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Miocene lamproite volcanoes in south-eastern Spain—an association of phreatomagmatic and magmatic products

Ioan Seghedi [a,*], Alexandru Szakács [a], Alfredo Hernandez Pacheco [b], Jose-Luis Brändle Matesanz [b]

[a] *Institute of Geodynamics, Romanian Academy, 19-21, str. Jean-Luis Calderon, Bucharest 70201, Romania*
[b] *Dpto. Petrologia y Geoquimica, Fac. Ciencias Geologicas, Instituto de Geologia Economica (CSIC-UCM) 28040 Madrid, Spain*

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Abstract

A series of small Miocene (8.3–6.7 Ma) lamproite rock occurrences (as monogenetic volcanoes and/or dykes) cover a large area in southeastern Spain. These rocks are associated with extensional basins filled by Neogene deposits in the Betic and Subbetic structural units. At Cancarix (Sierra de las Cabras), Calasparra, Barqueros, Cerro de Monagrillo, Jumilla, and Vera, eruptions occurred, whereas at Fortuna, Mula and Zeneta there were only small-scale intrusions (mainly dykes). This paper describes volcanic centers at Cancarix, Calasparra and Barqueros, which show initial phreatomagmatic eruptions driven by interaction of rising lamproite magma with groundwater. Tuff ring formed during this volcanic activity. Subsequent activity consisted of dome extrusion in the vent areas of Cancarix and Calasparra and by explosive to effusive magmatic activity accompanied by extensive lava flows at Barqueros.

Calasparra and Cancarix are relatively symmetric monogenetic tuff rings filled by late stage massive vertical plug, extruded as degassed crystalline high-viscosity magma along the volcanic conduit. Barqueros was initially a tuff ring, whose late stage Hawaiian-style fountaining generated spatter and clastogenic lavas that built the intra-tuff ring cone of Cabezo del Morron. Finally, extensive lava flows spread from the base of the cone toward the northern part of the edifice. Variations in the tectonic (extensional regime) and local hydrogeologic conditions (shallow aquifers) influenced the occurrence of these lamproite volcanoes. Late stage magma rise was dependent on the magmatic volatile regime, being already degassed at Calasparra and Cancarix, by showing higher viscosity (high crystallization rate) of intra-tuff ring dome extrusions, or still rich in volatiles at Barqueros, displaying lower viscosity lava fountaining and then lava flows.

Keywords: explosive volcanism; magmatic; phreatomagmatic; lamproite; tuff ring; Southeastern Spain

1. Introduction

More than 10 remnants of shallow intrusions and volcanic edifices, of lamproite composition are outcrop over a large area in southeastern Spain, mostly in the province of Murcia (Fig. 1). Volcanism occurred during Tortonian–Messinian time (8.3–6.7 Ma; Montenat et al., 1975; Nobel et al., 1981; Bellon et al., 1983; Turner et al., 1999; Duggen et al., 2005). The distribution of lamproite rocks is spatially associated with extensional basins (specifically along basin margins) that are filled by Neogene

* Corresponding author.
E-mail address: seghedi@geodin.ro (I. Seghedi).

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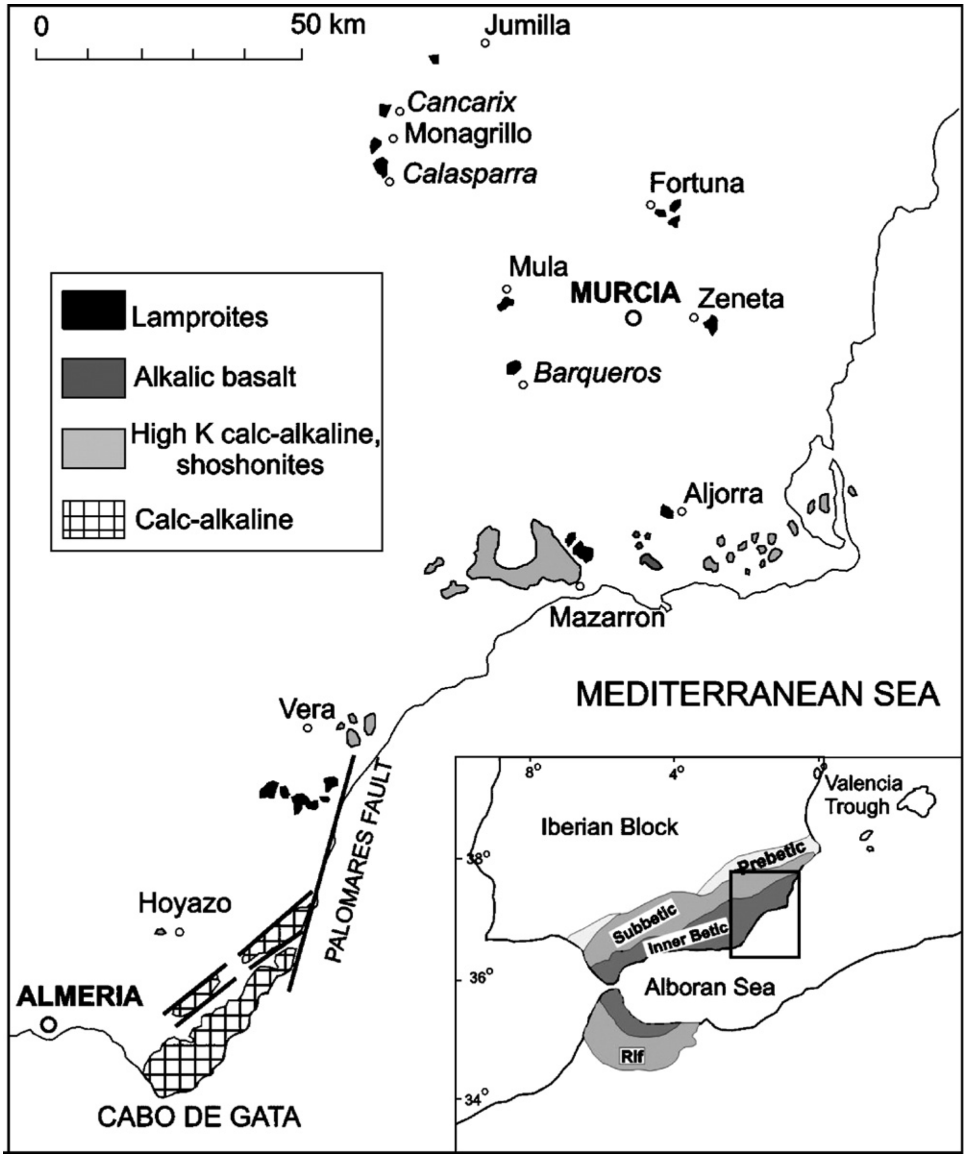


Fig. 1. Distribution of lamproite rock occurrences in the context of Miocene volcanism in south-eastern Spain. The inset shows the Prebetic, Subbetic, Rif and Inner Betic Alpine structural units.

continental-marine sediments in the Betic and Subbetic structural units (Fúster, 1956; Fúster et al., 1967; Fernandez and Hernandez-Pacheco, 1972; Montenat et al., 1975). They occur at Jumilla, Cancarix, Cerro del Monagrillo, Calasparra, Fortuna, Mula, Barqueros and Zeneta (Fig. 1). In the southernmost part, at Vera, Mazarron and Aljorra, high-K and shoshonitic rocks overlap with the lamproite rocks (Fúster et al., 1967; Pellicer, 1973; Lopez-Ruiz and Rodriguez-Badiola, 1980; Venturelli et al., 1988). To date mostly intrusive lamproite rock occurrences have been described: specifically necks, plug-like intrusions, or dyke swarms (Fúster et al., 1967). Breccias and contact metamorphic minerals are reported around the plugs and necks (Fúster et al., 1967). Effusive lamproite rocks forming remnants of lava flows have been described from Cancarix, Cerro de Monagrillo, Vera (Fúster et al., 1967), whereas only Barquerros was recognized as a volcano (Fúster and Gastesi, 1965). In this study we report volcanological field observations and interpret the complex magmatic evolution of three eroded lamproite volcanoes: Cancarix, Calsparra and Barquerros. In this paper we suggest that the hydrovolcanic eruption that generated the tuff ring edifice of studied volcanoes have been of phreatomagmatic type, driven by interaction of rising lamproite magma with

