This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Morphotectonic setting of maar lakes in the Campo de Calatrava Volcanic Field (Central Spain, SW Europe)

A. Martín-Serrano^a, J. Vegas^{b,*}, A. García-Cortés^b, L. Galán^a, J.L. Gallardo-Millán^c, S. Martín-Alfageme^a, F.M. Rubio^a, P.I. Ibarra^a, A. Granda^d, A. Pérez-González^e, J.L. García-Lobón^a

^a Instituto Geológico y Minero de España (IGME), E-28760-Tres Cantos, Madrid, Spain

^b Instituto Geológico y Minero de España (IGME), E-28003-Madrid, Spain

^c Department of Geological and Mining Engineering, Castilla-La Mancha University, E-13400-Almadén, Ciudad Real, Spain

^d International Geophysical Technology (IGT Inc.), E-28700-San Sebastián de los Reyes, Madrid, Spain

^e Centro Nacional de Investigación sobre la Evolución Humana (CENIEH), E-09004-Burgos, Spain

ARTICLE INFO

Keywords:

Maar lakes
Phreatomagmatic eruptions
Electrical tomography
Neogene

ABSTRACT

In the Campo de Calatrava Volcanic Field (CCVF, Central Spain), the eruption of Pliocene–Pleistocene maar craters into two clearly distinct types of pre-volcanic rocks allows the observation and comparison of hard-substrate and soft-substrate maar lakes. Hard-substrate maars formed when phreatomagmatic processes affected the jointed, Paleozoic igneous and metamorphic rocks (hard substrate), giving rise to funnel-like maar lake basins. Soft-substrate maars resulted from phreatomagmatic volcanic processes affecting poorly-consolidated Pliocene sediments, forming bowl-like maar lake basins. Pre-volcanic bedrock determined the post-eruptive lacustrine architecture in the craters and favored a higher preservation of hard-substrate maars in comparison to soft-substrate maars. This is because the hard-substrate maars, surrounded by a deep stable crater wall, are more capable of collecting sediments in their basins. These sediments could be preserved for longer than similar deposits in broad, shallow maars with a soft substrate. Ancient soft-substrate maars do not usually preserve their original morphology well and can be identified only by their lacustrine deposits. Carbonate lacustrine/palustrine deposits surrounding a bowl-like depression are the remnants of this second type of maar lake, and allow reconstruction of the original morphology of ancient soft-substrate maar craters. Geophysical (electrical tomography ground surveys) and geomorphologic–geologic mapping techniques were combined with fieldwork and facies analysis in order to locate and accurately characterize the Pliocene–Pleistocene soft-substrate maar volcanic structures of the CCVF.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Maars are a special type of volcanic structure formed by phreatomagmatic processes, characterized by circular craters, often filled with water and sediments and surrounded by a ring of pyroclastic deposits (Schmincke, 1988; Büchel, 1993). The entire volcano, including the tephra ring surrounding the maar crater, is called a maar–diatreme volcano (Lorenz, 1975; Lorenz, 1985). All terms are used in a purely descriptive, non-genetic way, and do not connote a specific emplacement process. More than any other type of volcanic activity, maar volcanism is strongly affected by the near-surface geologic setting (e.g. Lorenz et al., 1970; Kienle et al., 1980; Self et al., 1980; Lorenz, 1986; White, 1991; Aranda-Gómez and Luhr, 1996; Gevrek and Kazanci, 2000; Németh et al., 2001). Phreatomagmatic eruption mechanisms and the geology of maar–diatreme structures have been comprehensively discussed in several papers (e.g. Fisher and Schmincke, 1984; Lorenz,

1986; Lorenz et al., 2003; Wohletz and Zimanowski, 2000; Pirrung et al., 2003).

The detection of preserved maar structures is important not only for underground mapping, but also for paleoclimate research, since laminated maar lake sediments may contain very detailed archives of climate and environmental history in continental areas (e.g. Dodson, 1974; Negendank and Zolitschka, 1993; Creer and Thouveny, 1996; Roberts et al., 2001; Liu et al., 2001; Wagstaff et al., 2001; Caballero et al., 2003; Lücke and Brauer, 2004; Mingram et al., 2004; Schulz et al., 2005; Crausbay et al., 2006; Garcin et al., 2006; Zolitschka et al., 2006; Pirrung et al., 2008). The advantage offered by maar lake records is their high temporal resolution; their morphology favors the rapid and continuous accumulation of sediments (Gasse et al., 1997; Allen et al., 1999). Maar lake basins have a relatively small drainage basin, uniform geology, and a simple hydrologic regime. Most of them have sediments with annual lamination, which can be employed as an independent chronologic system.

In general terms, volcanic eruption style is primarily controlled by eruption rate, magmatic gas content, viscosity of magma, and magmatic source — basically the “source and en route” processes. Maar formation is

* Corresponding author. Fax: +34 913495834.
E-mail address: j.vegas@igme.es (J. Vegas).

affected by near-surface conditions, namely the physical parameters of the shallow substrate. Moreover, the potential eruption style (effusive versus phreatomagmatic) is strongly controlled by the host rock environment which the mafic melt encounters (Connor et al., 2000). Pre-volcanic country rocks control the morphology of maar formation and their related maar lake basins. Phreatomagmatic explosions take place simply because magma heats various groundwater aquifers. Two contrasting environments exist with regard to groundwater availability for phreatomagmatic explosions: (1) the “hard-rock” environment, which is a joint aquifer, and (2) the “soft-rock” environment, which is a pore aquifer (Lorenz, 2003). The water saturation (and style of water storage, e.g. porous media-soft rock, or fracture-controlled-hard rock aquifers) of the substrate will affect the potential for the occurrence of magma–water interaction, and, as a consequence, the phreatomagmatism. The “soft-rock environment” is a term used to refer to loose and water-saturated country rocks and sediments that the feeding dikes intrude, and which may enhance phreatomagmatism (Lorenz, 1985, 2002).

Both maar types (Figs. 1 and 2) have been identified in the Campo de Calatrava Volcanic Field (CCVF) (Ancochea, 1983; Poblete, 1995; Martín-Serrano et al., 2007). In hard-substrate maars, the explosive volcanic processes affected the basement metasediments (Precambrian slates and graywackes, Carboniferous sandstones, and Tremadocian–Arenigian (early Ordovician) slates and quartzites) with magma interacting with water in joint aquifers. On the other hand, in soft-substrate maars, the explosive volcanic processes affected the thick poorly-consolidated, fluvio-lacustrine Pliocene sediments (arkosic sands, marls, and silts). Thus, maar lake basins are controlled by the pre-volcanic environment.

