Quaternary Science Reviews 96 (2014) 204–221

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Hydrothermal activity and its paleoecological implications in the latest Miocene to Middle Pleistocene lacustrine environments of the Baza Basin (Betic Cordillera, SE Spain)

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ARTICLE INFO

Article history:
Received 24 March 2013
Received in revised form
25 June 2013
Accepted 1 July 2013
Available online 1 August 2013

Keywords:
Lacustrine systems
Hot springs
Paleohydrochemistry
Large mammals
Paleoecology
Plio-Pleistocene

ABSTRACT

The continental sedimentary record of the Baza Basin (Guadix–Baza Depression, Betic Cordillera, SE Spain) shows six sedimentary units of lacustrine origin deposited from the latest Miocene to the Middle Pleistocene. Depending on the interval considered, the lacustrine deposits are mainly composed of marls, carbonates or gypsiferous evaporites, showing lithological, mineralogical and geochemical features (i.e., magnesium, strontium and sulfur contents, celestine deposits and travertine growths) that are evidence of intense, tectonically-induced hydrothermal activity. According to the high concentrations of strontium and sulfur as well as the abundance of travertines and magnesium clays, the supply of hot waters was greater during the Zanclean, the Gelasian and the Calabrian, as a result of tectonic activity. Hydrothermal activity has continued until the present time and is responsible of the hot springs that are nowadays active in the Guadix–Baza Depression. The paleoenvironmental consequences of these sublacustrine hot springs were that during some intervals the lakes maintained a relatively permanent water table, not subject to periodic desiccations in the dry season, and warmer temperatures throughout the year. This resulted in a high level of organic productivity, especially for the Calabrian, which allowed the development of a rich and well diversified mammalian community, similar to those of modern African savannas with tree patches. In this mild environment, the permanent water sheet favored the presence of drought intolerant megaherbivores such as the giant extinct hippo *Hippopotamus antiquus*. The high standing crop biomass of ungulates resulted in the availability of abundant carcasses for scavengers such as hyenas and hominins, which explains the very high densities of skeletal remains preserved in the sediments distributed along the lake surroundings.

1. Introduction

During the last decades, a number of issues related to the earliest arrival of hominins in Europe have been subject to intense debate, including the chronology of the first human settlements, the dispersal routes, the techno-cultural developments of the population that dispersed out of Africa, and the ecological context and climatic conditions of the dispersal event (for reviews and references, see Arribas and Palmqvist, 1999; Jiménez-Arenas et al., 2011; Toro et al., 2013).

Up to the mid-nineties, most researchers considered that no significant habitation took place in Europe before Middle Pleistocene times, as evidenced at the Boxgrove and Mauer sites (Roberts et al., 1994; Wagner et al., 2010). However, this was soon overturned by the discoveries of Early Pleistocene human remains and tools in a number of Western European sites covering a chronological range of ~1.4 to ~0.7 Ma. These findings include Barranco León and Fuente Nueva-3 in the Baza Basin, southeast Spain (Martínez-Navarro et al., 1997; Palmqvist et al., 2005; Espigares et al., 2013; Toro et al., 2013); Sima del Elefante and Gran Dolina TD-6 in Atapuerca, northwest Spain (Carbonell et al., 1995, 2008; Bermúdez de Castro et al., 1997, 2010; Falguères et al., 1999), and Happisburgh-3 and Pakefield in England (Parfitt et al., 2010). In addition, an earlier dispersal of *Homo* out of Africa is well

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http://dx.doi.org/10.1016/j.quascirev.2013.07.009

documented in Dmanisi, a Caucasian site at the gates of Europe dated at ~1.8 Myr (Vekua et al., 2002; Lordkipanidze et al., 2007; Ferring et al., 2011; Mgeladze et al., 2011).

The comparative analysis of the large mammal assemblages from these circum-Mediterranean sites, particularly the ones located in the Guadix–Baza Depression (Betic Cordillera, Southeast Spain), with those from Africa, the Near East and Asia has provided increasing evidence of continued faunal turnover during the Early Pleistocene (Palmqvist et al., 1996, 1999; Arribas and Palmqvist, 1999; Viseras et al., 2006; Arribas et al., 2009; Martínez-Navarro et al., 2011; Ros-Montoya et al., 2012). Specifically, the study of the huge assemblages of large mammals from the Baza Basin has shown that hominins did not disperse alone out of Africa, but were accompanied by other immigrants such as the saber-tooth felid *Megantereon whitei*, the short-faced hyena *Pachycrocuta brevirostris*, the hippo *Hippopotamus antiquus* and the giant gelada *Theropithecus oswaldi* (Martínez-Navarro and Palmqvist, 1995, 1996; Arribas and Palmqvist, 1999; Martínez-Navarro, 2004, 2010; Rook et al., 2004; Palmqvist et al., 2007, 2011). Faunal dispersal was a major subject of research for the late Professor Alan Turner, whose seminal work on carnivore taxonomy and paleoecology focused on establishing the patterns of large mammal turnover during the Neogene–Quaternary, as well as on evaluating the changing interactions between carnivores and hominins (e.g., Turner, 1990, 1992, 1999, 2007; Turner and Anton, 1996; Palmqvist et al., 2007; Turner and O'Regan, 2007; Dennell et al., 2008; O'Regan et al., 2011).

From the early seventies onwards, the models of stratigraphic architecture for the continental infilling of the Baza Basin were based on the existence of a number of lacustrine systems fed by alluvial waters (Vera, 1970; Peña, 1979, 1985; Fernández et al., 1996a; García-Aguilar, 1997; García-Aguilar and Martín, 2000; Ruiz-Bustos, 2011). Depending on the interval considered, these lacustrine systems resulted in marly, carbonate or evaporitic deposition. The lakes developed intermittently during the last 7.5 Ma of the sedimentary history of the basin and are separated by hiatuses of variable duration (García-Aguilar and Martín, 2000; García-Aguilar and Palmqvist, 2011). Up to present times, the origin of the lacustrine systems has been related to hydrological supplies of runoff waters (Vera, 1970; Peña, 1979, 1985; Viseras et al., 2005; Pla-Pueyo et al., 2011).

However, new analytical data from the lacustrine deposits as well as the review of the tectonic context of the basin for the interval between the latest Miocene and the Middle Pleistocene suggest that the lacustrine environments were also fed, at least in part, by hydrothermal supplies. In fact, many hot springs in the Guadix–Baza Depression have been known for centuries and some of them are even used today as spas due to their therapeutic qualities (e.g., thirteen are catalogued as showing various physicochemical properties; Diputación de Granada-ITGE, 1990). Pentecost et al. (2003) defined as hot springs those waters emerging with a temperature in excess of the core human body temperature (36.7 °C) and discarded the use of other terms (e.g., thermal springs or warm springs) because they cannot be defined satisfactorily for all springs. There are 13 springs in the depression that show output temperatures in excess of 18 °C. Although only two of these springs emerge with a temperature in excess of 36 °C, from a hydrogeological point of view they are considered as hot springs (Diputación de Granada-ITGE, 1990).

Peña (1979) and Sebastián-Pardo (1979) interpreted the presence of celestine and fluorspar in Plio-Pleistocene sediments from the lacustrine formations of the Baza Basin as reflecting hydrothermal activity. Later, García-Aguilar (1997) proposed that sublacustrine hot springs resulted from extensive tectonic activity in the basin during its period of continental sedimentation (i.e., latest Miocene to Late Pleistocene). The sedimentary singularity of the lacustrine formations of the Baza Basin (Arribas et al., 1988; Anadón et al., 1995; García-Aguilar and Palmqvist, 2011) and the rich paleontological assemblages unearthed from them (Arribas and Palmqvist, 1998, 1999; Palmqvist et al., 2005, 2011; Oms et al., 2011; Espigares et al., 2013; Toro et al., 2013) could be the result of the feeding of the lacustrine systems by waters from hot springs; this allows reconstructing a new paleoenvironmental and paleoecological scenario for the basin.