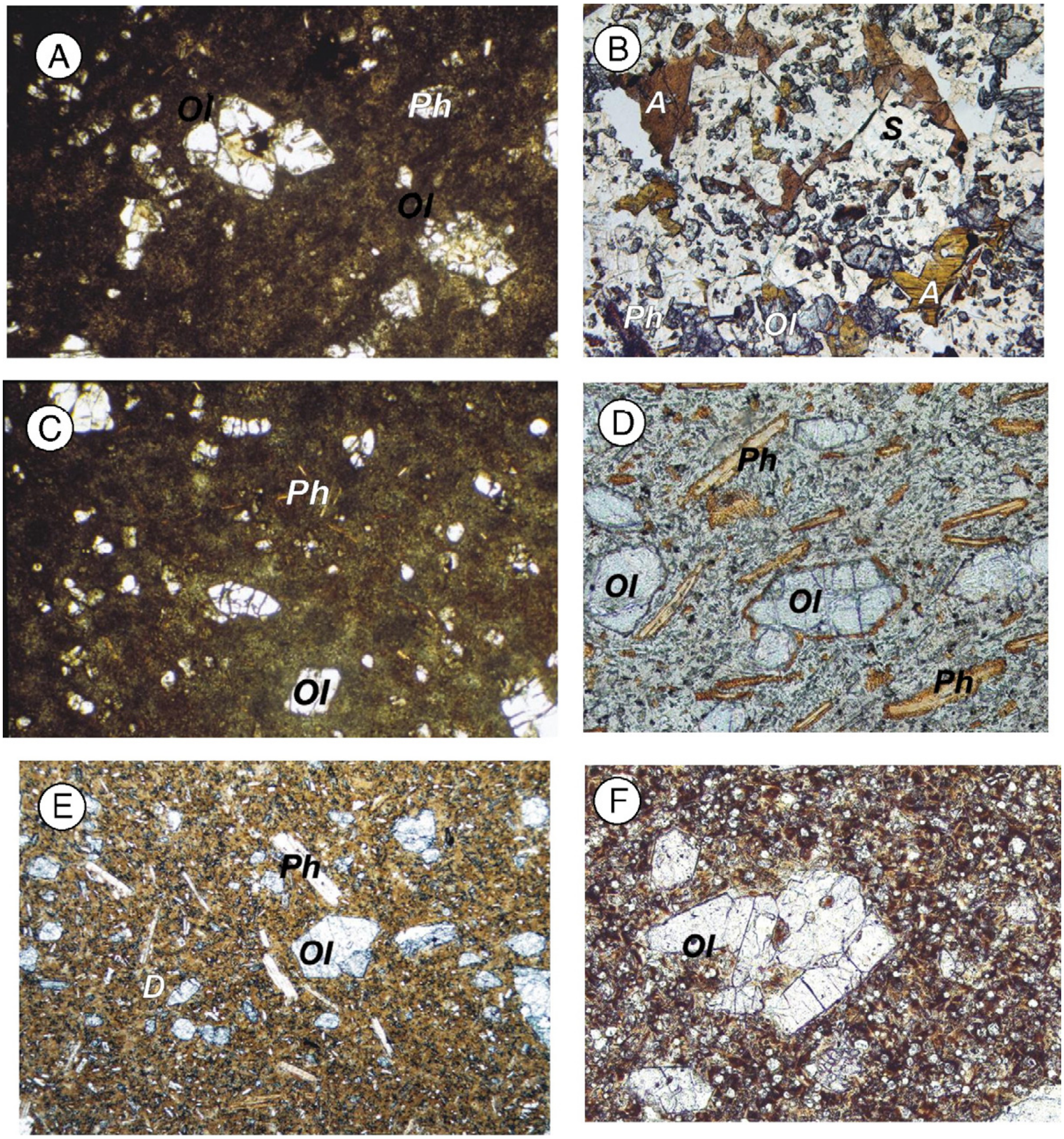


Plate I. Fig. A: Porphyritic lava flow (sample 106005-DP-Cancarix) showing Olivine (Ol) and phlogopite (Ph) phenocrysts in a brown vitreous glass. (NP), Field of view 1.5 cm. Fig. B: Central dome holocrystalline lamproite (sample 10881-ILM-Cancarix) showing subhedral olivine (Ol), phlogopite (Ph) and amphibole (A) embedded in poiquilític sanidine (S). (NP), Field of view 2.5 cm. Fig. C: Porphyritic lava fragment (sample 106004-DP-Calasparra.) showing phenocrysts of olivine (Ol) and phlogopite in a brown vitreous glass. (NP), Field of view 1.5 cm. Fig. D: Central plug porphyritic lamproite (sample 10699-IL-Calasparra.) showing phenocrysts of olivine (Ol) and phlogopite (Ph) in a microcrystalline groundmass and flow banding (NP), Field of view 2 cm. Fig E: Porphyritic lava flow (sample 11334-ILM-Barqueros) from the southern part of volcano, showing phenocrysts of olivine (Ol) and phlogopite (Ph) in a brown vitreous glass with diopside (D) as microcrysts (NP), Field of view 1.5 cm. Fig. F: Porphyritic lava flow (sample 11335-ILM-Barqueros), from northern part of volcano, with olivine phenocrysts (Ol) and olivine, clinopyroxene and phlogopite microcrysts in a vitreous glass. (NP), Field of view 1 cm.

groundwater. Hydromagmatic volcanoes (e.g. tuff rings, tuff cones, and maars) are common in subaerial or shallow water environment and are typically monogenetic (Cas and Wright, 1987; Vespermann and Schmincke, 2000). They are produced by explosive interactions of magma with surface water, groundwater, or wet sediment (Wohletz and

