that has happened to erupt exactly in the same place. This contrasts with the general pattern followed by the other monogenetic volcanoes of the CCVF that include continued eruption phases in their construction, or having the characteristic of volcanism in the neighboring CVZ where all volcanoes are monogenetic in a strict sense (Martí et al., 2011). However, this behavior is not rare in other monogenetic volcanic fields where similar episodic construction of volcanic edifices has also been observed (e.g., Vespermann and Schmincke, 2000; Schmincke, 2004; Brand and Clarke, 2009; De Benedetti et al., 2009; Németh, 2010; Kereszturi et al., 2010; Brenna et al., 2015), and still form part of the monogenetic volcanism sensu lato (see Smith and Németh 2017), and should not be confused with polygenetic volcanism responsible for composite volcanoes.

There are numerous vestiges of lava damming giving rise to the formation upstream of small lakes and the deposition of fluvial or fluvio-lacustrine terraces (e.g., Hamblin, 1990; Dalrymple and Hamblin, 1998; Veldkamp et al., 2012; Gorp et al., 2013). Although the Columba volcano is a Strombolian edifice of small dimensions, the lava flows emitted from this volcano twice had the ability to cross the valley of the Jabalón River, damming its waters and originating the fluvial and fluvio-lacustrine terraces. Indeed, the Jabalón valley, as it passes through the Columba volcano, undergoes a remarkable narrowing from a shallow wide plain to a more fitted morphology as a small gulley, in which there is evidence at least, of two pahoehoe lava flows dissected at 20 and 9 m, respectively, above the current base level. At present it is difficult to appreciate these morphological features, since the construction of the reservoir of the Vega del Jabalón has flooded a wide extension of the valley, hiding in part such morphological peculiarities. However, in the old photograph taken by Hernández-Pacheco (1932) in the same sector, the forms and geomorphological characteristics mentioned above can be clearly seen (Fig. 9). The first lava dam of the Jabalón River occurred when its base level was located 15 m higher, thus causing the obstruction of the water current, the temporary increase in the level of the river bed, and the formation of a small lagoon as a result of damming the waters (Fig. 10). It is evident, therefore, that the lava flow hanging at 20 m above the Jabalón River correlates stratigraphically with the fluvial terrace located 15 m high, located on the right bank downstream of the bridge, and whose OSL dating gives an age of 33.9 ± 2.36 ka to which the first lava dam is chronologically attributable. Upstream of the lava dam a temporary increase of the base level up to 20 m occurred, thus forcing the deposition of fluvial sediments and generating an extensive level of fluvio-lacustrine terrace. Later, once the waters overflowed and exceeded the height of the lava dam, water runoff was resumed with a morphogenetic phase of incision that progressively accentuated and fitted over the lava flow until finally carving a small gully.