The main objectives of this article are two: (1) to show the main lithological, mineralogical and geochemical evidence in support of this hypothesis; and (2) to discuss the sedimentary and paleoecological consequences.

2. Geological setting

The Guadix–Baza Depression is a postorogenic, intramontane sedimentary area, ~110 km elongated NE-SO at ~1000 m elevation, which developed on the boundary region between the Internal and External Zones of the Betic Cordillera (Fig. 1). This depression was endorheic (i.e., characterized by interior drainage) from latest Miocene times (Viseras et al., 2005; Minwer-Barakat et al., 2009; Hüsing et al., 2010; García-Aguilar and Palmqvist, 2011; Pla-Pueyo et al., 2011), developing two depocenters (Guadix Basin and Baza Basin, respectively) with several depositional environments (Figs. 1 and 2).

Two successive lithological sets have been differentiated in the sedimentary infilling of the Guadix–Baza Depression, separated by an angular unconformity that may be recognized throughout the whole depression (Vera, 1970; Sanz de Galdeano and Vera, 1992; García-Aguilar and Martín, 2000; Viseras et al., 2005; García-Aguilar and Palmqvist, 2011; Pla-Pueyo et al., 2011). The oldest set (~1000 m thick) outcrops along the borders of the depression and is mainly composed of marine deposits of Late Miocene (Tortonian) age (Fig. 1B). The most modern set, latest Miocene (Turolian) to Middle Pleistocene in age, consists of a ~600 m thick sequence of continental deposits and covers the greater part of the depression, representing the thickest and most continuous record of Plio-Pleistocene continental sediments known in the Iberian Peninsula (and probably also in Europe). This set comprises the deposits that correspond to three formations traditionally defined in the depression, which show lateral changes of facies (Fig. 1B): (1) the Guadix Formation (Von Drasche, 1879; Vera, 1970), which has an alluvial and fluvial origin, and outcrops mainly in the western sector of the depression (Guadix depocenter); (2) the Gorafe-Huélago Formation (Vera, 1970), which corresponds to a carbonate lacustrine environment and is located in the northwestern sector of the Guadix Basin; and (3) the Baza Formation (Vera, 1970), which has lacustrine origin, outcrops in the eastern sector of the depression (Baza depocenter) and is mainly composed of limestones, marls and gypsum.

Six major phases of lacustrine deposition, some of them separated by stratigraphic hiatuses, are recognized in this article for the sedimentary infilling of the Baza Basin (Fig. 2), following García-Aguilar and Martín (2000): (1) latest Miocene pink marls; (2) Zanclean white and gray marls and calcilutites; (3) cyclical sequences of marls and marly limestones deposited during the latest Early Pliocene and the Late Pliocene (hereafter referred to as Piacenzian); (4) marls and gypsiferous evaporites of Gelasian age; (5) marls, marly limestones and sands of Calabrian age; and (6) Middle Pleistocene marls, pelites and limestones. In addition to these lacustrine deposits, travertine buildings of Late Pleistocene age outcrop in the vicinity of hydrothermal waters, for example those at the localities of Zújar in the Baza Basin and Alicún de las Torres in the Guadix Basin (García-Aguilar, 1997; Prado-Pérez, 2011).

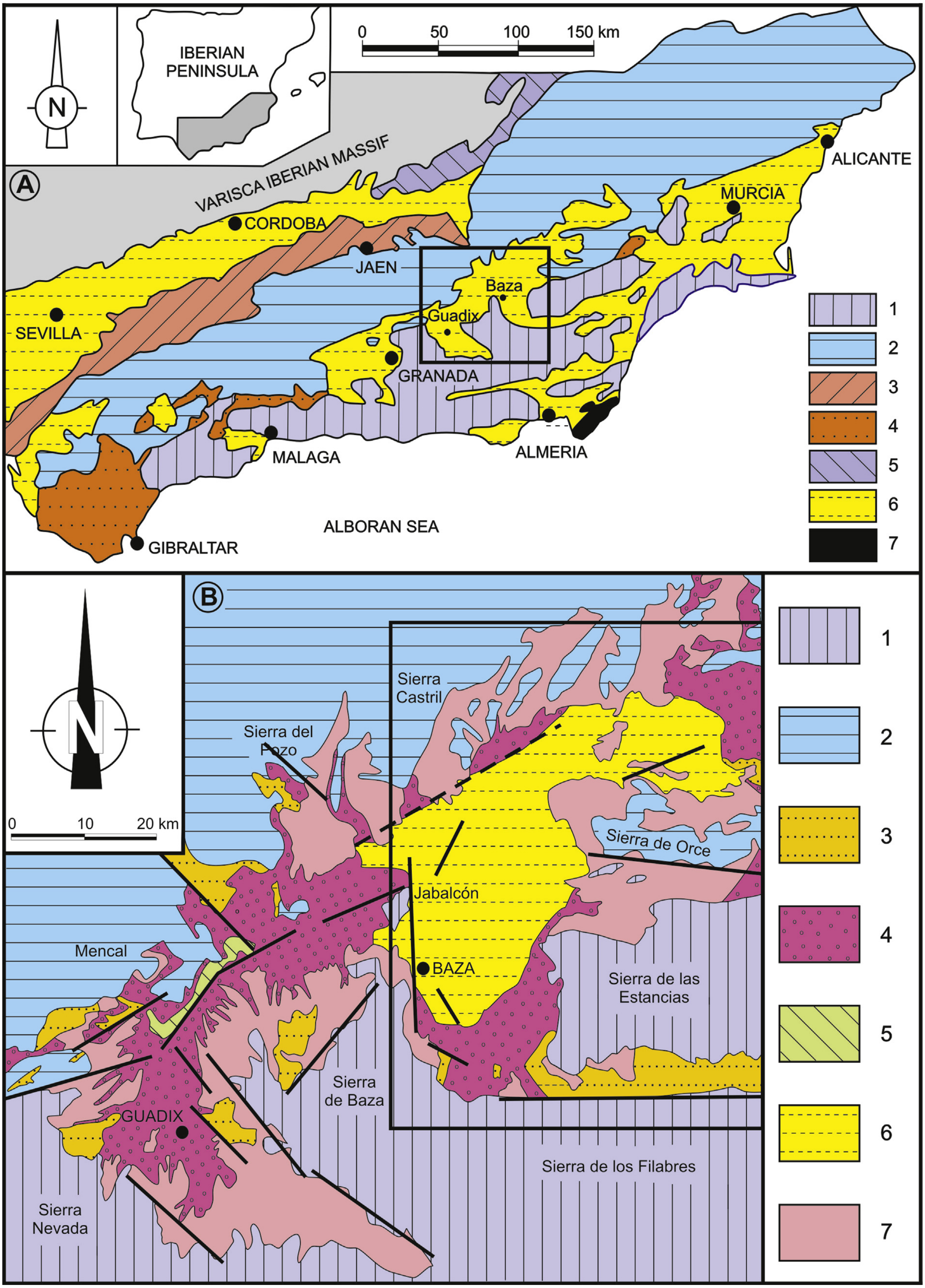

Fig. 1. Geologic context of the Guadix–Baza Depression. A: 1. Internal Zones of the Betic Cordillera; 2. External Zones; 3. Subbetic olitostromes in Miocene deposits of the Guadalquivir basin; 4. Flysch of the Campo de Gibraltar units; 5. Sedimentary cover of the Iberian Massif; 6. Neogene postorogenic basins; 7. Neogene volcanic rocks. B: 1. Internal Zones; 2. External Zones; 3. Marine sedimentary deposits of Miocene age; 4. Guadix Formation; 5. Gorafe-Huélago Formation; 6. Baza Formation; 7. Glacis surface. The upper and lower squares enclose the Guadix–Baza Depression (A) and the Baza Basin (B), respectively.