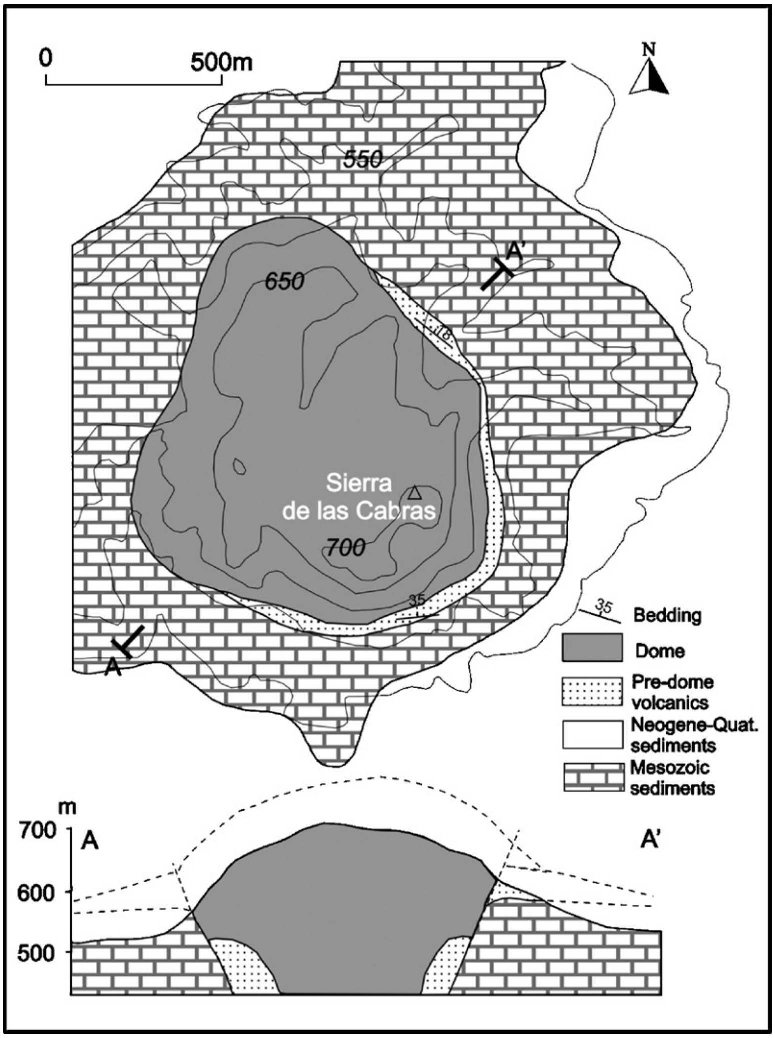


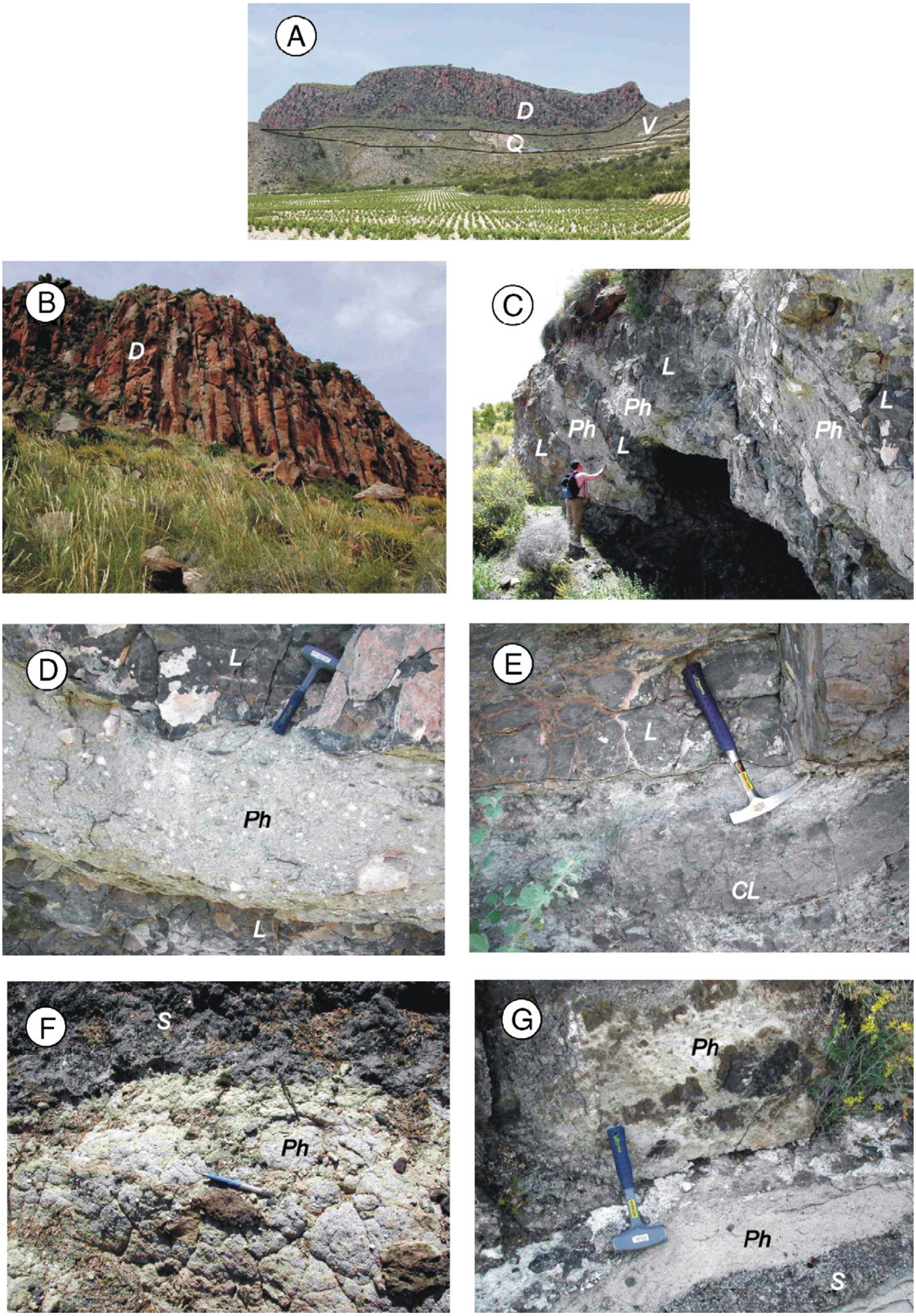
Fig. 2. Geological sketch and cross-section (2× vertical exaggeration) of Cancarix volcanic structure.

Sheridan, 1983; Kokelaar, 1986; White and Houghton, 2000). Tuff rings are typical volcanoes as result of magma/water interaction; they have a crater with small depth-to-width ratio near the ground level are commonly less than 50 m high and are surrounded by low-relief, gently dipping rim deposits (e.g. Vespermann and Schmincke, 2000). On land, the tuff rings result from phreatomagmatic eruptions, via mixing between ascending magma and ground or surface water. Their ring morphology of the tuff rings volcanoes is credited to eruption intensities and depositional processes, which are largely controlled by the modes of interaction between magma and water, amounts and properties of these interacting fluids, lithology and mechanical properties of conduit wall rocks, and vent geometry (Kokelaar, 1986; Sohn, 1996; White, 1996; White and Houghton, 2000). Mitchell and Bergman (1991), based from the study of large number of lamproite fields suggest a general model of the eruptive style of lamproite volcanism, which imply three major episodes: (1) crater formation and vent clearing; (2) pyroclastic sequence formation surrounding the vent; (3) eruption of lava, as lava lakes and/or hypabyssal rocks in the throat of the vent.

Field description of volcanic sequences according to grain-size, bedding and composition of the rock units follows the terminology defined by Fisher and Schmincke (1984), and forms the basis of later genetic facies interpretation.