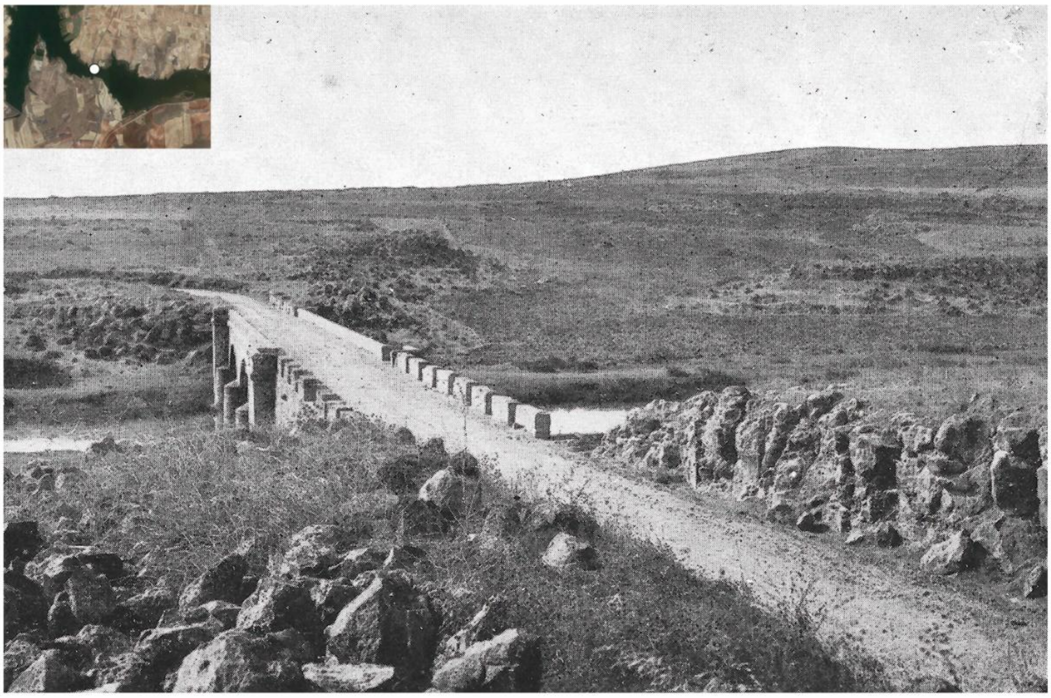

Fig. 9. The Columba crater is observed at the right side of the background, while at the foreground it is observed the lava flow located 20 m above the current base level, cut by the Jabalón River, thus forming a small throat. It may be observed how the bridge rests on both sections of the same lava flow (Photograph by Hernández-Pacheco, 1932). The inset aerial photograph shows a sector of the Jabalón River and the location of this observation point.