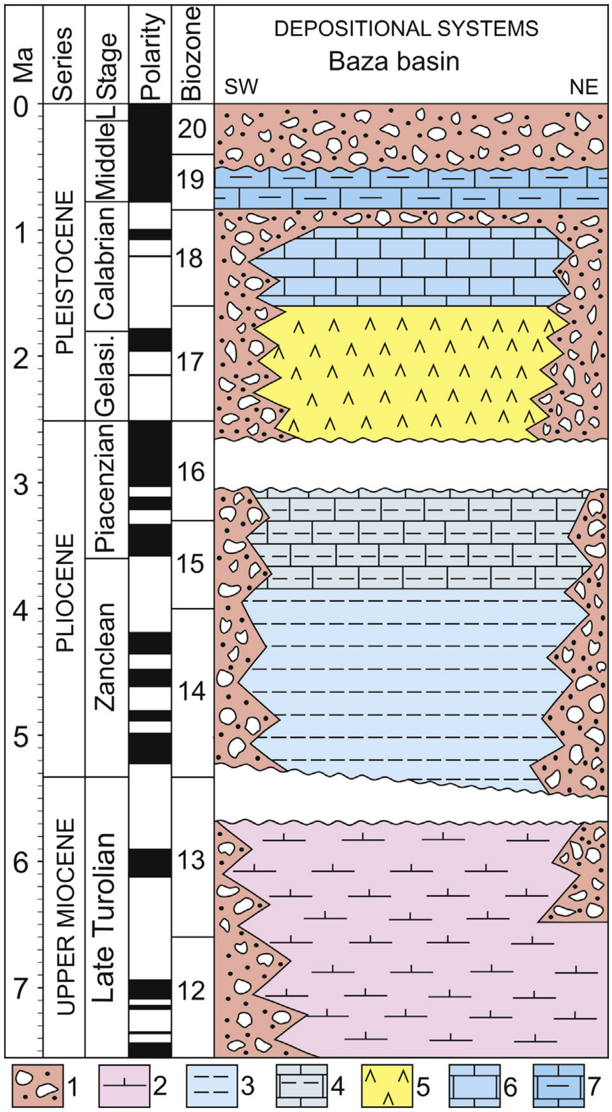

Fig. 2. Synthetic stratigraphic scheme for the period of continental sedimentation of the Baza Basin (adapted from García-Aguilar and Palmqvist, 2011). 1. Alluvial and fluvial sediments; 2. Lacustrine pink marls; 3. Lacustrine white and gray marls; 4. Lacustrine marly-limestone sequences; 5. Lacustrine marls and evaporites; 6. Lacustrine marls and limestones; 7. Lacustrine marls, lutites and limestones. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

It is worth noting that García-Aguilar and Palmqvist (2011) used a stratigraphic model based on the five tectono-sedimentary units defined by García-Aguilar and Martín (2000). However, we have considered here six stages of lacustrine sedimentation characterized by specific lithological patterns. Specifically, the tectono-sedimentary unit II of García-Aguilar and Palmqvist (2011), which has a Pliocene age, has been further subdivided in a lower (Zanclean) and an upper (Piacenzian) lacustrine stages.

Six major stratigraphic units have also been distinguished in the sedimentary infilling of the Guadix Basin (Fernández et al., 1996a; Viseras et al., 2005, 2006; Pla-Pueyo et al., 2009, 2011), although they correspond only in part to the ones used in this study. Specifically, the lower three units of the Guadix Basin were deposited during the period of marine sedimentation (Late Tortonian) and the upper three units cover the stage of exclusively continental sedimentation (Late Turolian to Late Pleistocene), when the Guadix Basin drained into the Baza Basin. Of the last three units, the second would include the Zanclean, Piacenzian, Gelasian and Calabrian lacustrine stages described above for the Baza Basin. Alluvial fans, fluvial sedimentation and ephemeral shallow ponds interpreted as wetlands predominate in the Guadix Basin, which only shows lacustrine sediments in its northern part (Fernández et al., 1993, 1996b; Viseras et al., 2005, 2006; Arribas et al., 2009; Pla-Pueyo et al., 2009).

The Guadix–Baza Depression underwent intense erosion since the capture of its hydrographic network by the Guadiana Menor River, a tributary of the Guadalquivir River. This event, which led to a stage in which erosion dominated over sedimentation, could took place in the late Middle Pleistocene (400 ka: García-Tortosa et al., 2008a, 2008b), or during the Late Pleistocene (100–17 ka: Viseras and Fernández, 1992; Calvache and Viseras, 1997; 42 ka: Azañón et al., 2006). As a result, a badlands landscape predominates now in the region, linked to a mean annual precipitation as low as ~200 mm in the inner parts of the depression.

3. Results

3.1. Lithostratigraphical and mineralogical characterization of the lacustrine sedimentation

This study is based on 20 out of 67 stratigraphic sections sampled by García-Aguilar (1997) through the Guadix–Baza Depression. Fig. 3 shows the location of these stratigraphic sections and Table 1 provides a synthesis of the major stratigraphic and tectono-sedimentary features of the six lacustrine stages defined in the Baza Basin, based on these sections. For the chronostratigraphic approach we considered: (1) the biostratigraphic information obtained from the mammalian fossil record of the Baza Basin (Agustí, 1986; Martínez-Navarro and Palmqvist, 1995; Turq et al., 1996; Arribas and Palmqvist, 1999, 2002; Oms et al., 2000a; Martínez-Navarro et al., 2011; Ruiz-Bustos, 2011; Ros-Montoya et al., 2012; Espigares et al., 2013); (2) the ages estimated for a number of archaeological and paleontological sites in the basin using U-series and the ESR method (Duval et al., 2011, 2012; Toro et al., 2013); and (3) available magnetostratigraphic data (Agustí et al., 1997, 1999, 2010; Garcés et al., 1997; Martínez-Navarro et al., 1997; Oms et al., 2000b, 2011; Toro et al., 2013).

Mineralogical and geochemical analyses (Table 2) were performed on 38 samples taken from 15 stratigraphic sections that comprise the latest Miocene to Middle Pleistocene lacustrine stages (Fig. 3). Mineralogical analyses of the marly facies were made with X-ray diffraction techniques (oriented aggregate), developed on both the total mineral fraction and the $<2\ \mu$ decarbonated fraction. In addition, mineralogical and geochemical analyses were made on samples from the organic-rich black levels present in both the Zanclean (black level 1) and Piacenzian (black levels 2–4) lacustrine facies (Fig. 3). García-Aguilar (1997) provides extensive information on the origin, sedimentological characteristics and facies relations for the black levels, as well as on the stratigraphical logs where these levels appear (for a summary, see legend of Fig. 3). Micro-textural analyses carried out on the calcareous facies are other sources of information for this study. Finally, data on the hydrochemistry of active hot springs at the basin were also used (Diputación de Granada-ITGE, 1990). Tables 2–4 provide a synthesis of all these data.