2. Petrography

The term lamproite was initially used by Niggli (1923) to identify high K and Mg rocks and it is recommended presently by IUGS (Le Maitre et al., 1989; Mitchell and Bergman, 1991; Woolley et al., 1996),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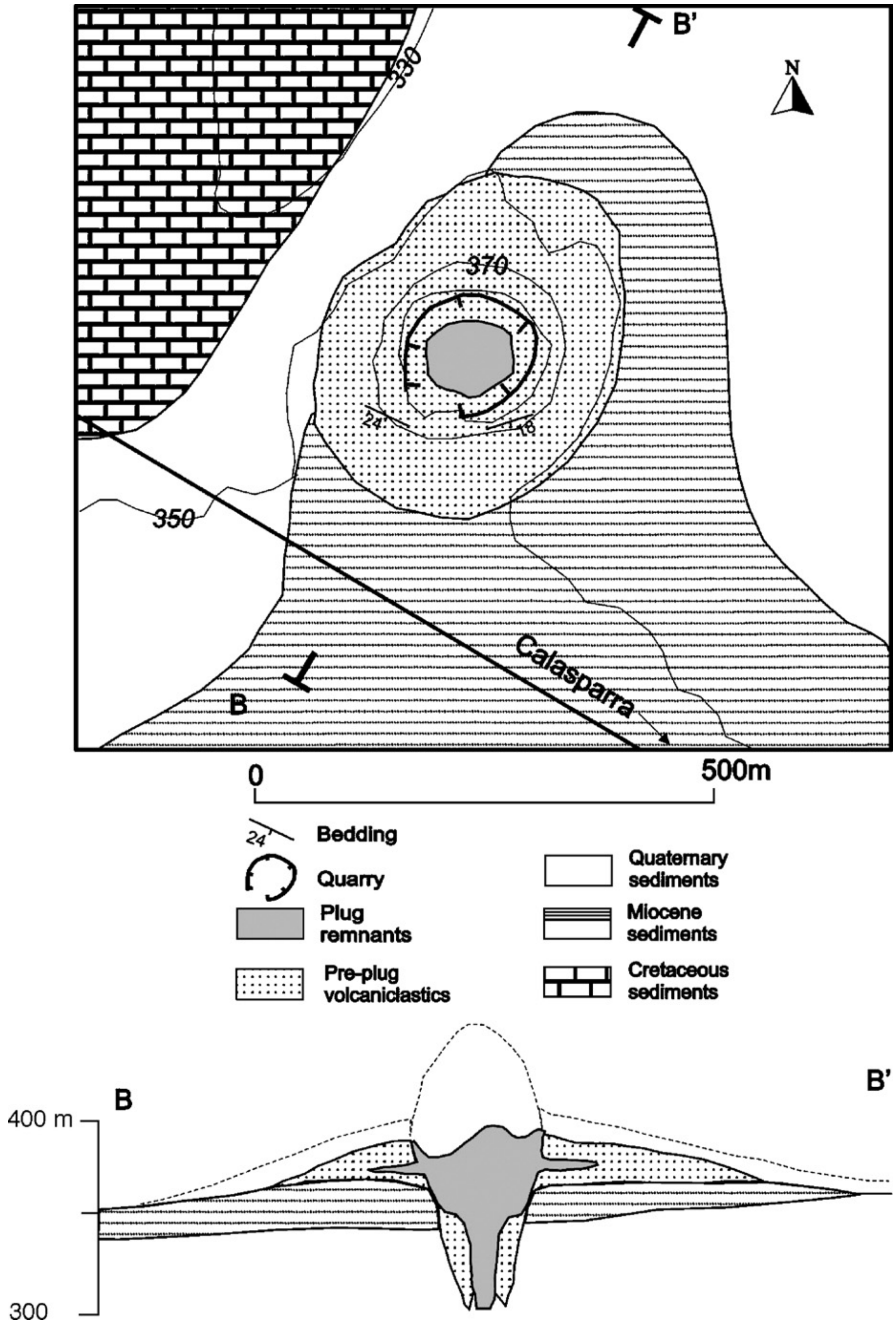
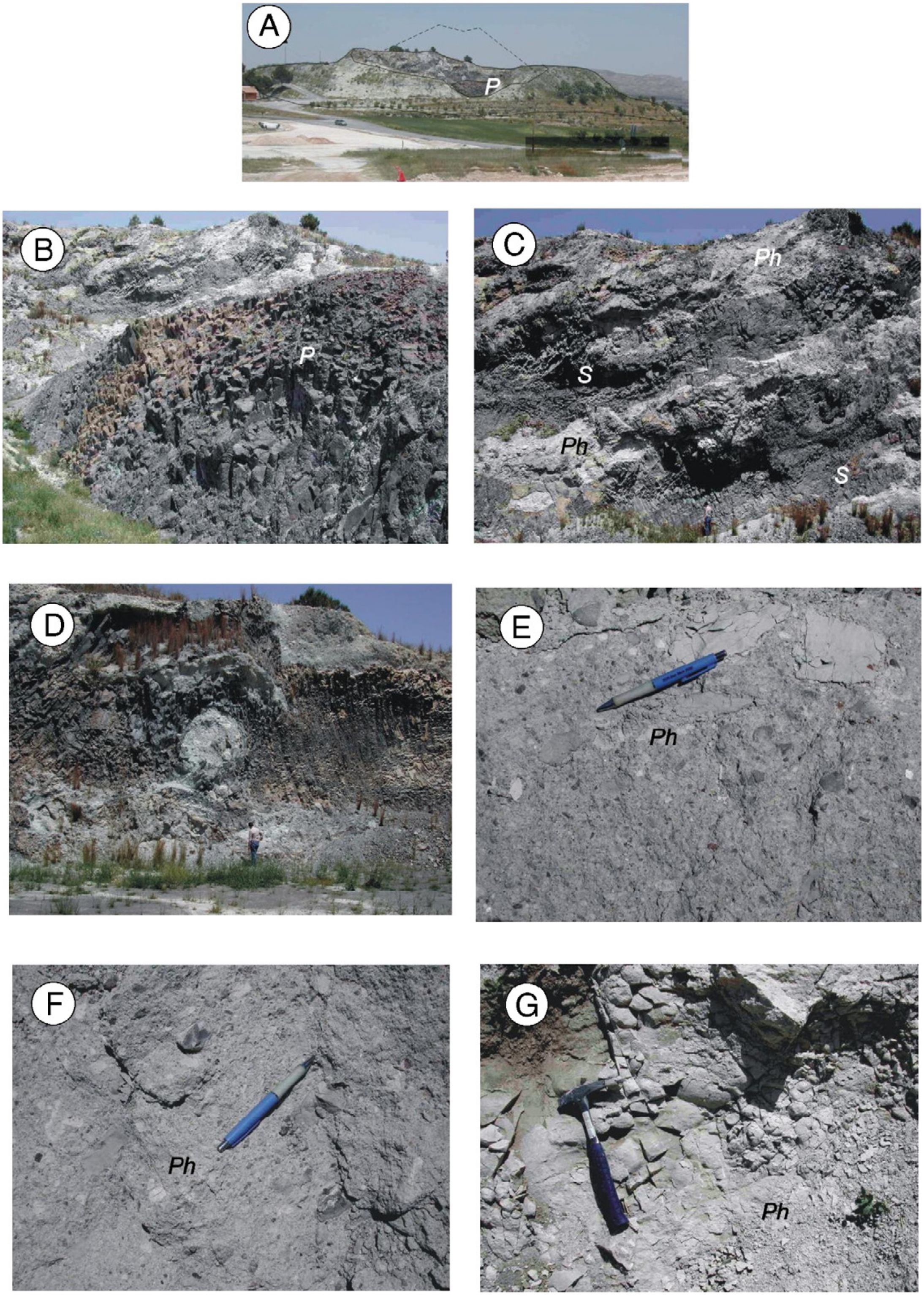


Fig. 3. Geological sketch and cross-section (2.5× vertical exaggeration) of the Calasparra volcanic structure.

Plate II. Cancarix volcano. Fig. A: Cancarix structure view from the southeast. Q-quarry; bottom line shows the geological limit between the sedimentary basement and pre-dome volcanic sequence (V); top line shows the irregular limit between the volcanic sequence (V) and central dome (D). Fig. B: Columnar jointing belonging to the central dom (D). Fig. C: Upper volcanic section showing a succession of hydromagmatic deposits (Ph) and lava flows (L). Fig. D: Intercalation of phreatomagmatic deposits (Ph) in lava flows (L) at upper part of volcanic sequence. Fig. E: Contact between clastogenetic lava (CL) and flow-banded massive lava (L). Fig. F: Massive phreatomagmatic lappili tuff (Ph), which includes highly/moderately vesicular bombs covered by a spatter type scoria deposit (S). Fig. G: Succession of strombolian lapillistone (S) and bedded phreatomagmatic lapilli tuffs (Ph).