Hard-substrate maars, surrounded by a deep stable crater wall, are more capable of collecting sediments in their basins which could be preserved for longer than similar lacustrine deposits in a broad, shallow maar formed in a soft-substrate environment. This situation favors a higher preservation of hard-substrate maar lakes because their country rocks are more resistant to collapse and erosion, as opposed to soft-substrate maars where the less resistant materials can subside and collapse into the newly-formed depression. Also, the surface morphology of soft-substrate maars is changed more easily, after eruption, by erosion and compaction, or is hidden by younger sediments. Ancient soft-substrate maar basins can be identified by their lacustrine infill (Martín-Serrano et al., 2007; Németh et al., 2008), or their exposed diatreme and peperitic zones (Auer et al., 2007; Németh and Martín, 2007). Maar crater morphologies, and, thus, maar lake basin size, erosion–sedimentation processes, and lacustrine facies are clearly determined by the pre-volcanic country rocks.

The Valverde de Calatrava area of Central Spain is studied here because its Campo de Calatrava Volcanic Field features both types of pre-volcanic maars and their related lakes. The post-eruptive sedimentation–erosion history of maars has not yet been studied in detail, and clues to the relationship between phreatomagmatism and subsequent maar lake formation and evolution can confirm the differences in maar development in soft- and hard-substrate areas.

2. Site description and geology

The study site is mainly located in the Ciudad Real Province of Central Spain, in the area known as the Campo de Calatrava Volcanic Field (CCVF) in the Central Volcanic Region (Hernández-Pacheco, 1932; Ancochea, 1983) (Fig. 1). Volcanism of the CCVF developed individual small-volume mafic volcanoes in a continental monogenetic volcanic field where maar craters, scoria cones, and lava flows are the most abundant features. According to K–Ar and Ar–Ar ages from the lava (Ancochea, 1983; Bonadonna and Villa, 1984), there were at least two volcanic stages. The first stage involves mafic extrusives of ultra-potassic character and occupies the center of the volcanic region with age ranging between 8.7 and 6.4 Ma. The second stage contains an alkaline and ultra-alkaline volcanism, with its main activity phase between 4.7 and 1.75 Ma. Later, there was some volcanic activity in the early Pleistocene

that greatly extended the period of volcanic activity in the region, between 1.3 Ma and 0.7 Ma (Gallardo-Millán and Pérez-González, 2000; Gallardo-Millán et al., 2002; Gallardo-Millán, 2004). Large-scale tectonic processes in the CCVF, related to the Alpine Orogeny, affected the Paleozoic basement rocks, forming faults and overthrust faults with NE–SW and SE–NW trends (Galindo-Zaldívar et al., 1993; Muñoz and de Vicente, 1998). Two main tectonic stages are identified. The first stage is compressional that originated faults with a NE–SW trend, and conjugate faults with a SE–NW trend, all during the Miocene. A second stage was active from the Pliocene to the present day, but was less compressive than the previous one.

According to Lorenz (1985, 2002, 2003), formation of Pliocene–Pleistocene phreatomagmatic maars in the CCVF took place in hard rocks and soft rocks (Fig. 1). Maar craters are lined up according to NW–SE and NE–SW tectonic trends in Central Spain.

3. Methods

Geologic and geomorphologic maps at 1:25,000 scale were composed through field work and interpretation of aerial photographs (1:18,000). For each maar identified in the CCVF, values of maximum and minimum diameters have been measured (D_{max} and D_{min} , measured from the crest of the tephra ring). Mean radius (R) is calculated as the half of the diameters. The average surface area (S) for craters and their associated lakes (s) was estimated.

Electrical tomography (ET) methods were employed to characterize the internal structure of the maar lake sediments (thickness, sedimentary facies, and sedimentary basin architecture) in two selected maar lakes: i) Fuentillejo Lake, a hard-rock substrate maar, and ii) Galiana palaeolake, a soft-rock substrate maar. The apparent resistivity measurements for the ET study made on Fuentillejo Lake used dipole–dipole electrode configurations. ET equipment consisted of an Iris VIP-3000 transmitter fed by a 4 KVA generator (0.04 and 4 Amperes), Iris Elrec-6 and Elrec-10 transmitters, and steel electrodes. However, measurements for the ET study made on the Galina palaeolake used a Lund system (Abem) equipped with a dipole–dipole and Wenner electrode configurations.

A borehole was drilled in 2002 in the sediments of Fuentillejo Lake to recover the 142.4 m-thick lacustrine sequence (FUENT-1 core). Cores were stored in a core repository at 4 °C. Analyses of mineralogy of the lacustrine sediments were carried out by X-ray powder diffraction using a copper K α -tube on a XPERT Pro of PANalytical (PTE-RX-004) at IGME laboratories. Authigenic minerals, particle morphologies, and textural relationships were observed by thin sections and scanning electron microscopy (SEM) at Luis Brú Microscopy Center (Universidad Complutense de Madrid). SEM observations were performed with a JEOL JSM 6400 operated at 20 kV and equipped with a Link System energy dispersive X-ray microanalyzer (EDX).

4. Maar lakes on CCVF hard-rock substrate

4.1. Basic features

A total of 60 hard-substrate maars have been identified on the crystalline Paleozoic basement, and their craters usually are not coalescent. This type originated as the explosive volcanic processes affected the basement metasediments (Precambrian slates and graywackes, Carboniferous sandstones and Tremadocian–Arenigian slates and quartzites) where magma interacted with water in joint aquifers. They commonly show tephra rings composed of pyroclastic deposits with large exotic country rock fragments floating in a fine-grained matrix outside crater walls. Half of them are concentrated in the southern part of the CCVF (Fig. 1), and 26 of them do not have lacustrine records because their craters are filled with rock falls.

Surface morphologic measurements of hard-rock substrate maars are indicated in Table 1 and Fig. 3. The average crater radius (R) is

A Hard-substrate maar lakes

B Soft-substrate maar lakes

Fig. 2. A. Diagram representative of a hard-substrate maar and related lake type from the CCVF (modified from Büchel, 1993 and Lorenz, 2000). B. Diagram representative of a soft-substrate maar and related lake type from the CCVF (modified from Büchel, 1993; Lorenz, 2000).

339.4 m, and most of them have an R between 100 and 600 m. Lake basins have a mean radius (r) of 254.7 m, and there is none greater than 500 m. Nevertheless, some craters of large, hard-rock substrate maars have $R = 750$ m and $S = 1.77$ km² (e.g. La Nava and Caracul maars). The smallest crater (Cervera maar) has a radius of 88 m and a surficial area of 0.24 km². Inner slopes dip towards the interior of the crater, with nearly vertical crater walls comprising slopes of 30° on interior alluvial fans. Normally in the CCVF, this type of maar basin has a greater inner slope angle than a soft-substrate maar. The internal crater wall usually has a height difference of 120–40 m. Formation of rockfalls, rock slumps, and scree material is very common.

4.2. Maar lacustrine deposits

Hard-substrate maar craters have a circular shape and host lakes in the post-eruptive stage with their funnel-like shape (Fig. 2). Such cone-shaped structures cut sharply into the “hard rock” hills, providing a competent and stable substrate for lake basin development. These types of maar lakes are ephemeral closed systems today with the largest maar lakes drained for farming.