The earliest lacustrine unit, latest Miocene in age, consists mainly of pink marls and, secondarily, of interbedded detrital levels. This unit outcrops in the perimeter of the Guadix–Baza Depression and especially in the northern border of the Guadix–Basin (sector ‘Huélago-Cortes de Baza’). The $<2\ \mu$ mineral fraction of these marls shows high contents of smectite, illite, chlorite and, in most samples, palygorskite, as well as traces of fluorspar

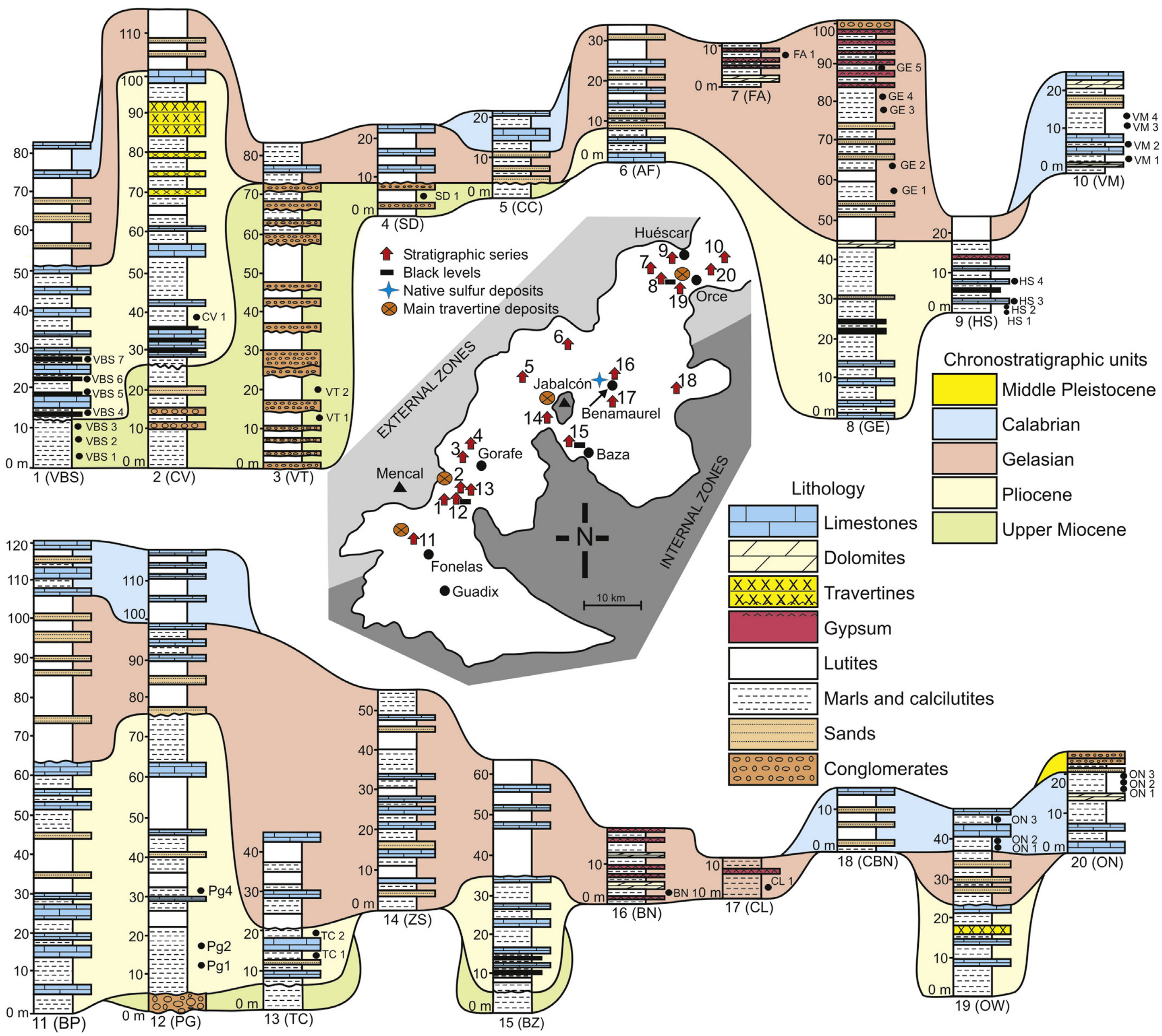

Fig. 3. Stratigraphic series sampled in the Guadix–Baza Depression and their lateral facies relationships (AF: Arroyo del Fique; BN: Benamaurel; BP: Barranco de las Palomas; CBN: Cúllar Baza Norte; CC: Cuevas del Campo; CL: Cortijo de la Legua; CV: Cortijo de Vera; FA: Fuente Amarga; GE: Galera este; HS: Huéscar sur; ON: Orce norte; OW: Orce oeste; PG: Puente de Gorafe; SD: Solana de las Dehesas; TC: Tollo de Chiclana; VBS: Veredas Blancas sur; VM:Venta Micena; VT: Villanueva de las Torres; ZS: Zújar sur). The location of the black levels and the main travertine and sulfur deposits is also shown.

(Table 2). The frequent presence of palygorskite could suggest that magnesium clays were originated mostly by neoformation, as discussed below, which would also account for part of the smectite contents.

After the first sedimentary hiatus (Fig. 2) there is a Zanclean lacustrine unit, which consists basically of light marls (Table 1). Its mineral fraction is dominated by smectite and illite, showing a nearly absence of palygorskite (Table 2). This unit outcrops between the localities of Fonelas and Gorafe in the Guadix Basin, as well as in the localities of Baza, Galera and Orce in the Baza Basin (Fig. 3). It is worth noting the presence of levels with high contents of both sepiolite (hs-2) and celestine (pg-1), and there is also a black level (vbn-1) at the top of this unit with a total fraction dominated by celestine (Table 2).

The Piacenzian lacustrine unit, in conformity over the previous one, is mainly composed of alternations of marls and limestone-rich beds (Table 1), although there are also thin sandy levels at the top of the unit. This unit outcrops in the same areas of the previous one and also in the localities of Fonelas and Huélago in the Guadix Basin, and Huéscar in the Baza Basin (Fig. 3). The mineralogy of the marls is similar to those of the previous unit (Table 2), with a general predominance of smectite and illite. Some levels show also an abundance of celestine (pg-4 and tc-2) and a significant presence of palygorskite (pg-4 and cv-1). Concerning the limestone facies, the presence of travertine growths and stromatolites stands out, and there are also several black levels (Fig. 3) with high contents of celestine in the total-rock fraction (Table 2).

Actively forming travertine and tufa sites are widespread in temperate and warm climates, such as the Mediterranean region. Physico-chemical precipitation of calcium carbonate is usually considered as the main mechanism contributing to tufa and travertine deposition. Rapid cooling of waters further aids the process

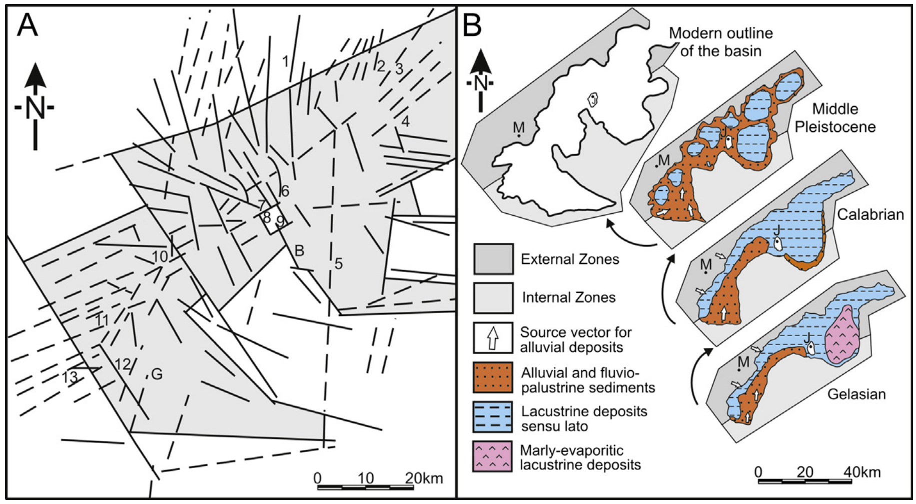

Fig. 4. A: Map of fractures of the Guadix–Baza Depression, drawn from satellite images. B: Paleogeographic evolution for the Guadix–Baza Depression since the Gelasian (modified from García-Aguilar and Martín, 2000). Position of hydrothermal springs according to Diputación de Granada-ITGE (1990): 1. Los Tubos; 2. Parpacén; 3. Fuencaliente-Huéscar; 4. Fuencaliente-Orce; 5. Cortijo de Curcás; 6. Baños de Zújar; 7. Fuencaliente; 8. Las Calenturas; 9. Panadero; 10. Baños de Alicún; 11. Fuente Alta; 12. Baños de Graena; 13. Los Bañuelos. (B: Baza, G: Guadix, J: Jabalcón Mountain –1492 m, M: Mencal Mountain –1447 m).