which include lamproites and kimberlites in the category of lamprofidic rocks. From the mineralogical point of view, the lamproites include potassic mafic minerals like: titanium phlogopite or tetraferi-phlogopite, titanium potassic richterite also forsteritic olivine, low Al diopside, leucite and Fe-rich sanidine. As common accessory this rocks contain apatite, magnesio-chromite and rare jeppeite, armalcolite, scherbakovite and ilmenite (Mitchell and Bergman, 1991). From the chemical point of view the lamproites show several molecular relationships: $K_2O/Na_2O>3$, $K_2O/Al_2O_3=0.8–1$, $(K_2O+Na_2O)/Al_2O_3>1$, $FeO<10\%$, $CaO<10\%$, $1\%<TiO_2<7\%$, as well as high Ba = 2000–5000 ppm, Zr > 500 ppm, Sr > 1000 ppm and La > 200 ppm. Based on textural and morphological variation of lamproite igneous bodies, Mitchell and Bergman (1991) separated four main facies groups: lavas; crater and pyroclastic, hypabyssal; and plutonic. Lamproite lavas are vesicular (15–40%), slightly porphyritic (with a glassy to aphanitic groundmass) and flow banded (suggesting fluidity); Hypabyssal or intrusive facies is dominantly massive, made by holocrystalline rocks, considered to be formed by the *in situ* crystallization of a degassed low-viscosity lamproite magma; they may intrude, as late stage, an initial central vent in the form of intrusive plugs or necks. It was suggested that during the lamproite magma ascent and decompression, the least dense and most volatile rich portion of the melt was first to ascent and erupt, last eruption resulting of degassed magma that filled the initial vent (Mitchell and Bergman, 1991).

Due to their mineralogical complexity, the Spanish lamproites received special names which identify them with the closest localities of characteristic outcrops (jumillites, verites, fortunites and cancarixites). The lamproites from Cancarix and Calasparra show different mineralogical and textural features for the effusive and intrusive facieses, dependent on the crystallization degree (e.g. Fúster et al., 1967). For example, olivine which is a characteristic mineral for glassy rocks is almost disappearing in the holocrystalline ones; the amphiboles are mainly present in holocrystalline rocks.

The Cancarix central plug is formed by holocrystalline rocks, which contain subhedral olivine, showing sometime corrosions, subhedral or euhedral diopside and phlogopite. Interstitially there is amphibole and sanidine, which sometimes develop poikilitic crystals (Plate I, Fig. B). The volcanic varieties show a porphyritic texture with glassy groundmass and small microcrysts (Plate I, Fig. A). The intrusive rocks from Calasparra are porphyritic with olivine and phlogopite phenocrysts in a microcrystalline matrix, where besides diopside, phlogopite and amphibole there is also ortopyroxene (Plate I, Fig. D). The juvenile lithic fragments are vesicle-rich, porphyritic with a glassy matrix (Plate I, Fig. C). At Barqueros the microscopic observations attest a slight porphyritic to aphanitic texture for most of the lavas, with olivine and phlogopite as phenocrysts. The rock matrix is glassy showing variable degree of crystalinity, incorporating microcrysts of sanidine, diopside, richterite and rare ortopyroxene and apatite and spinel as accessory minerals (Plate I, Figs. E, F).

3. Description of the eruptive centers

3.1. Cancarix

3.1.1. Description of deposits

First described by Hernandez Pacheco (1935), the volcanic rocks at "Sierra de las Cabras", named after the highest point on the volcanic dome (Fig. 2), are situated ca. 2 km west of the village of Cancarix. The dome is a prominent hill which has up to 1000 m in diameter and it is up to 150 m higher then the surrounding plain (Fig. 2, Plate II, A), showing vertical columnar jointing around an irregular contact with volcaniclastic rocks and lavas along the southern and the northeastern border of the extrusion (Plate II, B). The poor exposure in the western part suggests a discordant contact with the Mesozoic sedimentary strata and does not permit the reconstructions of the pyroclastic sequence. Mitchell and Bergman (1991) recognized the volcanic sequence around the dome and they interpreted the columnar jointed lamproites, inside the Cancarix vent, to be a lava lake, occupying the core of the pyroclastic facies vent complex.

Excluding the dome, the volcanic sequence is ca. 30–40 m thick and its eroded remnants dip 15–20° outward and 30–45° inward at the margin of the presumed crater. The basal part (3 m), exposed in the eastern part, consists of yellowish thinly bedded fine lapilli tuff with juvenile lapilli of low to moderate vesicularity. The next sequence (0.5 m) contains thin partially welded bomb-and-lapilli deposits, showing a massive structure. The clasts show a partially round shape and are highly vesicular. The next 2.4 m is represented by a succession (Plate II, G) of thinly bedded lapilli tuff layers in the base, a welded bomb-and-lapilli deposit (~0.4 m) in the middle, capped by massive lapilli tuffs containing round, moderately

Plate III. Calasparra volcano. Fig. A: Calasparra volcano viewed from the south. Dashed line suggests the shape of the extrusive plug (P), before quarrying (after Fúster and Sagredo, 1966). Fig. B: Vertical columnar jointing in the central plug (P). Fig. C: Irregular sill-like intrusions (S) penetrating the volcaniclastic sequence (Ph) viewed from the inside of the volcanic cone. Fig. D: Remnants of the central plug showing inward convergent columnar jointing inside the crater walls. Fig. E: Lapilli tuff (Ph) including clasts of soft Miocene sediments, showing imbrication. Fig. F: Phreatomagmatic lapilli tuff (Ph) including lobate shape juvenile fragments. Fig. G: Fine-grained phreatomagmatic tuff deposit (Ph) at the southern margin of tuff ring.

vesicular juvenile fragments (Plate II, F). The top contact of the lapilli tuff is strongly deformed by large ballistic blocks of round and flattened scoria.

The next 1.5 m thick deposit consists of welded flattened bombs and lapilli, then there is 0.2 m of thinly bedded fine tuff, then another 2 m thick welded bomb and lapilli deposit. The next sequence is represented by a succession of lava flows. The 3 m thick basal flow is highly vesicular and displays discontinuous lenses of strongly welded spatter, which include flattened vesicle-rich glassy clasts. Numerous parallel lenses show a flame-like appearance. This unit grades upward, over the next 5–7 m into slightly vesicular lava flow (showing flow-banding and the disappearance of clastogenic characteristics) (Plate II, E). Above these massive lava flow overlie the partially welded flows (3–5 m thick), in places intercalated with thick-bedded tuffs and lapilli tuffs made up of block and lapilli-sized accidental clasts in a fine to medium lapilli and coarse ash matrix (0.5–2 m thick); (Plate II, Fig. C). The sequence is poorly sorted and rich in large, mostly rounded, limestone blocks (with differentially heat-altered margins).

A central dome, presenting vertical columnar jointing (Plate II, Fig. B) at its eroded margins and showing irregular contacts with the earlier volcanic sequence, was possibly filling up the main vent produced by earlier hydrovolcanic activity. Significant erosion has resulted in the actual degradation of the volcanic edifice, which preserved mostly the central dome extrusion, represented by massive, coarse grained rock.

3.1.2. Interpretation of the deposits

We interpret the basal first 3 m of the sequence found in the eastern part of the vent as turbulent, low-concentration 'wet' base surges, as the dominant eruptive mechanism, based on the features such as fine lamination, advanced fragmentation of the ash-sized fraction, as well as argillic alteration of the deposit (Fisher and Schmincke, 1984, 1994). The next sequence of 0.5 m results from a short episode of near-vent deposition from Strombolian–Hawaiian fallout. The next 2.4 m of volcaniclastic material resulted from low-concentration base surges followed by a short near-vent Strombolian fallout episode and then a pyroclastic flow. Next deposits of 1.5 m and 2 m suggest an increase of the near-vent Strombolian fallout deposition mechanism, interrupted by a short hydromagmatic episode (0.2 m). The next 3 m and 5–7 m lava units indicate that the eruption was purely magmatic, specifically lava fountaining (Hawaiian-style), generating clastogenetic lava flows. The following 3–5 m thick lava flow intercalated with 0.5–2 m thick bedded tuffs and lapilli tuffs including block and lapilli-sized accidental clasts in a fine to medium lapilli and coarse ash matrix. The volcaniclastic sequence is poorly sorted and rich in large, mostly rounded, limestone blocks (with differentially heat-altered margins), which suggest deposition from a collapsing phreatomagmatic eruption column, intimately associated with the lava flow, which are massive and weakly vesicular. The extrusive dome filling the throat of the vent represents the last magmatic event.