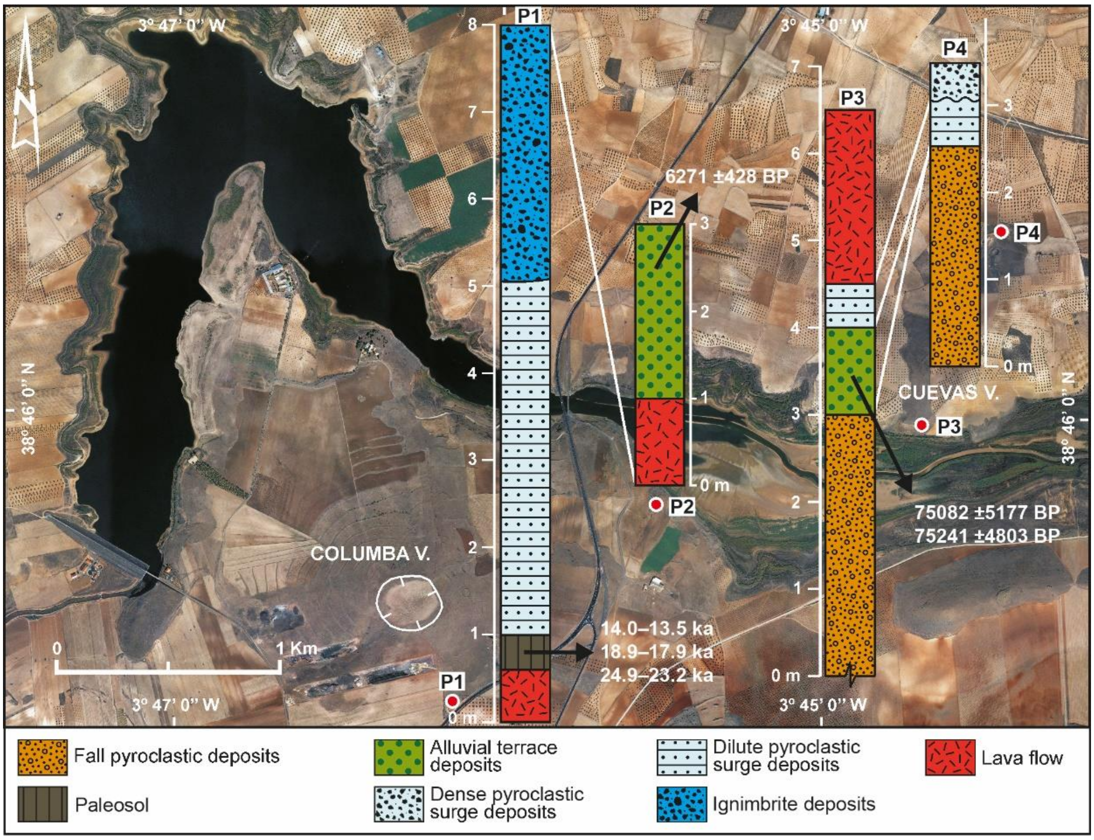

Fig. 10. Stratigraphic successions from Las Cuevas and Columba volcanoes in the mid-sector of the Jabalón River.

The second Jabalón lava dam was produced when the base level of the river was located 5 m higher than now, also clogging the water course, the temporary increase of the base level of the river up to 9 m, and the formation of a new lagoon. Once again, a second phase of forced alluvial flow of the Jabalón River occurred with the deposition of fine sediments and the formation of a fluvio-lacustrine terrace located 9 m high on the left margin of the river, and a level lacustrine carbonates on the right margin near Las Cuevas. The OSL dating of the quartz sands of this deposit provided an age of 6.27 ± 4.28 ka, from which we infer that the second lava deposition and, therefore the end of the eruptive activity of the Columba volcano, occurred earlier. Finally, the overflow of the waters and the reactivation of the water runoff took place again, thus giving rise to a second phase of excavation that formed another small gully. A long period of volcanic inactivity took place between the first and second lava damming of the Jabalón River, during which the volcanic paleosoil located on the southern slope of the Columba cone originated.

In summary, the interference of the Columba volcano on the Jabalón River has contributed to significantly increase the fluvio-lacustrine behavior of its hydrodynamics (already affected by a very steady rainfall regime), with forced sedimentation, and giving rise to the chronological inversion of the levels of fluvial terraces. This resulted in that the terraces appearing at higher altitudes (upstream of the lava dams) have a more recent chronology than the fluvial terraces suspended at a lower height downstream. Therefore, the fluvio-lacustrine terraces at 20 and 9 m above the current river’s course are not equilibrium terraces that derive from oscillations under climatic or tectonic conditions, but rather respond exclusively to local changes in the base level that are represented by erosion and aggradation pulses.

Previous K-Ar dates (Ancochea and Giuliani, 1979; Ancochea, 1983) and magnetostratigraphic analyses (Gallardo et al., 2002) suggested that the most recent eruptive activity in CCVF occurred between 1.5 Ma and 0.7 Ma. However, the new data presented here, based on volcano-stratigraphic correlations and geomorphological evidence described above, as well as the new OSL and C14 ages, reveal that the volcanic activity in CCVF has lasted until much more recent, until the early Holocene (Table 2). This agrees with the most recent ages of volcanism in other volcanic provinces of the southern sector of the European Rift System (Bolós et al., 2014; Négrel et al., 2015). According to the data presented in this study, the apparent lack of agreement between the previous ages and the new ones is due to the fact the previous stratigraphy was incomplete, so probably the rocks dated were not the most representative to infer the complete age span of the volcanism in the study area.