in hot spring travertine sites and biomediation of calcium carbonate, associated with prokaryote–microphyte biofilms (cyanobacterial, heterotrophic bacterial and diatoms), is recognized as equally important for carbonate precipitation (Pedley, 2009). However, although the terms travertine and tufa are sometimes applied indiscriminately, each has a specific definition. According to Pentecost (1993), most travertines are formed by degassing of calcium bicarbonate rich-waters (>90% in $CaCO_3$ contents) and use to be composed of calcite crystallized as micrite or microspar, as happens in the Baza Basin (García-Aguilar, 1997). In contrast, the term tufa refers to freshwater meteogene carbonates resulting from precipitation under a cool or near-ambient temperature (Ford and Pedley, 1996). Late Pleistocene to Holocene tufa deposits have been identified in a high-gradient and stepped fluvial system of the central sector of the Betic Cordillera (García-García et al., 2013).

It is worth noting that although travertine growths can show different facies, including stromatolites, stromatolites can be related to both travertines (thermogene) and tufas (meteogene) (Pentecost, 1993; for a good example of stromatolitic deposits associated to Quaternary tufa, see Vázquez-Urbez et al., 2012). For this reason, the presence of stromatolites is not indicative by itself of the presence of a hot water spring, as they can develop in a lacustrine setting without the supply of hot waters or as part of a fluvial tufa system (e.g., Vázquez-Urbez et al., 2010; García-García et al., 2013).

In the case of the Guadix–Baza Depression, travertine bodies are associated to a number of hot springs which are now active, for example the one of ‘Alicún de las Torres’. However, it is worth noting that a recent study has dated the starting of the travertine formation of this hot spring in only 250 ka (Prado-Pérez, 2011). This means that, at least for this hot spring, hydrothermal activity was not significant during the Pliocene and the Early Pleistocene.

The Pliocene travertines of the Baza Basin can be interpreted as carbonated rocks of massive fabric originated near water springs and include abundant vegetal remains (Pentecost, 1993, 1995, 2005; Pentecost and Viles, 1994). They show pseudostratiform levels of limited lateral continuity (~100 m) and an average thickness of 80–120 cm. These levels are frequently superimposed in banks which thickness can exceed 8 m, for example in the zone of ‘Cortijo de Vera’, placed to the north of the locality of Gorafe (Guadix Basin). Travertines are sometimes interbedded in levels of white massive marls with an average thickness of 10 cm. It is also

Table 1
Main stratigraphic and tectono-sedimentary features of the six lacustrine units defined in the Baza Basin for the interval between the latest Turolian and the Middle Pleistocene. Sedimentation rates were calculated in the lacustrine deposits *sensu lato* (García-Aguilar and Martín, 2000; García-Aguilar et al., 2013). Correspondence with the five genetic units and the three stratigraphic formations traditionally defined in the Guadix–Baza Depression (GF: Gorafe-Huélago, G: Guadix, B: Baza) after García-Aguilar and Palmqvist (2011).

Formation	Genetic unit	Lacustrine unit	Temporal limits (Ma)	Maximum thickness (m)	Sedimentation rate (cm/ka)	Tectonic features	Thickness of limestones (%)	Thickness of marls (%)	Thickness of clastics (%)
G, B	V	Middle Pleistocene	0.8–0.4	8	1.9	Fracturing	19 (dolomite 6)	20	61
G, B	IV	Calabrian	1.55–1.25	10	2.3	Fracturing	40 (dolomite 8)	32	28
G, B	III	Gelasian	2.5–1.6	240 visible (400 in seismic profiles)	26.6 (44.4 according to seismic profiles)	Major axis NNE-SSO oriented, slumpings	4 (dolomite 3.6)	70	21
GH	II	Piacenzian	3.8–3.1	50	7.1	50°–70°NE aligned, fracturing	31 (travertines 4)	55	13
		Zanclean	5.1–3.8	30	2.3	50°–70°NE aligned, slumpings	0	90	9
GH, G	I	Latest Turolian	7.3–5.7	170 visible (600 in seismic profiles)	10.6 (37.5 according to seismic profiles)	15°S 50–70°NE aligned	0	86	13

Table 2
Mineralogical analyses of marls from the six lacustrine units of the Guadix–Baza Depression (data from García-Aguilar, 1997). Values represent percentages (%) over the total contents of each sample. Key for minerals: C (calcite), D (dolomite), Q (quartz), Ph (phyllosilicates), G (gypsum), Fd (feldspars), Cl (chlorite), Cel (celestine), Pr (paragonite), Sm (smectite), I (illite), K (kaolinite), Pl (palygorskite), S (sepiolite). A: sum of total averages of inherited clay minerals per unit (Pr + I + K + Cl); B: sum of total averages of neoformed clay minerals per unit (Pl + S + Cel). Smectites are not considered given their dual origin (Sebastián-Pardo, 1979). Key for samples: bn – Benamaurel, cl – Cortijo de la Legua, cv – Cortijo de Vera, fa – Fuente Amarga, ge – Galera este, hs – Huéscar sur, on – Orce norte, ow – Orce oeste, pg – Puente de Gorafe, tc – Tollo de Chiclana, vbs – Veredas Blancas sur, vm –Venta Micena, vt – Villanueva de las Torres (for location of sampling localities, see Fig. 3).

Units	Samples	Total fraction								<2 μ fraction										
		C	D	Q	Ph	G	Fd	Cl	Cel	Pr	Sm	I	K	Cl	Pl	Cel	S	A	B	B/A
Middle Pleistocene	on-3	64	3	18	15						15	31	6	12	36			68	12	0.18
	on-2			46	54					7	27	52	10	4						
	on-1	51	9	18	22						18	61	12	9						
Calabrian	vm-4	0	46	38	16						6	34		7	53			52.6	32.1	0.61
	vm-3	56		16	28						4	38	4	4	50					
	vm-2	79		19	2						10	52		5			33			
	vm-1		42	15	43						8	58	8	4	22					
	ow-3		47	22	31						10	50	4	5	31					
	ow-2	49		25	26						55	37		8						
	ow-1										15	40	3	7	36					
Gelasian	ge-5	19	19	20	2	40												34.8	1.9	0.05
	ge-4		73	9	18	0					63	35		2						
	ge-3		45	13	28	14					43	52		5						
	ge-2	17	24	16	8	35														
	ge-1	57	1	14	27	1					39	52	5	4						
	fa-1		50	8	39		3				61	24	2	4		3				
	cl-1	19	53	2	7	19				18	51	16				10				
	bn-1		44	9	13	34				3	39	44	7	5	2					
Piacenzian	tc-2			20	50		9		21		11	46		9		27		30.5	10.5	0.34
	tc-1	12	11	9	59		5	4			78	10	2	6						
	cv-1	75	1	4	15				2	3	62	16	2	8	9					
	pg-4	60			15	15			10	6	30	32	1	4	5	22				
	black level 4 (vbs-7)		42	10	11		11		26											
	black level 3 (vbs-6)		5	28	16		10		41											
	black level 2 (vbs-5)			22	14		10		54											
	hs-4	71	2	5	22						62	32	3	3						
	hs-3	18	4	30	48															
Zanclean	black level 1(vbs-4)		3	27	10		6		54									36.3	23.8	0.66
	pg-2	95		5			0			3	73	11	1	9	1					
	pg-1	67	1	5	20	2	5				27	45	2	10		16				
	hs-2	99			1						5	15	1	1			78			
	hs-1	97	1	1	1						53	33	8	6						
Latest Miocene	vbs-3	65		15	15				5	4	30	30	8	8	10	2		38.1	20.2	0.53
	vbs-2	89		7		4				7	49	20		5	10	2				
	vbs-1	67		5	20	2	5				30	23		10		22				
	sd-1	50	1	3	45						2	42		20	36					
	vt-2	72	2	3	23						33	47		3	17					
	vt-1	55	5	5	35						28	47		3	22					

common the appearance of pisolitic gravels composed of reworked travertine fragments at the base of each travertine level. Internally, these rocks have abundant pores and hollows of pseudocylindrical shape, with mean diameters of millimetric scale and decimetric length, together with plates, concretions and calcareous halos of millimetric thickness (Fig. 5). In some cases, the high porosity of these deposits allows to classify them as "calcareous tufa" (Pentecost, 1993). However, given the lateral and vertical variations