3.2. Calasparra

3.2.1. Description of deposits

This occurrence, situated ca. 2 km northeast of the village of Calasparra was first described as a lava flow by Fallot and Jeremine (1929) and later as a spine surrounded by pyroclastic breccias, by Fúster and Sagredo (1966), but they did not discuss the origin of pyroclastic rocks. A quarry allows us direct observations inside the volcanic edifice (Fig. 3, Plate III, Fig. A).

The edifice at Calasparra suggests a tuff ring, which has a ca. 100-m-diameter crater. The height of the crater rim is ca. 20 m above the surrounding ground level. Beds dip outward at 18–24°. Yellowish, massive, weakly bedded and poorly sorted matrix-supported lapilli tuffs represent the base of the volcanic succession. The juvenile components are dominant and have angular or lobate shapes, being either dense or moderately to poorly vesiculated (Plate III, Figs. E and F). Miocene mudstone and siltstone (Plate III, Fig. E) represent fragments of country rocks. Both juvenile and accidental fragments show imbrication directed away from the vent (Plate III, Figs. E and F).

The upper sequence is represented by 8–10 m thinly bedded to laminated fine tuff (Plate III, Fig. G). In the central part of the volcanic vent there is a columnar-jointed central plug (Plate III, Fig. B). The columnar jointing as seen in a photo in Fúster and Sagredo (1966) before quarrying was upward-convergent above the crater rim, whereas it is mostly inward convergent below the crater rim, at its margins (Plate III, Fig. D). This jointing pattern suggests a bulb-like morphology of the original plug. In the interior of the vent area exposed in the quarry, some irregular sill-like intrusions were observed at the contact between the plug and the volcaniclastic sequence that extend into and deform (Plate III, Fig. C) bedding in the volcaniclastic deposits.

3.2.2. Interpretation of deposits

The volcanological features of initial volcaniclastic deposition suggest high concentration pyroclastic density current, resulted probably from collapsing of a phreatomagmatic eruption column, possibly related to initial vent opening. The upper volcaniclastic sequence possibly

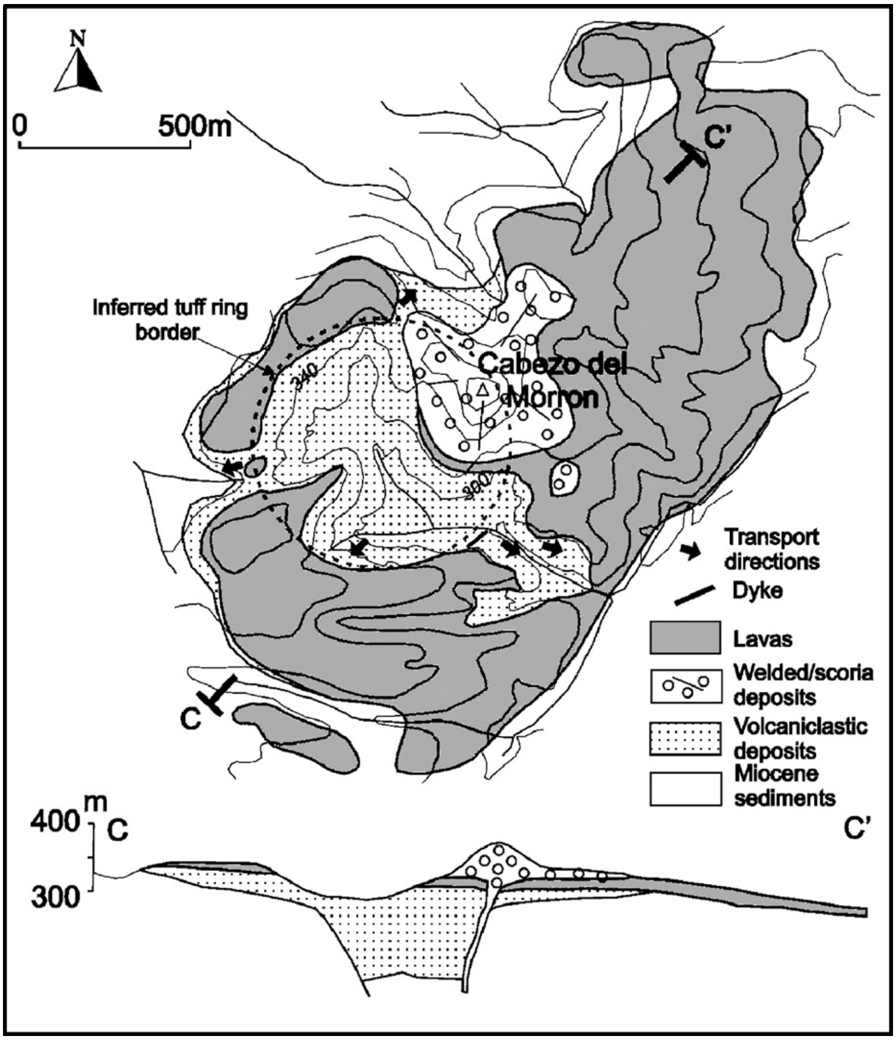


Fig. 4. Geological sketch and cross-section (2× vertical exaggeration) of the Barqueros volcanic structure. Flow directions of base surge and ballistic transport directions inferred from asymmetric impact sag.