Fuentillejo Lake has been chosen here as a model for hard-substrate maar lakes in the CCVF (Fig. 4). This maar is associated with a pyroclastic flow that includes more than 5%, and rarely up to 30%, of country rock fragments (quartzites and slates), indicating basement excavation. Xenocrysts of olivine and amphibole are common in the entire pyroclastic succession, but large crystals of amphibole (>5 cm) are more common close to the crater rim.

Table 1

Measurements made on hard-rock maar craters and their maar lakes from Campo de Calatrava Volcanic Field.

Dmax	Dmin	dmax	dmin	Mean R	Mean r	R/r	S	s	S/s
1000	700	550	550	425	275	1.55	567,451.5	237,583.5	2.39
1150	1000	700	450	538	288	1.87	907,627.9	259,672.9	3.50
1000	900	550	250	475	200	2.38	708,823.5	125,664	5.64
750	250	–	–	250	–	–	196,350.0	–	–
250	225	–	–	119	–	–	44,264.2	–	–
1250	1200	900	550	563	363	1.55	994,021.9	412,825.9	2.41
400	250	–	–	163	–	–	82,957.9	–	–
450	400	–	–	213	–	–	141,862.9	–	–
1050	950	450	250	500	175	2.86	785,400.0	96,211.5	8.16
550	475	–	–	256	–	–	206,290.2	–	–
350	300	–	–	163	–	–	82,957.9	–	–
450	450	–	–	225	–	–	159,043.5	–	–
750	700	–	–	363	–	–	412,825.9	–	–
1700	1500	1150	700	800	463	1.73	2,010,624.0	672,007.9	2.99
1000	550	600	300	388	225	1.72	471,730.9	159,043.5	2.97
950	400	550	400	363	238	1.53	412,825.9	177,205.9	2.33
1050	900	850	550	488	350	1.39	746,620.9	384,846	1.94
650	300	500	150	238	163	1.46	177,205.9	82,957.9	2.14
400	200	–	–	150	–	–	70,686.0	–	–
1150	500	700	350	413	263	1.57	534,562.9	216,475.9	2.47
275	250	–	–	107	–	–	35,632.8	–	–
200	150	–	–	88	–	–	24,052.9	–	–
1400	1350	500	400	438	225	1.94	601,321.9	159,043.5	3.78
1650	1575	1100	900	375	250	1.50	441,787.5	196,350	2.25
500	450	–	–	238	–	–	177,205.9	–	–
400	400	–	–	200	–	–	125,664.0	–	–
1650	700	–	–	588	–	–	1,084,342.9	–	–
1350	1000	800	600	588	350	1.68	1,084,342.9	384,846	2.82
1250	800	750	500	725	313	2.32	1,651,303.5	306,796.9	5.38
650	450	400	200	275	150	1.83	237,583.5	70,686	3.36
650	450	400	200	275	150	1.83	237,583.5	70,686	3.36
350	325	250	200	169	113	1.50	89,409.0	39,760.9	2.25
800	600	450	400	350	213	1.65	384,846.0	141,862.9	2.71
650	400	300	250	263	138	1.91	216,475.9	59,395.9	3.64
1400	1250	950	750	663	425	1.56	1,378,867.9	567,451.5	2.43
1250	1150	1000	850	600	463	1.30	1,130,976.0	672,007.9	1.68
600	500	350	200	275	138	2.00	237,583.5	59,395.9	4.00
650	550	500	250	300	188	1.60	282,744.0	110,446.9	2.56
1050	950	600	500	500	275	1.82	785,400.0	237,583.5	3.31
400	300	–	–	175	–	–	96,211.5	–	–
600	550	–	–	288	–	–	259,672.9	–	–
1600	800	650	600	600	288	2.09	1,130,976.0	259,672.9	4.36
1050	900	700	654	488	350	1.39	746,620.9	384,846	1.94
650	600	350	250	313	150	2.08	306,796.9	70,686	4.34
500	450	–	–	238	–	–	177,205.9	–	–
1050	650	–	–	425	–	–	567,451.5	–	–
1250	1250	750	750	625	375	1.67	1,227,187.5	441,787.5	2.78
1150	1100	500	500	563	250	2.25	994,021.9	196,350	5.06
1100	950	700	700	513	350	1.46	825,160.9	384,846	2.14
900	950	–	–	463	–	–	672,007.9	–	–
1750	1250	–	–	750	–	–	1,767,150.0	–	–
650	650	–	–	325	–	–	331,831.5	–	–
500	450	–	–	238	–	–	177,205.9	–	–
1150	750	650	500	475	288	1.65	708,823.5	259,672.9	2.73
300	250	–	–	138	–	–	59,395.9	–	–
500	450	–	–	238	–	–	177,205.9	–	–
700	575	–	–	319	–	–	319,191.5	–	–
1350	1250	850	750	650	400	1.63	1,327,326.0	502,656	2.64
1000	800	–	–	450	–	–	636,174.0	–	–
1600	1300	1150	750	725	475	1.53	1,651,303.5	708,823.5	2.33

For each hard-rock maar identified in the CCVF, values of maximum and minimum diameters have been measured (D_{max} and D_{min} , measured from the crest of the tephra ring). Mean radius (R) is calculated as the half of the diameters. d_{max} , d_{min} and r are values corresponding to their hard-rock maar lakes. The average surface area (S) for craters and their associated lakes (s) was estimated. All measurements were expressed on meters.

Hard-substrate, lake basin morphology has been inferred by three electrical tomography profiles made on the Fuentillejo Lake basin (García-Cortés et al., 2007). The funnel-like morphology of the lake basin was reconstructed using the ET profile and depth from the

Fig. 1. A. Location map of the study area in the Iberian Peninsula. B. Simplified geologic map of the Campo de Calatrava Volcanic Field. C. Situation map of maar crater types of the Campo de Calatrava Volcanic Field. Valverde study site in Fig. 2 is marked by a rectangle.

Fig. 3. Plots of frequency of maars with respect to mean radius of craters (R) and mean radius of lake basins (r). Mean radius is calculated as the half main value of maximum and minimum diameters. D_{max} and D_{min} were measured from the crest of the tephra ring; d_{max} and d_{min} were measured over modern lake surface. Black bars correspond to maar lake basins, and white bars correspond to maar craters.

FUENT-1 core (Fig. 5). Resistivity measurements provided the most detailed information about the internal structure of the maar lake sediments in this site (Fig. 5). An ET-FUENT-1 resistivity profile showed this lacustrine basin to be 90 m deep, and has also permitted the deduction of interesting aspects of its sedimentary architecture (Fig. 5). Zones of very low resistivity represented distal fine-grained facies of the post-eruptive period.

Pirung et al. (2003) generalized the lithofacies of maar structures and described five lithozones of typical stages of maar formation within a diatreme structure (A: diatreme breccia, B: syn-eruptive collapse breccia and the maar crater lake sediments, C: debris flow deposits, D: lacustrine laminated sediments with interbedded turbidites, E: peat and deltaic sediments). The 142.4 m deep research borehole (FUENT-1 core) from the center of Fuentillejo Lake contained a complete lacustrine record corresponding to lithofacies C, D and E of the post-eruptive phases.