Table 3
Physico-chemical analyses of thermal springs from the Guadix–Baza Depression (modified from Diputación de Granada-ITGE, 1990). All ionic values are in meq L^{-1}. The number of each water source appears in the map of Fig. 3.

Source of spring waters	T (°C)	Water flow (L s^{-1})	Conductivity (μS cm^{-1})	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	Cl^-	SiO_2
1. Los Tubos	22	100	600	3.2	2.7	1.0	R	5.3	0.7	0.9	–
2. Parpacén	18	150	750	5.1	3.7	0.6	R	4.7	3.0	0.6	–
3. Fuencaliente Huéscar	19	400	1034	4.8	4.0	3.0	0.1	4.2	2.7	3.1	–
4. Fuencaliente Orce	21	80	1034	6.4	3.6	2.3	0.4	5.4	4.8	2.6	–
5. Cortijo del Curcás	28	1	–	–	–	–	–	–	–	–	–
6. Baños de Zújar	38	180	4700	30.2	12.3	34.2	0.4	2.5	35.2	36.2	42
7. Fuencaliente	21	15	1250	7.7	3.3	0.9	0.1	4.8	6.5	0.7	–
8. Las Calenturas	18	2	1790	7.7	11.4	2.0	0.4	7.0	12.0	2.4	–
9. Panadero	18	1	1420	6.8	7.9	0.6	0.1	7.3	7.9	0.7	–
10. Baños de Alicún	34	240	1525	17.4	7.0	2.8	0.1	4.2	21.9	2.5	16
11. Fuente Alta	22	150	610	6.2	2.4	1.7	0.1	3.4	3.6	2.2	11
12. Baños de Graena	44	10	2650	30.4	8.0	0.9	0.2	2.3	31.4	0.6	54
13. Los Bañuelos	30	1	3410	26.8	9.4	4.7	0.4	2.8	31.5	6.1	–
Mean	26	Total: 1330	1731	12.7	6.3	8.4	0.2	4.5	13.5	4.9	31

Table 4
Comparative analysis (units in %) between physico-chemical parameters of lignite (data from Espinosa and Rey de la Rosa, 1984) and those of the black levels from the Pliocene lacustrine units of the Guadix–Baza Depression (data from García-Aguilar, 1997).

Factor	Lignite s.s.	Early Pliocene unit (black level 1)	Late Pliocene unit (mean for black levels 2–4)
Hygroscopic moisture	48	3.8	4.7
Ashes	20	89.0	69.3
Volatile matter	42	15.3	17.5
Fixed carbon	32	0.5	3.6
Mineral matter	–	96.0	96.3

in porosity, they must be classified under the more general term of “travertine”.

The black levels of Pliocene age are found in the transition between the Zanclean and Piacenzian lacustrine units, which outcrops in the surroundings of the localities of Fonelas, Gorafe, Baza, Galera and Huéscar (Fig. 3). Depending on the stratigraphic sequence, there are between four and eight black levels of centimetric thickness, dark gray tones and massive internal structure, and it is frequent the appearance of small gastropods in them. These black levels are found at the bottom and the top of the marly-limestone strata, interbedded between alternations of marls and light-toned calcilutites, or interbedded between levels of bioturbated lutites.

The lacustrine unit of Gelasian age (Fig. 3, Table 1) outcrops only in the Baza Basin and consists of a sequence of marls alternating with gypsum. The mineralogical composition of the marls does not differ to a great extent from that of the previous Piacenzian stage, although they show higher contents of illite and only traces of palygorskite. The high contents of dolomite and gypsum in the total mineral fraction are also prominent (Table 2). Another aspect of geochemical interest is the finding of deposits of native sulfur in the central sector of the Baza Basin, represented by thin levels interbedded in the rhythmic marly-evaporitic series or found as infillings in the cavities and hollows of this series.

The lacustrine unit of Calabrian age outcrops mainly in the Baza Basin, in the surroundings of Orce and Huéscar, and consists of alternations of carbonates, marls and sandy levels (Fig. 3, Table 1). The carbonates show biomicritic-travertine facies with similar features to those of the Piacenzian unit and travertines preserved as reworked blocks. The marls of this unit show alternations of levels with high contents of calcite or dolomite, and compared to the preceding unit there is also an increase of quartz in the total mineral fraction (Table 2). The $<2\ \mu$ mineral fraction records a decrease in the abundance of smectite and an increase of illite, and palygorskite is abundant in most levels (Table 2). Concerning the sepiolite, a level (vm-2) from the fossil site of Venta Micena shows important concentrations, with values of up to 33% of the $<2\ \mu$ mineral fraction.

The last unit with lacustrine deposits has a Middle Pleistocene age and outcrops exclusively in the Baza Basin, mainly in the surroundings of Orce and Cúllar (Fig. 3). It is made of detrital facies with levels of marls and limestones intercalated (Table 1). The marls (samples on-1 and on-3) show higher contents of calcite than of dolomite, and also an increase in both the abundance of quartz