NAME	LOCATION	HEIGHT	VOLCANO TYPE	DATING TECNIQUES		AGE
				ABSOLUTE	**RELATIVE**	
Columba	38º45'30.3" N 03º46'11.7"W	736 m	Strombolian	OSL, AMS	GE and VS (the lava flows fossilize the terrace levels + 15 and y 5-6 m and reverse the upstream terrace levels	Second erupt.= 14-13.5 cal ka BP and 6.27±0.428 ka BP[1] Paleosol=24.9-13.5 cal ka BP[1] First erupt.= 33.9±2.5 ka BP[1]
Cuelgaperros	38º55'28.2" N 03º59'15.2"W	659 m	Maar	OSL	GE and VS (the rim fossilizes the terrace level + 15 m of the river Jabalón)	34.2±2.2 ka BP[2] 35.05±2.8 ka BP[2]
Las Cuevas	38º46'03.9" N 03º44'42.6"W	671 m	Strombolian	OSL	GE and VS (fosiliza T + 20 m del Jabalón)	75.08±5.17 ka BP[1] 75.24±4.8 ka BP[1]
Espejuelos-Bernejil	38º55'28.2" N 03º59'15.2"W	644 m	Bruched maars	MS	----------------------------------	700,000 yrs BP[3]
Cornudilla	38º48'37.1" N 03º47'04.3"W	775 m	Strombolian	--------	GE and VS (the delta lava flow fossilizes accumulation glacis)	*Post quem* Lower Pleistocene[4]
Atalaya I	38º38'51.8" N 03º48'00.5"W	1,118 m	Exogenous domo	K-Ar	GE and VS (the lava flow forms an interfluve through incisión of ravines)	1.750.000 yrs BP[5]
Atalaya II	38º38'32.9" N 03º47'47.7"W	1,070 m	Exogenous domo	K-Ar	----------------------------------	1.750.000 yrs BP[5]

Cabezuelo	38º44’18.3” N 03º46’48.9”W	674 m	Strombolian	K-Ar	----------------------------------	2,800,000 yrs BP[5]
Hoya de los Muertos	38º44’59.5” N 03º47’41.3”W	642 m	Maar with diatreme subsidence	--------	GE and VS (the bottom is filled with upper pliocene sediments)	Lower Pliocene[4]

1. Present study. 2. Poblete et al. 2016. 3. Gallardo et al., 2002. 4. Poblete and Ruiz, 2002. 5. Ancochea, 1983. GE= Geomorphological evidences. VS= Volcanostratigraphical sequence. MS= Magnetostratigraphy.

Table 2. Summary of the chronology of eruptive activity of volcanoes of the study area and near.

6. Conclusions

The geomorphological and volcanostratigraphic analyses of the Columba and Las Cuevas volcanoes indicate that the chronology of their eruptive activity is much more recent (Upper Pleistocene and beginning of the Holocene) than the ages initially assumed for the volcanism of the CCVF. In both cases, Columba and Las Cuevas, their eruptive sequence shows the presence of phreatomagmatic episodes between Strombolian ones, which reflect the influence of substrate (i.e., presence of shallow aquifers) on their eruption dynamics. Moreover, we have been able to verify the complex interaction between these volcanoes—particularly the Columba volcano—with the Jabalón River, which was dammed several times with the emplacement of lava flows into its channel, thus causing the chronological inversion of the terraces upstream. This corroborates the usefulness of the study of interactions between volcanic activity and modelling dynamics—in this case fluvial processes—for determining the evolution of the eruptive activity, its morphological results, and the relative chronologies. Finally, it was possible to identify the polycyclic character of the Columba volcano, which clearly originated as a consequence of two time-separated eruptions, a still poorly known behavior in monogenetic volcanism. The first one took place around 33.9 ± 2.36 ka ago and the second, after a period of inactivity of more than 20,000 years, at around 14–13.5 ka.

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Geomorphological evolution and chronology of the eruptive activity of the Columba and Cuevas volcanoes (Campo de Calatrava Volcanic Field, Ciudad Real, Central Spain)

Highlights

The volcanism of Calatrava is more recent than previously thought.
Columba is a clear example of polycyclic volcano in a monogenetic volcanic field.
The second eruption of the Columba volcano occurred between 14 and 6.2 ka ago.
The Jabalón River was dammed several times with the emplacement of lava flows.
The damming of the river caused the chronological inversion of the terraces upstream.