Major lithostratigraphic units (total of 23) have been identified in the core, showing variations in clastic input, water chemistry and organic fractions throughout the history of the lake during the upper Pleistocene and Holocene (Vegas et al., 2006). The early lake period is characterized by coarse-grained debris flow and turbidites of higher resistivity values (Fig. 6). Distal lake sediments consist of siliciclastic and organic-carbonate mm-thick rhythmites deposited during high lake level stages. Ephemeral sedimentation periods are indicated by evaporites (mainly consisting in gypsum and carbonate minerals, including dolomite), units of bioturbated massive blue dolomiticrites and silts with desiccation horizons. Thick, massive to laminated black oil shale units also occur in units 17 and 20 where the principal source of organic matter is the microalgae *Botriococcus braunii*.

All carbonate phases are composed of euhedral crystals (2–10 μm), suggesting precipitation within the lake (Fig. 7). Dolomite (dolomite) formation of primary origin indicates evaporative processes, low lake level, and higher salinity, and is probably linked to a more arid climate. Dolomite, calcite, and zeolites (mainly analcime and minor chabazite–merlinoite; Fig. 7) of primary or early diagenetic origin were identified in the FUENT-1 sequence. The presence of analcime and other zeolites in lacustrine sediments has been interpreted to reflect changes in the salinity and alkalinity of the lake water, induced by climatic shifts (Stoffers and Holdship, 1975).

Las Higuieruelas is an example of an ancient, hard-substrate maar lake in the CCVF (Figs. 2 and 8). Outcrops representative of shoreline talus and lacustrine debris flow sediments can be observed in the western area (Fig. 8). The Higuieruelas palaeontologic site contains mammalian fossils (mainly *Anancus arvernensis*, *Hipparion rocinantis*, *Cervus cf. cusanus*, *Cervus cf. perrieri* and *Equus cf. stenonis*) in the uppermost 3 m of the lacustrine sediments, corresponding to a palustrine mudflat environment (Alberdi, 1984; Arribas and Antón, 1997). Dolomite and zeolites (phillipsite) are the main minerals identified at this site. This maar lake record is 3.5 Ma old, estimated by the application of K–Ar methods made on volcanic bombs associated with the fossil bones (Bonadonna and Villa, 1984).

5. Maar lakes on CCVF soft-rock substrate

5.1. Basic features

Soft-substrate maars of the CCVF exploded within a thick Neogene succession of fluvio-lacustrine sediment, characterized by unconsolidated and water-saturated materials. There is clear evidence of 66

Fig. 4. Simplified geologic map of the pre-volcanic substrate in the Valverde area (selected study site). Fuentillejo and Valdurillo are examples of hard-substrate maars. Alcolea is a preserved, soft-substrate maar. Cantarranas, Peñalgatos, Galiana, and Las Parras paleolakes are examples of ancient, soft-substrate maar lakes. Las Higuieruelas is an example of an ancient, hard-substrate maar lake. Electrical tomography profiles were constructed across Fuentillejo (ET-F-3) and Galiana (ET-G-1) lake basins, and they are shown in Figs. 5 and 9, respectively.

soft-substrate maars in this region (Fig. 1). Their craters usually have a circular shape, but some are elliptical, due to early post-eruptive subsidence and inner wall erosion. Moreover, some of the soft-substrate craters are coalescent (Fig. 1), probably a consequence of surficial unconsolidated material that may provide connected sites for steam release (White and McClintock, 2001; Sohn and Park, 2004). A thin tephra ring usually surrounds the maar craters. They can host a lake basin that resembles a bowl-like shape, providing a good site for water accumulation (Fig. 9).

Surface morphologic measurements (Table 2 and Fig. 3) indicate that soft-substrate craters are larger than hard-substrate craters. Soft-

substrate craters have an average radius (R) of 565.59 m, and an average surface area (S) of 1.86 km², while their average maar lake radius (r) is 288.37 m with a mean surface area of 0.56 km². The largest soft-substrate craters are significantly larger than hard-substrate craters and have a radius (R) of 3079–2950 m, and S from 1.88 to 5.94 km² (e.g. Torralba and Granátula maars). Seventy-two percent of craters have a radius ranging from 300 to 700 m (Fig. 3), and 39.4% of lakes have a radius of between 200 and 300 m. The radius (r) of the biggest lake is 1485 m, whereas the smallest lake is only 75 m. Craters form walls with shallower angles than the hard-substrate types, and they commonly have collapse structures and sand flows towards the crater center.

Fuentillejo hard-substrate maar lake basin

Fig. 5. A. Resistivity profile using electrical tomography in the Fuentillejo hard-substrate lake basin (after García-Cortés et al., 2007). B. Fuentillejo maar lake morphology (intermittent line) has been reconstructed from the electrical tomography interpretation of ET-F-3 profile (in Fig. 4) and the F-1 core of 142.2 m deep (from Vegas et al., 2006).

5.2. Soft-substrate lacustrine deposits

Craters have a circular or elongated shape, and always contain a lake basin with a bowl-like shape (Fig. 2), corresponding to the post-eruptive period. Circular dolostone rock outcrops outline the ancient soft-substrate volcanic structures in the study site (Fig. 4) corresponding to soft-substrate maar craters filled with lacustrine sediments. Ancient soft-substrate maar lakes in the CCVF are almost filled by post-eruptive sediments and, in some cases, tephra rims are eroded (Martín-Serrano et al., 2007). The surface morphology of the maar structures is changed significantly by erosion and compaction or is hidden by younger sediments (Schulz et al., 2005). Surface measurements on selected dolostone lacustrine outcrops reveal radii (*r*) that range from 0.9 to 2.2 km, and surface areas from 2.54 to 15.20 km². These ancient parameters are greater in size than those of modern maars. This could be due to post-eruptive inner wall erosion which enlarged maar craters. Moreover, in soft-substrate maars, compaction of the diatreme fill causes differential subsidence and marginal dragdown of suitable country rock sediments (Francis, 1962; Lorenz, 1971, 2003; Suhr et al., 2006).

We choose Galiana paleolake as an example of an ancient soft-substrate maar lake (Fig. 4). The geologic cartography and ET profiles of the Galiana carbonate paleolake area clearly reveal the bowl-like structure of the maar lake basin (Fig. 9). A detailed electrical tomography survey was carried out to determine the depocenter of this lake basin,

where high resistivity values correspond to the lithified carbonate lake sediments. Results from the ET profile indicate a lake depocenter of 60 m depth (Fig. 9). Subsidence processes can be identified by centripetal dipping angles of nearshore carbonate facies on the TE profile (Fig. 9). Surrounding this bowl-like structure, there are sediments from the Pliocene age which represent the pre-volcanic setting.