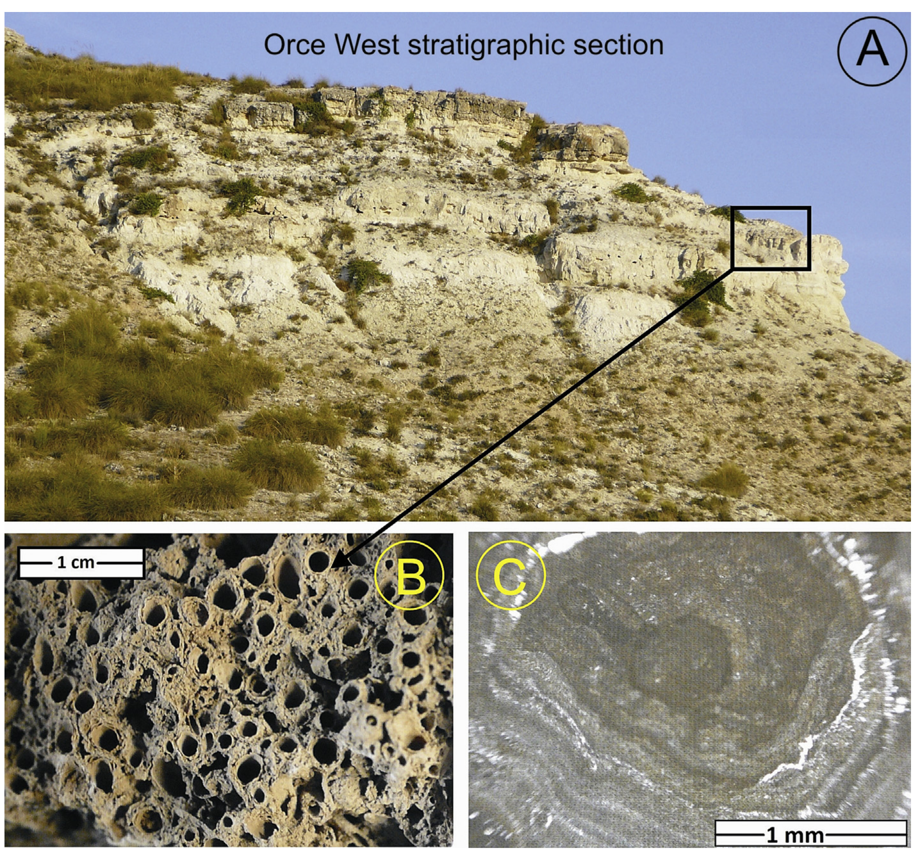

Fig. 5. A: photograph of the lower part of the Orce West stratigraphic series, which shows marls of Zanclean age to the bottom and marls, limestones and travertines of Piacenzian age to the top. The square indicates the outcropping of a travertine level that has limited lateral continuity and an average thickness of two meters. B: photograph taken at centimetric scale of the travertine level, which shows cylindrical casts of vegetal remains surrounded by concentric growths of carbonates. C: photograph taken at millimetric scale of a section of these $CaCO_3$ concretions.

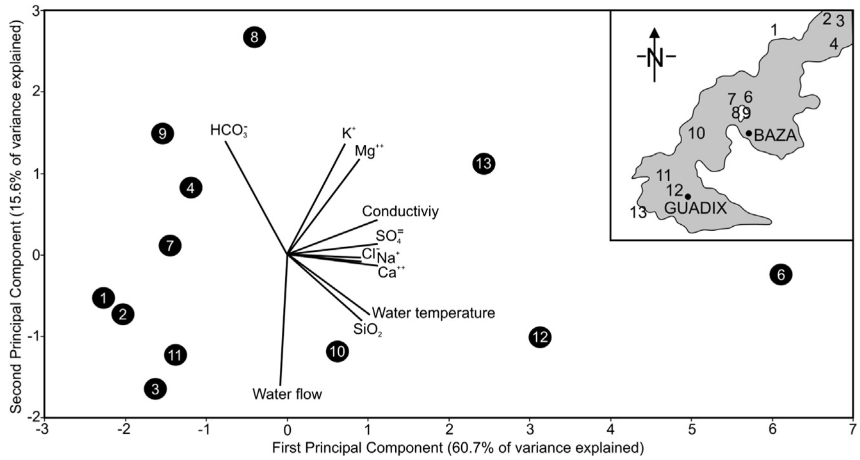

Fig. 6. Bivariate plot for the scores of the hydrothermal springs that are nowadays active in the Guadix–Baza Depression on the two first axes of the principal components analysis (PCA), which jointly account for 76.3% of the original variance of the hydrochemical variables analyzed (Table 3). Spring number 5, 'Cortijo del Curcás', was excluded from this analysis given the absence of data on ionic contents. For those variables in which data were missing for some springs, the means were used in PCA.

and phyllosilicates compared to the preceding units (Table 2). Illite is more abundant than smectite in the <2 μ mineral fraction, as in the previous unit, and palygorskite contents are relatively high in one sample (on-3) (Table 2).

3.2. Tectonic activity during the lacustrine sedimentation

The main tectonic features of the Guadix–Baza Depression can be synthesized in: (1) a dense and complex faulting network that is evidence for intense tectonic activity; (2) high rates of subsidence estimated for specific periods of continental deposition; and (3) the presence of paleoseismites in its sedimentary record.

The well-developed faulting network includes three major systems of fractures (NE-SW, NW-SE, and NNE-SSW oriented) which affect both the substrate and the sedimentary infilling (Fig. 4A). The main system belongs to the Cádiz-Alicante Fault, a major transcurrent-faulting system associated with the contact between the External and Internal Zones of the Betic Cordillera (Sanz de Galdeano and Vera, 1992; Sanz de Galdeano, 2008). This system crosses the basin in a N50–70E direction and its greater transcurrent activity took place during the Early-Middle Miocene. It is affected by faults from the other two systems (NW–SE and NNE–SSW oriented), which developed mainly during the Late Miocene. They acted usually as normal faults, delimiting tectonic blocks that allowed the differentiation of various sectors or sub-basins with different subsidence and sedimentary evolution (Sanz de Galdeano and Vera, 1992; Sanz de Galdeano and Peláez, 2007). The Baza Fault, a 37-km-long NE-dipping normal fault, stands out in the NW-SE system. It created a half-graben in its hanging wall, which divided the depression into two sectors: Guadix Basin to the West and Baza Basin to the East (Alfaro et al., 2008).

Tectonic activity during the period of continental sedimentation determined to a large extent the sedimentary and paleogeographic evolution of the Guadix–Baza Depression. For example, the outcrops of the latest Miocene unit show a cartographic association with the main traces of fractures of the basin, especially with the major N50–70E faulting system. In addition, the unconformity to the top of this unit relates to a tectonic phase, which caused the tilting of the latest Miocene deposits. Similarly, the elongated, N70E oriented lake where the Gorafe-Huélago Formation was deposited (Zanclean and Piacenzian units) relates to the Cádiz-Alicante Fault (García-Aguilar and Martín, 2000).

Tectonic activity resulted also in high rates of subsidence and sedimentation during the latest Miocene and the Gelasian (García-Aguilar and Martín, 2000). These rates have been calculated in the lacustrine units of the Baza Basin using stratigraphic, seismic, magnetostratigraphic and biostratigraphic data (Table 1). The increase in subsidence and sedimentation seems to be linked to a significant ENE-WSW tectonic expansion of the basin, which affected the central sector of the Betic Cordillera (Galindo-Zaldívar et al., 1999; Sanz de Galdeano and López-Garrido, 2000; García-Aguilar et al., 2013). The Baza Basin showed a decrease in the rate of sedimentation during the Calabrian and the Middle Pleistocene, as deduced from the lower thickness of these two units (Table 1). This suggests a relaxation of tectonic activity in the region. The Guadix Basin experienced also a decrease in the sedimentation rate during this time interval. This has been attributed to a decrease in the accommodation space creation, which could be related to a relaxation of tectonic activity, but also to the fact that the basin was almost filled (Soria et al., 1999; Pla-Pueyo et al., 2009).

Tectonic activity during the Gelasian and the Calabrian is also indicated by the presence of paleoseismites and slumpings of Early Pleistocene age (Alfaro et al., 1997, 2010). This activity continues today and is manifested by seismic movements and hot springs (Rodríguez-Pascua, 2005; Sanz de Galdeano and Peláez, 2007). Moreover, there is a relationship between the main faults and the position of the hot springs (Fig. 4A), which is more evident in those cases where different types of faults interweave. Thus, the network of fractures could have determined the formation of hot springs, which are still significant today.

3.3. Recent hydrothermal activity in the basin

Table 3 synthesizes the physico-chemical properties of the hot springs that are active in the Guadix–Baza Depression. Among the data provided, the values of mean output temperature (26 °C), total input flux (1330 L s^{-1}) and hydrochemical variability stand out, with a predominance of calcium-sulfate facies.

Three of the hot springs (numbers 3, 6, and 10 in Fig. 4A) concentrate more than half of the total water flux. Although there are important differences of output temperature, ionic contents and conductivity among the hot springs, a principal components analysis showed that there is no evident pattern for the variations of these factors and the geographic position or geological context of the hot springs (Fig. 6). However, water temperature correlates positively with conductivity ($r = 0.709$, $p < 0.01$) and also with the contents of calcium (r = 0.921, p < 0.001), sulfates (r = 0.878,

$p < 0.001$) and silica ($r = 0.899$, $p < 0.001$), showing a negative correlation with carbonate contents ($r = -0.757$, $p < 0.01$).