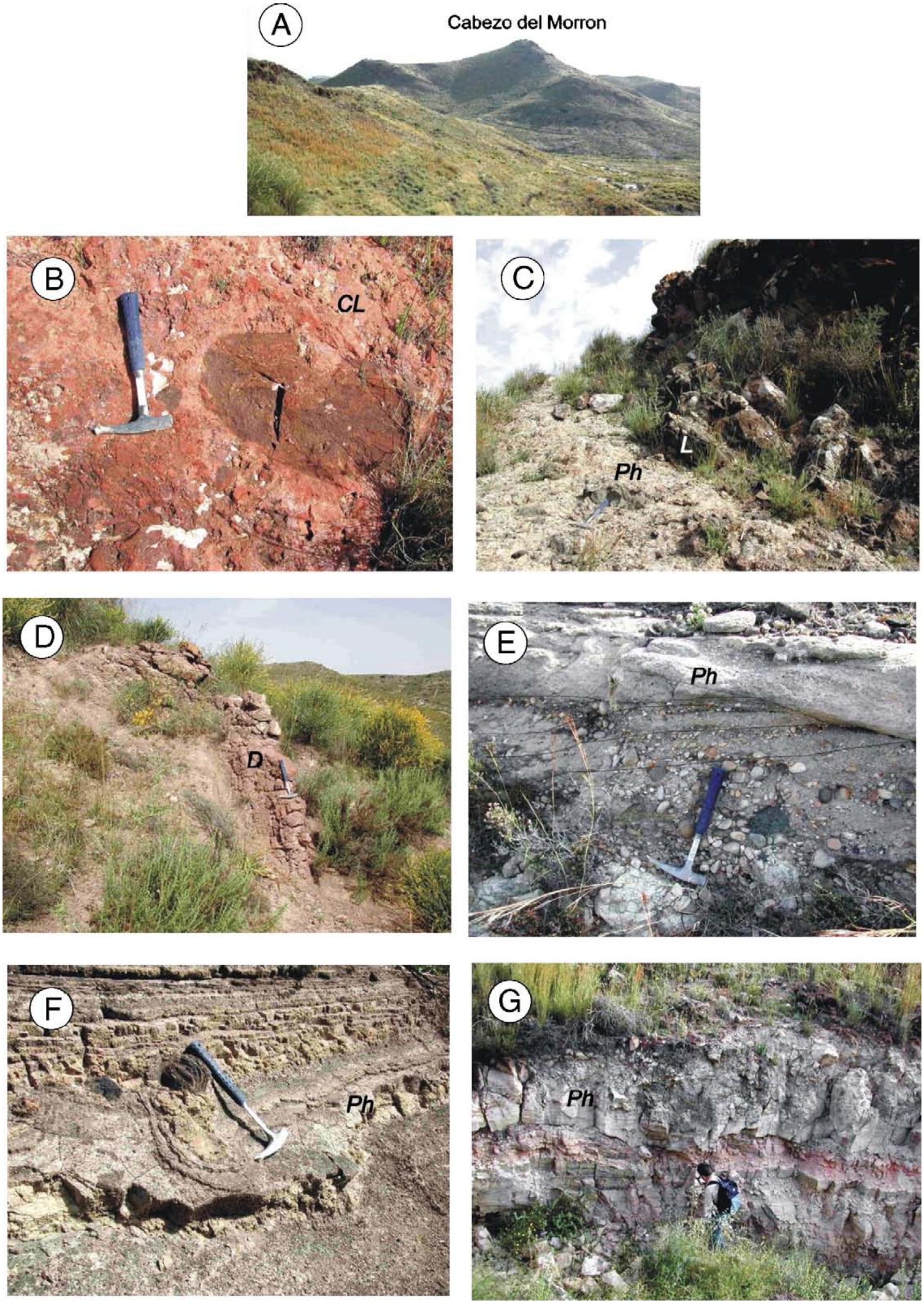
suggests deposition by low-concentration 'wet' surges (Fisher and Schmincke, 1994). The central plug (spine) is a late intrusion filling the vent. In addition the central plug is extending as sill and dyke-like intrusions piercing laterally in the former tuff ring volcaniclastic sequence.

3.3. Barqueros

3.3.1. Description of deposits

Barqueros volcano (Fig. 4) is situated north of the village of Barqueros, being the largest known lamproite volcanic center (of ca. 3 km^2) in the area (Fúster et al., 1967). It has been previously described as an effusive volcano, with the main eruptive center in Cabezo del Morron (Plate III, Fig. A), where "agglomeratic breccias" of pyroclastic origin have been recognized (Fúster and Gastesi, 1965). Mitchell and Bergman (1991) supposed base surge characteristics of some volcaniclastic deposits in Barqueros.

Our observation revealed the presence of well-preserved volcaniclastic deposits in the south-western part of of Cabezo del Morron, exposed in an erosional valley cutting toward the east (Fig. 4). Since the outcrops are scattered and covered by lavas, it is difficult to reconstruct the volcaniclastic sequence, which records the early stage of volcanic activity of the Barqueros volcano. The radial outward-dipping beds, flow direction indicators in surge deposits, and inferred transport direction from asymmetrical impact sags–well-preserved on the eastern, southern and western sides of the volcano–suggests the presence of a symmetric tuff ring (Fig. 4).



A succession of ca. 7 m of poorly sorted and crudely stratified fine lapilli tuffs to fine tuffs, showing large wavelength undulation, followed by crudely to well-bedded tuffs with accretionary lapilli (up to 4 mm) are found in the southern part of the volcano, at the lowest stratigraphic level exposed (Plate IV, Fig. G).

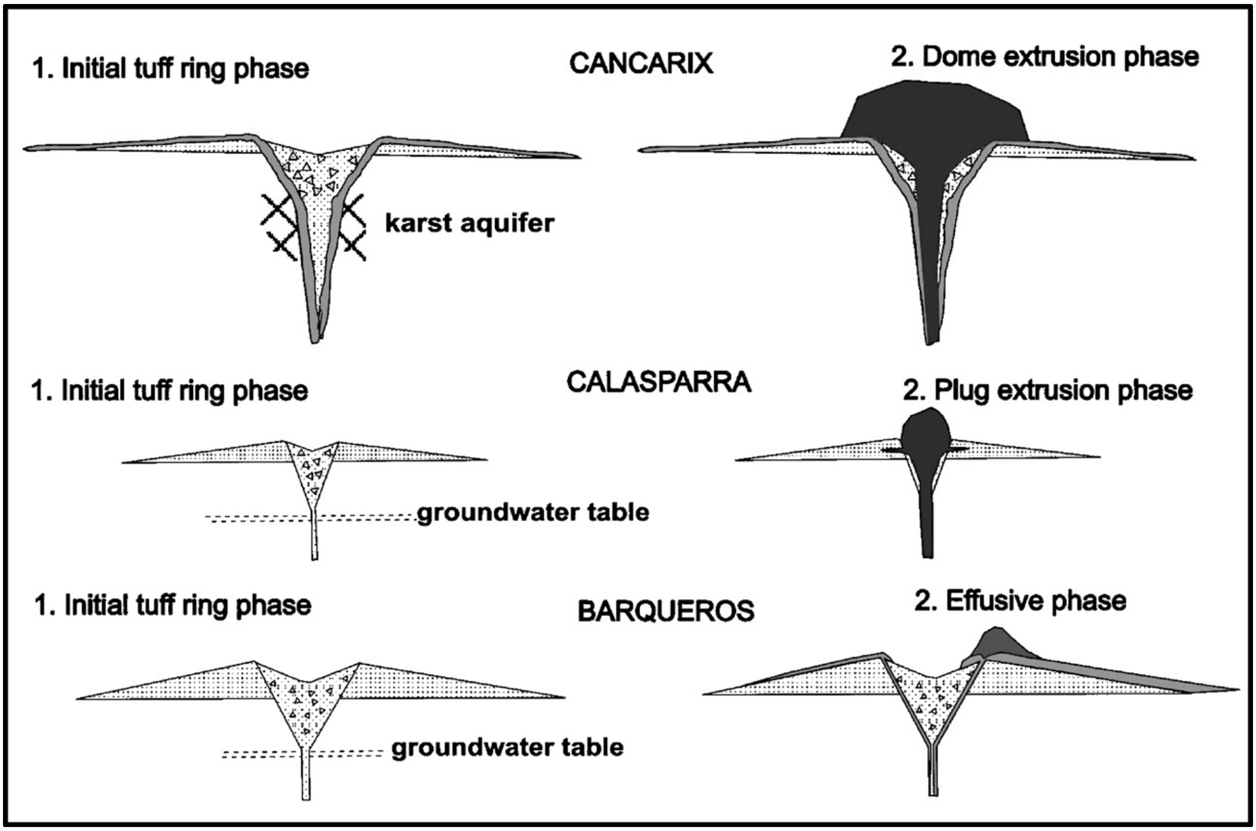


Fig. 5. Theoretical model of evolution of lamproite volcanoes (see discussion in the text).

In the southeastern part of the tuff ring, in the main section of the breached valley, at higher stratigraphic levels, there is a succession of well stratified beds (10–25 cm thick) of massive and well-sorted lapilli tuff affected by deep impact sags occupied by juvenile bombs (Plate IV, Fig. F). In the western margin of the tuff ring at high stratigraphic levels the deposits are represented by well-bedded slightly undulated (pinch-and-swell bedded) fine tuffs; sometimes showing low-angle cross-lamination, that contain variable amounts of accidental clasts represented by round quartz and limestone pebbles (Plate IV, Fig. E).