The Galiana paleolake sedimentation model may be representative of other soft-substrate maars; other circular carbonate lacustrine outcrops with uncertain stratigraphy positions in the CCVF should be carefully re-examined in the near future. The lacustrine deposits at Cantarranas record the development of another maar lake basin which has been eroded (Figs. 4 and 8). Lithified circular carbonate bodies exhibit a wide variation in morphology as well as in depositional and diagenetic fabric (Vegas et al., 2007). The carbonate mineral suite of soft-substrate maar lake basins consists mainly of dolomite and calcite, with smaller amounts of hydromagnesite and magnesite (Hoyos et al., 1984; Vegas et al., 2007). Zeolites are also present in lacustrine distal facies (analclime and minor chabazite–merlinoite). High Mg content in carbonate minerals is related to the pyroclastic rocks from the eroded tephra rim. In addition to the carbonates in the distal deep-water facies, the lacustrine basins also contain a girdle of nearshore carbonate. Mottled dolostones from lake girdles reveal subaerial exposure, organisms, root traces, desiccation, and pedogenic features typical of palustrine environments (after Alonso-Zarza, 2003). Palustrine carbonates typically occur in lakes with low gradient, relatively flat surfaces,

Fig. 6. Stratigraphic section of the Fuentillejo maar lacustrine record that corresponds to core F-1 core (142.40 m thick) (Vegas et al., 2006). A simplified description of facies and their sedimentary environments is included. Relative lake level reconstruction is proposed on the base of facies interpretation (Vegas et al., 2006).

FUENTILLEJO HARD-SUBSTRATE MAAR LAKE RECORD

low energy margins, and a carbonate provenance (Platt and Wright, 1991). The primary micrite mud is composed of relatively euhedral dolomite crystals 1–3 μm across which were affected by pedogenic modification as the lake level dropped. Cracks are visible under the microscope, and they may remain empty, or be filled with microspar and sparry calcite. Moreover, there are abundant peloids and fenestral structures identified in thin section.

6. Conclusions

Hard-substrate and soft-substrate maar volcanoes have been identified in the Campo de Calatrava Volcanic Field (CCVF) through the combination of electrical tomography ground surveys with geomorphologic and sedimentary facies analysis. Maar formation in the CCVF occurred over a long time range from the Pliocene to upper Pleistocene with the resultant basins containing thick sedimentary

lacustrine records. Pre-volcanic setting determines maar morphology and post-eruptive lacustrine architecture in the maar craters. The preservational potential of hard-substrate maar showing original volcanic features is greater than that of soft-substrate maars. Steep-sided maar lakes with a funnel-like basin form in the hard-substrate settings of Precambrian slates and graywackes, Carboniferous sandstones, and Tremadocian–Arenigian slates and quartzite. In the CCVF, the crater is generally filled with limnic sediments of low density, and mainly fine-upward from meter-thick, detrital graded layers to finely laminated dolomicrite facies.

Unlike hard-substrate maars, soft-substrate maars of the CCVF exploded within a thick succession of Neogene fluvio-lacustrine sediment that is not consolidated as well as water saturated. Craters have a circular or elongated shape and host a lake basin with a bowl-like shape. Early lacustrine sedimentation phases contain to detrital graded layers with abundant epiclastic fragments. Later facies

Fig. 7. SEM images: A. Analcime crystals. Blue massive carbonates of Unit 21 (17.42 m deep). B. Analcime crystal on a matrix of detrital kaolinite. Black mud facies of Unit 18 (22.69 m deep). C. Minute primary dolomite rhombi, alternating with analcime and organic matter. Finely laminated carbonate rich sediments with mm-thick laminae from Unit 19 (23.71 m deep). D. Minute dolomite rhombi on a matrix of detrital particles. Massive carbonate-rich layers of Unit 23 (8.10 m deep). E. Lamina with abundant analcime and merlinoite crystals. Finely laminated carbonate-rich sediments with mm-thick laminae from Unit 19 (23.71 m deep). F. Minute dolomite rhombi interpreted as primary in origin. Blue massive carbonates of Unit 21 (15 m deep).

comprise massive to laminated dolomicrites of a distal origin and mottled dolostones exhibiting subaerial exposure features typical of a nearshore palustrine environment. Dolomite is the main carbonate mineral present in both maar lake types, due to a high influence of volcanic and carbonate catchments.

The shape of both crater types, primarily determined by substrate type, controls lake basin geometry and lacustrine sedimentation patterns. The hard-substrate maars, surrounded by a deep and stable crater wall, can collect sediments and preserve them more effectively. The soft-substrate maars, formed in a less cohesive substrate, contain broad shallow craters with collapse structures and are more exposed to erosive processes. This makes soft-substrate maars more difficult to identify in the landscape; circular outcrops of lacustrine dolostones in the CCVF revealed the location of ancient maars.

The sedimentary records of the maar lakes are influenced by their pre-volcanic substrate as well as climate. Fuentillejo Lake in a hard-substrate maar has thick black, finely laminated mud sediments corresponding to periods of high lake levels in a high-walled, stable crater. Paleolakes Galiana and Cantarranas, forming in a soft-substrate maar crater, contain mostly shallow lacustrine and palustrine sediments in a shallow broad area with unstable, non-cohesive crater walls.

Acknowledgments

This work was funded by the Spanish Inter-Ministry Commission of Science and Technology (CICYT), project CGL2004-06212/BTE “Variabilidad climática y ambiental en el centro de la Península Ibérica durante el Cuaternario. Estudio de alta resolución del registro lacustre del sondeo FU-1 (laguna de Fuentillejo, Ciudad Real)” and the IGME through the project CC 54.020 “Estudio Paleoclimático del Maar de Fuentillejo (Ciudad Real)”. We thank Elizabeth Gierlowski for her suggestions and language revision. Formal reviews by Károly Németh, an anonymous reviewer, and Lluís Cabrera (Invited Scientific Editor) significantly improved the manuscript, many thanks for it.

References

- Alberdi, M.T. (Coord.), 1984. Geología y Paleontología del yacimiento del Villafrankense inferior de Las Higuieruelas y su entorno (Campo de Calatrava, Ciudad Real). *Actas de Castilla-La Mancha. Espacio y Sociedad* 3, pp. 229–275.
- Allen, J.R.M., Brandt, U., Brauer, A., Hubberten, H.W., Huntley, B., Keller, J., Kraml, M., Mackensen, A., Mingram, J., Negendank, J.F.W., Nowaczyk, N.R., Oberhänsli, H., Watts, W.A., Wulf, S., Zolitschka, B., 1999. Rapid environmental changes in southern Europe during the last glacial period. *Nature* 400, 740–743.
- Alonso-Zarza, A., 2003. Palaeoenvironmental significance of palustrine carbonates and calcretes in the geological record. *Earth Sci. Rev.* 60, 261–298.

Fig. 8. A. Stratigraphic section of Las Higuieruelas Lake; an ancient hard-substrate maar lake (from Hoyos et al., 1984; Alberdi, 1984). B. Stratigraphic section of Cantarranas is representative of an ancient soft-substrate maar lake. Valverde study site (CCVF, Ciudad Real).

Fig. 9. A. Galiana maar lake basin (intermittent line) was reconstructed from electrical tomography interpretation of the ET-G-1 profile showed in Fig. 4. B. Subsidence of maar-diatreme is interpreted by the TE profile. Galiana circular carbonate (dolostone) outcrop is a well-preserved example of an ancient soft-substrate maar lake sedimentary succession.

- Ancochea, E., 1983. Evolución espacial y temporal del volcanismo reciente de España Central. Ph-D. thesis, Ed. Complutense University, Madrid.
- Aranda-Gómez, J.J., Luhr, J.F., 1996. Origin of the Joya Honda maar, San Luis Potosí, Mexico. *J. Volc. Geotherm. Res.* 74, 1–18.
- Arribas, A., Antón, M., 1997. Los carnívoros de los yacimientos pliocenos de Las Higuieruelas y Piedrabuena (Ciudad Real, España). *Bol. Geol. Min.* 108, 111–120.
- Auer, A., Martin, U., Németh, K., 2007. The Fekete-hegy (Balaton Highland Hungary) "soft-substrate" and "hard-substrate" maar volcanoes in an aligned volcanic complex – implications for vent geometry, subsurface stratigraphy and the palaeoenvironmental setting. *J. Volc. Geotherm. Res.* 159, 225–245.
- Bonadonna, F.P., Villa, J.M., 1984. Estudio geocronológico del vulcanismo de las Higuieruelas. I Reunión Estratigrafía Regional Castilla-La Mancha (Albacete), vol. 3. Espacio y Sociedad, pp. 249–253.
- Büchel, G., 1993. Maars of the Westeifel, Germany. In: Negendank, J.F.K., Zolitschka, B. (Eds.), *Paleolimnology of European Maar Lakes*. Springer-Verlag, pp. 1–13.
- Caballero, M., Vilaclara, G., Rodríguez, A., Juárez, D., 2003. Short-term climatic change in lake sediments from lake Alchichica, Oriental, Mexico. *Geofis. Int.* 42, 529–537.
- Connor, C.B., Stamatakis, J.A., Ferrill, D.A., Hill, B.E., Ofoegbu, G.I., Conway, F.M., Sagar, B., Trapp, J., 2000. Geological factors controlling patterns of small-volume basaltic volcanism: application to a volcanic hazards assessment at Yuca Mountain, Nevada. *J. Geophys. Res.* 105, 417–432.
- Crausbay, S.D., Russell, J.M., Schunrennenberger, D.W., 2006. A ca. 800-year lithologic record of drought from sub-annually laminated lake sediment, East Java. *J. Paleolim.* 35, 641–659.
- The EUROMAARS Project. In: Creer, K.M., Thouveny, N. (Eds.), *Special Issue: Quat. Sci. Rev.*, vol. 15. 146 pp.
- Dodson, J.R., 1974. Vegetation and climatic history near Lake Keilambete, Western Victoria. *Australian J. Bot.* 22, 709–717.
- Fisher, R.V., Schmincke, H.-U., 1984. *Pyroclastic rocks*. Springer Verlag, Berlin-Heidelberg-New York-Tokyo.
- Francis, E.H., 1962. Volcanic neck emplacement and subsidence structures at Dunbar, south-east Scotland. *Trans. R. Soc. Edin.* 65, 41–58.
- Galindo-Zaldívar, J., González-Lodeiro, F., Javaloy, A., 1993. Stress and paleostress in the Betic-Riff cordilleras (Miocene to the present). *Tectono.* 227, 105–126.
- Gallardo-Millán, J.L., 2004. Evolución geodinámica de las cuencas neógenas del Campo de Calatrava (Ciudad Real) y su relación con el volcanismo reciente. Ph-D. thesis. Complutense University, Madrid.
- Gallardo-Millán, J.L., Pérez-González, A., 2000. Magnetoestratigrafía del relleno neógeno en las cuencas del Campo de Calatrava (Ciudad Real). *Geotemas* 1, 101–104.
- Gallardo-Millán, J.L., Ancochea, E., Pérez-González, A., 2002. Secuencia magnetoestratigráfica y edad de los materiales volcánicos y sedimentarios de Poblete (Ciudad Real). *Geogaceta* 32, 35–38.
- García-Cortés, A., Vegas, J., Granda, A., Galán, L., Pérez-González, A., 2007. Reconstrucción de la arquitectura lacustre cuaternaria del maar de Fuentillejo mediante tomografía eléctrica. Campo de Calatrava. In: Lario, J., Silva, P.G. (Eds.), *Contribuciones al estudio del periodo Cuaternario*. AEQUA, Ávila. Sección de Publicaciones de la Escuela Técnica Superior de Ingenieros Industriales. Universidad Politécnica de Madrid, pp. 191–192.
- Garcin, Y., Williamson, D., Taieb, M., Vincens, A., Mathé, P.E., Majule, A., 2006. Centennial to millennial changes in maar-lake deposition during the last 45,000 years in tropical Southern Africa (Lake Masoko, Tanzania). *Palaeogeog. Palaeoclim. Palaeoecol.* 239, 334–354.
- Gasse, F., Oldfield, F., Kroepelin, S. (Eds.), 1997. PEP III: The Pole-Ecuador-Pole Transect through Europe and Africa. *PAGES Reports*, pp. 97–102. <http://www.pages.unibe.ch/products/reports.html>.
- Gevrek, A.I., Kazanci, N., 2000. A Pleistocene, pyroclastic-poor maar from central Anatolia, Turkey: influence of a local fault on a phreatomagmatic eruption. *J. Volcan. Geotherm. Res.* 95, 309–317.
- Hernández-Pacheco, F., 1932. Estudio de la región volcánica central de España. *Mem. R. Acad. Cienc. Exactas Fís. Nat. Madr., Ser. Cienc. Nat.* 3, 1–235.
- Hoyos, M., Bonadonna, F.P., Ancochea, E., de la Rubia, R., Marfil, R., 1984. Características geológicas del yacimiento de Las Higuieruelas (Ciudad Real). *Actas de Castilla-La Mancha. Espacio y Sociedad*, vol. 3, pp. 231–240.
- Kienle, J., Kyle, S., Self, S., Motyka, R.J., Lorenz, V., 1980. Ukinrek Maars, Alaska: 1. April 1977 eruption sequence, petrology, and tectonic settings. *J. Volcan. Geotherm. Res.* 7, 11–37.
- Liu, J.Q., Liu, T.S., Negendank, J.F.W., 2001. The Chinese Maar Drilling Programme: a Chinese-German cooperation for paleoclimatic reconstructions. *PAGES News* 9, 10–11.
- Lorenz, V., McBirney, A.R., Williams, H., 1970. An investigation of volcanic depressions: part III. Maars, tuff rings, tuff-cones and diatremes. *NASA Progress Rpt. (NGR-38-003 012)*, Houston, Texas, pp. 1–198.
- Lorenz, V., 1971. Collapse structures in the Permian of Saar-Nahe-area, southwest Germany. *Geol. Rund.* 60, 924–948.
- Lorenz, V., 1975. Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to kimberlite diatremes. *Phis. Chem. of the Earth* 9, 17–27.
- Lorenz, V., 1985. Maars and diatremes of phreatomagmatic origin: a review. *Trans. Geol. Soc. South Africa* 88, 459–470.
- Lorenz, V., 1986. On the growth of maars and diatremes and its relevance to the formation of tuff-rings. *Bull. Volcanol.* 48, 265–274.
- Lorenz, V., 2000. Formation of maar-diatreme volcanoes. *Terra Nostra* 2000/6, 284–291.
- Lorenz, V., 2002. Hard rock and soft rock environments of explosive phreatomagmatic monogenetic volcanism. In: Ulrych, J., Cajz, V., Adamovic, J., Bosak, P. (Eds.), *Hibsch 2002 Symposium. Czech Geological Survey, Prague, Tepla near Trebenice, Usti nad Labem, Mariánské Lázně (Czech Republic)*, p. 89.
- Lorenz, V., 2003. Maar-diatreme volcanoes, their formation, and their setting in hard-rock and soft-rock environments. *Geolines-Journal of the Geological Institute of AS Czech Republic* 15, 72–83.