The southern part the tuff ring is covered by a thin lava flow (up to 3–4 m thick), which preserves the initial cone shape. These lavas, which show a constant thickness (3–4 m) all around the vent edifice, were probably released from several linear dykes. One of these dykes was observed on the eastern side of the tuff ring) tangentially oriented with respect the crater rim (Fig. 4; Plate IV, Fig. D). Most of the lava flows and dykes consist of crystal-poor glassy lamproites showing flow banding and indicating high fluidity. The main effusive vent area is represented by a small asymmetric cone (Cabezo del Morron) situated at the northern margin of the tuff ring, whose lavas are well developed toward the north-east and west (Plate IV, Fig. C). Cabezo del Morron peak area presently measures 500 m across and has a height of ~80 m. The peak area is made up of a deposit containing abundant, highly oxidized agglutinated bombs and lapilli. The juvenile fragments are poorly to moderately vesiculated and sometimes round and flattened (Plate IV, Fig. B). Because large pyroclasts retain heat for longer than smaller

Plate IV. Barqueros volcano. Fig. A: Cabezo del Morron cone formed of spatter and clastogenetic lavas. Fig. B: Round bomb incorporated in highly oxidized clastogenetic lava (CL); flow resulted inferred to record lava fountaining. Fig. C: Steeply dipping contact between flow-banded lava flows (L) and phreatomagmatic deposits (Ph) in the northwestern side of the tuff ring rim. Fig. D: Lamproite dyke (D), which cut the phreatomagmatic deposits on the eastern rim of the inferred tuff ring. Fig. E: Low-angle cross-laminated fine-grained tuffs, variably rich in rounded pebbles accidental clasts (Ph) situated at the southwestern outer rim of the tuff ring. Fig. F: Impact sags in stratified lapilli tuffs (Ph), caused by juvenile bombs at the eastern outer rim of the tuff ring. Fig. G: Succession of stratified medium to fine lapilli tuffs, with large amplitude undulations (Ph) at the southern inner rim of the tuff cone.

ones, they could experience plastic deformation upon landing, whereas smaller ones will be solidified (Wolf and Summer, 2000).

3.3.2. Interpretation of deposits

The 7 m succession of volcaniclastic deposits at the southern edge of their vent suggests a deposition from low-concentration wet base surges similar with LT9 and T9 part of LFS4 facies described by Sohn and Chough (1989) or LT14 and T4 facies defined by Nemeth et al. (2001). The following volcaniclastic deposit in the southeastern part of the vent suggests near-vent deposition from wet surges and co-surge fallout, mainly of ballistic origin. The deposit situated at the western margin of the tuff ring, at high stratigraphic levels suggests a surge-like dilute density currents depositional mechanism (Fisher and Schmincke, 1984). The facial characteristics of initial volcaniclastic deposits suggest hydrovolcanic eruptions. The next event was effusive, having a vent area a small asymmetric cone whose deposit suggests Hawaiian-style lava fountaining, followed by extensive lava flows toward the northeast.

4. Interpretation of eruption mechanism

Our study summarizes the volcanological field observation of three lamproite volcanoes generated during Miocene time in the southeastern part of Spain. We interpret them as subaerial volcanoes formed when magma intercepted aquifers during its ascent (e.g. Lorenz, 1986; Aranda-Gomez and Luhr, 1996; Nemeth et al., 2001). In all cases the initiation of volcanic activity was phreatomagmatic and generated tuff rings. The subsequent activity was dry and its products fill the interiors of the initial volcanic vents, crosscut tuff rings, as dykes or sills, or overlie the phreatomagmatic deposits. The relative proportion of the described eruptive styles is particular to each of the examined volcanoes. An eruption model for each volcanic structure is given in Fig. 5.

At Cancarix, where Mesozoic limestones represent the basement, the groundwater was stored in rather shallow fracture-controlled aquifers and/or as karst water, which could have provided a significant water source to initiate magma/water interaction. Initial explosion excavated a broad vent. The later dominance of strombolian deposits over phreatomagmatic deposits suggests a rapid decline of the magma/water interaction. When magma–water interaction ended, volcanic activity rapidly became effusive, initially showing a low fountaining phase. The intercalation of lava flows and phreatomagmatic deposits found at the top of the sequence suggests that suddenly a large amount of water, probably of karst origin again entered the vent area. This new water supply did not mix completely with the magma. The mixing suggests an open system magma/water interaction (Aranda-Gomez and Luhr, 1996), which generated successive phreatomagmatic explosions rich in sedimentary material (mostly fragments of limestone) followed, by outpouring of lava. The final magma was crystal-rich and therefore had a much lower fluidity. It formed a viscous dome that filled the former explosively generated crater.

At Calasparra, phreatomagmatic eruptions were probably controlled by the existence of a shallow aquifer in the unconsolidated Miocene sediments. Additionally the tuff ring is rather small and therefore was not supplied by a large batch of magma. Therefore, shortly after this shallow water supply was exhausted following phreatomagmatic eruptions, which mainly generated low-concentration pyroclastic density currents, the magma filled the interior of the crater depression as a plug-like extrusion. As in the case of Cancarix, the early-erupted magma had low crystal content and the late magma was rich in crystals, thus more viscous, generating a bulb-like plug extrusion.

At Barqueros initial phreatomagmatic eruptions were probably also controlled by a porous aquifer in the Miocene sediments, but the volume of magma available was greater than at Calasparra and Cancarix. The predominance of dilute pyroclastic density currents and co-surge fallout deposits suggests that the ascending magma interacted with water in shallow aquifers, as high water influx is interpreted to be related to high magma/water ratio and shallow water/magma interaction (e.g. Fisher and Schmincke, 1984), leading eventually to exhaustion of the near-vent aquifer. Subsequently, lava flows fed by dikes broke through the southern and northern part of the tuff ring, which broke through the surface along the flanks of the symmetrical tuff ring edifice. The main feeding area occurred in the northern part of the tuff ring and generated a Hawaiian style spatter cone in Cabezo del Morron as well as widespread lava flows directed to the north. Some of the lava flows also filled the tuff ring edifice.

5. Conclusion

Volcanism related to lamproite magmatism in southeastern Spain (Cancarix, Calasparra and Barqueros) shows similar sequence to many common mafic magmas (e.g. Fisher and Schmincke, 1984; Cas and Wright, 1987), even it illustrate a rare composition (e.g. Fúster et al., 1967; Venturelli et al., 1988; Mitchell and Bergman, 1991). Each volcano shows initial magma/water interaction producing phreatomagmatic eruptions that excavated the pre-existing country rock and built tuff rings. Their features were dependent on the volume of the erupted magma, as well as on the hydrological conditions of the country rocks.

The tuff ring deposits suggest high water content during deposition (i.e. accretionary lapilli, bomb-sags and plastic deformation) or post-depositional argillic alteration, as a result of water influx during eruption. After the tuff ring stage each volcano evolved differently, either by infilling of the crater with lava flows and central dome extrusion or by subsequent Hawaiian or Strombolian fall deposits followed by lava flows. The change from explosive to effusive activity must be related to changes in near-surface hydrological and/or magmatic volatile regime. We assume that the last magmatic eruption sequence was dependent of the magma volatile behaviour. At Cancarix and Calasparra the formation of edifices follow the Mitchell and Bergman (1991) model, which suggest initial crater formation (1), phreatomagmatic sequence formation (2) and eruption of lava and plug/dome intrusion in the throat of the vent (3), which suppose significant loss of magmatic volatiles in the first episodes, last eruption resulting in a slow effusion of a degassed magma, showing a higher crystallinity, as well as a higher viscosity. At Barqueros after the initial crater and phreatomagmatic sequence formation the magma still has enough volatile content to generate a Hawaiian explosive eruption and after degassing to generate lava flows. Since the lamproite rocks are rare worldwide we consider these volcanoes, which involve a range of explosive to effusive and intrusive activity, to be of a great volcanological interest.

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