Table 2

Measurements made on soft-rock maar craters and their maar lakes from Campo de Calatrava Volcanic Field.

Dmax	Dmin	dmax	dmin	Mean R	Mean r	R/r	S	s	S/s
1200	800	750	300	500	262	1.91	785,400	216,476	3.63
1500	1250	950	550	688	375	1.83	1,487,058	441,787	3.37
1350	850	750	400	580	288	2.01	950,334	260,577	3.65
1250	1000	600	500	566	275	2.06	1,006,430	237,584	4.24
1250	1000	400	400	566	200	2.83	1,006,430	125,664	8.01
1400	1250	800	300	663	275	2.41	1,380,950	237,584	5.81
700	650	300	250	338	138	2.45	358,909	59,829	6.00
1500	1300	650	600	700	313	2.24	1,539,384	307,779	5.00
1350	1050	400	350	600	188	3.19	1,130,976	111,037	10.19
750	700	400	300	363	175	2.07	413,965	96,212	4.30
750	550	300	250	325	138	2.36	331,831	59,829	5.55
1100	950	600	500	513	275	1.87	826,772	237,584	3.48
1100	900	600	450	500	263	1.90	785,400	217,301	3.61
2000	1500	1000	750	888	425	2.09	2,477,290	567,451	4.37
1800	1500	700	600	825	325	2.54	2,138,251	331,831	6.44
1250	950	550	400	550	238	2.31	950,334	177,953	5.34
1000	650	650	450	413	150	2.75	535,850	70,686	7.58
1200	1000	950	650	550	325	1.69	950,334	331,881	2.86
1050	950	550	400	500	238	2.10	785,400	177,953	4.41
1000	700	650	450	425	275	1.55	567,451	237,584	2.39
550	400	250	100	238	88	2.70	177,953	24,329	7.31
850	800	400	350	413	188	2.20	535,860	111,037	4.83
1600	1250	1150	700	713	463	1.54	1,597,092	673,462	2.37
900	800	600	550	425	288	1.48	567,451	260,577	2.18
1300	1100	950	750	600	425	1.41	1,130,976	567,451	1.99
1200	1000	700	650	550	338	1.63	950,334	472,949	2.01
650	550	500	450	300	175	1.71	282,744	96,211	2.94
800	700	500	450	375	238	1.58	441,787	177,953	2.48
1000	650	350	250	413	200	2.07	535,860	125,664	4.26
1000	850	500	400	463	223	2.08	673,462	156,229	4.31
700	600	400	350	325	188	1.73	331,881	111,037	2.99
1100	750	550	400	466	238	1.96	682,217	177,953	3.83
1250	1100	800	700	588	376	1.56	1,086,189	444,147	2.45
1400	1050	550	450	613	250	2.45	1,180,516	196,350	6.01
550	500	350	250	263	150	1.75	217,301	70,686	3.07
1600	850	1050	350	613	350	1.75	1,180,516	384,846	3.07
750	350	150	150	275	75	3.67	237,584	17,672	13.44
750	650	500	350	350	213	1.64	384,846	303,592	1.27
1550	1100	850	600	663	363	1.83	1,380,950	413,965	3.34
1000	900	650	450	475	275	1.73	708,823	237,583	2.98
1250	600	900	250	463	288	1.61	673,462	260,577	2.58
2250	1750	1400	500	1000	480	2.08	3,141,600	723,825	4.34
1000	600	400	300	400	175	2.29	502,656	96,212	5.22
1550	1350	700	500	730	300	2.43	1,674,159	282,744	5.92
900	600	600	300	375	225	1.67	441,787	159,043	2.78
750	750	400	250	375	163	2.30	441,787	83,469	5.29
2500	1400	1550	800	975	588	1.66	2,986,483	1,086,189	2.75
950	600	600	200	388	200	1.94	472,949	125,664	3.76
1100	750	650	400	463	263	1.76	673,462	217,301	3.10
1600	1350	650	500	737	363	2.03	1,706,420	413,965	4.12
1350	1100	800	650	625	288	2.17	1,227,187	260,577	4.71
1300	1100	800	650	550	363	1.52	950,334	413,965	2.30
1050	1000	650	600	513	313	1.64	826,772	307,779	2.69
650	600	600	350	313	238	1.32	307,779	177,953	1.73
1250	1150	1000	450	600	363	1.65	1,130,976	413,965	2.73
1400	900	1000	650	575	413	1.39	1,038,691	535,860	1.94
900	450	600	300	338	225	1.50	177,953	159,043	1.12
1600	1550	650	650	788	325	2.42	1,950,758	331,831	5.88
2000	1550	800	650	888	368	2.41	2,477,290	411,688	6.02
2750	1600	1600	1150	1088	688	1.58	3,718,850	1,487,057	2.50
1150	850	550	500	500	263	1.90	785,400	217,301	3.61
2932	1000	1000	900	1966	950	2.07	8,809,258	2,835,294	3.11
4433	1725	1724	1250	3079	1487	2.07	21,883,112	6,946,698	3.15
4300	1600	1600	1250	2950	1425	2.07	19,820,831	6,379,411	3.11
1890	800	800	500	1345	650	2.07	4,124,002	1,327,326	3.11
2358	850	850	700	1604	775	2.07	5,862,671	1,886,923	3.11

For each soft-rock maar identified in the CCVF, values of maximum and minimum diameters have been measured (Dmax and Dmin, measured from the crest of the tephra ring). Mean radius (R) is calculated as the half of the diameters. dmax, dmin and r are values corresponding to soft-rock maar lakes. The average surface area (S) for craters and their associated lakes (s) was estimated. All measurements were expressed on meters.

- Lorenz, V., Goth, K., Suhr, P., 2003. Maar-Diatrem-Vulkanismus – Ursachen und Folgen. Die Guttauer Vulkangruppe in Ostsachsen als Beispiel für die komplexen Zusammenhänge. Z. geol. Wiss., Berlin 31, 267–312.
- Lücke, A., Brauer, A., 2004. Biogeochemical and micro-facial fingerprints of ecosystem response to rapid Late Glacial climatic changes in varved sediments of Meerfelder Maar (Germany). Palaeogeogr. Palaeoclimatol. Palaeoecol. 211, 139–155.
- Martín-Serrano, A., Vegas, J., García-Cortés, A., Granda, A., Galán, L., Martín-Alfageme, S., Rubio, F.M., García-Lobón, J.L., Ibarra, P.I., Pérez-González, A., Gallardo-Millán, J.L., 2007. Tipología de los maares del Campo de Calatrava mediante criterios geomorfológicos, geofísicos y sedimentarios de sus registros lacustres asociados. In: Lario, J., Silva, P.G. (Eds.), Contribuciones al estudio del periodo Cuaternario. AEQUA, Ávila. Sección de Publicaciones de la Escuela Técnica Superior de Ingenieros Industriales. Universidad Politécnica de Madrid, pp. 205–206.
- Mingram, J., Schettler, G., Nowaczyk, N., Luo, X., Lu, H., Liu, J., Negendank, J., 2004. The Huguang maar lake—a high resolution palaeoenvironmental and palaeoclimatic changes over the last 78,000 years from South China. Quat. Int. 122, 85–107.
- Muñoz, A., de Vicente, G., 1998. Origen y relación entre las deformaciones y esfuerzos alpinos de la zona centro-oriental de la Península Ibérica. Rev. Soc. Geol. España 11, 57–70.
- Negendank, J.F.K., Zolitschka, B. (Eds.), 1993. Paleolimnology of European Maar Lakes. Springer-Verlag.
- Németh, K., Martin, U., 2007. Shallow sill and dyke complex in western Hungary as a possible feeding system of phreatomagmatic volcanoes in “soft-rock” environment. J. Volcan. Geotherm. Res. 159, 138–152.
- Németh, K., Martin, U., Harangi, S.Z., 2001. Miocene phreatomagmatic volcanism at Tihany (Pannonian Basin, Hungary). J. Volcan. Geotherm. Res. 111, 111–135.
- Németh, K., Goth, K., Martin, U., Csillag, G., Suhr, P., 2008. Reconstructing paleoenvironmental, eruption mechanism and paleomorphology of the Pliocene Pula maar, (Hungary). J. Volcan. Geotherm. Res. 177, 441–456.
- Pirrung, M., Fischer, C., Büchel, G., Gaupp, R., Lutz, H., Neuffer, F.O., 2003. Lithofacies succession of maar crater deposits in the Eifel area (Germany). Terra Nova 15, 125–132.
- Pirrung, M., Büchel, G., Lorenz, V., Treutler, H.C., 2008. Post-eruptive development of the Ukinrek East Maar since its eruption in 1977 A.D. in the periglacial area of south-west Alaska. Sed. 55, 305–334.
- Platt, N.H., Wright, V.P., 1991. Lacustrine carbonates: facies models, facies distribution and hydrocarbon aspects. In: Anadón, P., Cabrera, L., Kelts, K. (Eds.), Lacustrine Facies Analysis: Special Publication International Association of Sedimentologists, vol. 13, pp. 57–74.
- Poblete, M.A., 1995. El relieve volcánico del Campo de Calatrava (Ciudad Real). Junta de Comunidades de Castilla-La Mancha Ed., Gijón.
- Roberts, N., Reed, J.M., Leng, M.J., Kuzucuoglu, C., Fontugne, M., Bertaux, J., Woldring, H., Bottema, S., Black, S., Hunt, E., Karabiyikoglu, M., 2001. The tempo of Holocene climatic change in eastern Mediterranean region: new high-resolution crater-lake sediment data from central Turkey. The Holocene 11, 721–736.
- Schmincke, H.-U., 1988. Vulkane im Laacher See-Gebiet, ihre Entstehung und heutige Bedeutung. Bode, Haltern, pp. 1–119.
- Schulz, R., Buness, H., Gabriel, G., Pucher, R., Rolf, C., Wiederhold, H., Wonik, T., 2005. Detailed investigation of preserved maar structures by combined geophysical surveys. Bull. Volcan. 68, 95–106.
- Self, S., Kienle, J., Huot, J.-P., 1980. Ukinrek Maars, Alaska: II. Deposits and formation of the 1977 crater. J. Volcan. Geotherm. Res. 7, 39–65.
- Sohn, Y.K., Park, K.H., 2004. Composite tuff ring/cone complexes in Jeju Island, Korea: possible consequences of substrate collapse and vent migration. J. Volcan. Geotherm. Res. 141, 157–175.
- Stoffers, P., Holdship, S.A., 1975. Diagenesis of sediment in an alkaline lake: Lake Manyara, Tanzania. Proc. IXth Int. Conf. of Sedimentology. Nice 7, 211.
- Suhr, P., Goth, K., Lorenz, V., Suhr, S., 2006. Long lasting subsidence and deformation in and above maar-diatreme volcanoes – a never ending story. Zeitsch. Gessells. Geowissens. 157, 491–511.
- Vegas, J., García-Cortés, A., Galán, L., Pérez-González, A., Martín-Serrano, A., 2006. El registro sedimentario lacustre del maar de Fuentillejo (Ciudad Real). Bol. Geol. Min. 117, 339–349.
- Vegas, J., Martín-Serrano, A., García-Cortés, A., Granda, A., Martín-Alfageme, S., Rubio, F.M., García-Lobón, J.L., Ibarra, P.I., Galán, L., Pérez-González, A., Gallardo-Millán, J.L., Bernat, M., 2007. Morphotectonic setting of maar lakes in central Spain (Campo de Calatrava Volcanic Field). Abstracts of 4th International Limnogeology Congress (ILIC 2007): Limnogeology: Tales of an Evolving Earth, p. 155.
- Wagstaff, B.E., Kershaw, A.P., O Sullivan, P.B., Harle, K.J., Edwards, J., 2001. An Early to Middle Pleistocene palynological record from volcanic crater of Pejark Marsh, Western Plain of Victoria, southeastern Australia. Quat. Int. 83–85, 211–232.
- White, J.D.L., 1991. The depositional record of small, monogenetic volcanoes within terrestrial basins. SEPM Spec. Pub. 45, 155–171.
- White, J.D.J., McClintock, M.K., 2001. Immense vent complex marks flood-basalt eruption in a wet, failed rift: Coombs Hills, Antarctica. Geol. 29, 935–938.
- Wohletz, K.H., Zimanowski, B., 2000. Physics of phreatomagmatism; Part 1: Explosion physics. Terra Nostra 2000/6, 515–523.
- Zolitschka, B., Schabitz, F., Lücke, A., Corbella, H., Ercolano, B., Fey, M., Haberzettl, T., Janssen, S., Maidana, N., Mayr, C., Ohlendorf, C., Oliva, G., Paez, M.M., Schleser, G.H., Soto, J., Tiberi, P., Wille, M., 2006. Crater lakes of the Pali Aike next term Volcanic Field as key sites for paleoclimatic and paleoecological reconstructions in southern Patagonia, Argentina. J. South Am. Earth Sci. 21, 294–309.