Another feature that must be taken into account is the appearance of sub-recent travertine formations associated with hot springs, some of them >10 m thick, for example the ones in the vicinity of the spas of 'Alicún de las Torres' and 'Baños de Zújar' (10 and 6 in Fig. 4A, respectively) (García-Aguilar and Palmqvist, 2011; Prado-Pérez, 2011; Prado-Pérez and Pérez del Villar, 2011).

The presence of these hot springs, their association with the regional tectonic context of the basin as well as the physicochemical and biological properties of the hot waters should all be extrapolated to the different intervals of continental sedimentation of the basin. As indicated before, this is indicated by the continued tectonic dynamism of the region during this period and also by the presence of mineralogical, geochemical, lithological and paleoecological indicators that are all in agreement with the presence of past hydrothermal activity. This suggests that the Plio-Pleistocene lakes were frequently subject to sublacustrine feeding by hot springs. However, it should be noted that this does not mean that environmental conditions remained constant throughout the whole period of continental sedimentation of the Guadix–Baza Depression. In contrast, there is strong evidence of: (1) pronounced changes in the composition of the mammalian assemblages during the Late Miocene and the Plio-Pleistocene, which would relate to faunal dispersal events favored by climate oscillations (e.g., Arribas and Palmqvist, 1999; Martínez-Navarro, 2004, 2010; Minwer-Barakat et al., 2005, 2009; Palmqvist et al., 2007; Arribas et al., 2009; Martínez-Navarro et al., 2011); (2) sedimentological drastic changes in both the Guadix Basin (Pla-Pueyo et al., 2009, 2011) and the Baza Basin (García-Aguilar and Palmqvist, 2011); (3) changes in tectonic activity resulting from a relaxation towards the end of the sedimentation in the last lacustrine units of the Baza Basin, as described before; and (4) changes in the abundance of travertines and clay minerals in the marly sediments of the lacustrine units, which indicate variations in hydrothermal activity.

4. Discussion

The lithological, mineralogical and geochemical data from the latest Miocene to Middle Pleistocene lacustrine units of the Baza Basin suggest the existence of hydrothermal supplies to the lake waters. Specifically, the main evidence includes the finding of: (1) magnesium clays (palygorskite and sepiolite); (2) strontium anomalies (celestine); (3) deposits of native sulfur; and (4) travertine formations.

Although poorly represented in the Zanclean unit, magnesium clays are found in the six lacustrine units and tend to concentrate in the localities placed near the major tectonic fractures, close to those hot springs that are nowadays active. In contrast, there is no significant concentration of these clays in the localities where tectonothermal phenomena are absent (Fig. 3, Table 2). The presence of magnesium clays in sediments from lacustrine environments is frequently interpreted as resulting from mechanisms of concentration of magnesium during the early stages of diagenesis in sedimentary environments with significant magnesium and silicon contents, and with low aluminum concentrations (Isphording, 1973; Khoury et al., 1982; García-Romero, 2004). In this way, palygorskite and sepiolite use to be associated to hypersaline environments with alkaline pH values (8–10), which indicate arid conditions (Siffert and Wey, 1962; Wollast et al., 1968; La Iglesia, 1977).

Khoury et al. (1982) cited the presence of magnesium clays in the Nevada Desert linked to hot springs in Plio-Pleistocene alkaline lacustrine environments with low evaporation rates. The same deposits are associated with numerous active hot springs that show a range of output temperatures of 21–34 °C. This model suggests an origin for the thermal waters linked to a tectonically active landscape and the alteration of volcanic sediments located at depth. In addition, Isphording (1973) associated the presence of palygorskite and sepiolite to precipitation of carbonate rocks (limestones, dolomites and travertines) in magnesium-rich waters of hydrothermal origin. Therefore, it seems logical to consider a more prominent role for hydrothermal phenomena at those sites of the Guadix–Baza Depression where higher contents of sepiolite and palygorskite have been detected (e.g., the Orce-Venta Micena sector for the Calabrian and the area of Gorafe for the Piacenzian).

In the case of an intense washing of sediments or under precipitation of >300 mm per year, the clays are hydrolyzed (Paquet and Millot, 1972). For this reason, finding such clays in the sedimentary infillings of the basin could suggest, at first glance, the presence of a poorly drained lacustrine environment subject to intense evaporation. However, it is not possible to explain magnesium anomalies as resulting from intense evaporation, as this would have not caused a shift to the very alkaline pH values recorded in the sedimentary environment. Instead, this suggests that the lake waters had high concentrations of magnesium, thus reaching chemical stability and generating significant deposits of palygorskite and sepiolite. Most mineral sites with these clays are linked to source areas composed of volcanic rocks or with endogenous fluids of hydrothermal origin (García-Romero, 2004). In our case, given that there is no volcanic source in the immediate vicinity of the Guadix–Baza Depression, the most plausible mechanism to explain the finding of magnesium anomalies is the contribution of hydrothermal waters to the lacustrine system, as suggested by Khoury et al. (1982) for the Amargosa Desert. Moreover, a prominent contribution of magnesium from hot springs to the sedimentary environment also accounts for the presence of dolomite levels in the lacustrine sedimentation during the Gelasian and the Calabrian.

Celestine contents are found in 8 out of 35 samples of marly sediments from latest Miocene to Gelasian age (Table 2). It is worth noting that this mineral is associated with the black levels found in the Pliocene units. Although these levels were originally identified as lignite deposited in a lacustrine environment (Peña, 1979), subsequent analyses (García-Aguilar, 1997) showed that their values of fixed carbon, volatile components, hygroscopic humidity and ash contents are quite different from those of lignite (Table 4), which suggests an inorganic origin (Espinosa and Rey de la Rosa, 1984). Elevated strontium contents use to be associated with high levels of phytoplankton productivity and thus, to an elevated concentration of organic matter in the water–sediment interface, which causes anoxia and the preservation of organic matter in the sediment (Reolid et al., 2010).

Tritlla et al. (2006) explained the presence of strontium in 'Mississippi Valley' sediments of Mexico from lacustrine environments with a model of circulation of strontium-rich fluids through the stratigraphic series. This flow resulted in mineralized stratiform bodies of simple composition (celestine) associated to high concentrations of organic matter and temperatures of formation comprised between 90 °C and 150 °C, which seems to be the case for the black levels of Zanclean age in the Guadix–Baza Depression. The association between strontium deposits in lacustrine sediments and endogenous activity was cited by Neat et al. (1979), who described detritic inputs of volcanogenic components with high strontium contents. There is no source of volcanic detritus in the Guadix–Baza Depression, except for some isolated outcrops in the surroundings of the 'Negratín' water reservoir, which belong to small masses of ophites included in the Triassic Keuper facies of the Subbetic units. However, the presence of these units at depth could explain strontium intake as resulting from sublacustrine hot springs linked to the well-developed network of tectonic fractures of the depression, which would be in agreement with the finding of celestine contents in the black levels.

C. Jones et al. (1994) related the presence of hydrothermal fluids with an increase of strontium contents in the sediment. Similarly, Pisarskii et al. (1998) cited strontium anomalies in Quaternary carbonate deposits from Tanzania associated with hot waters, which have an output temperature of 65 °C in the African Rift Valley. These thermal waters show elevated concentrations of CO_2, SiO_2, Mg^{2+}, carbonates and alkalis. In this case, the hot springs originate from deep zones with strontium-rich, alkaline-carbonate magmatic rocks. Canals et al. (1990) described a similar model for concentration of strontium in Neogene sedimentary rocks from La Garriga (Spain), linked to geothermal anomalies that generated thermal waters with an output temperature of 60 °C. These waters altered deep granite rocks, incorporating high concentrations of sodium and strontium.

Deposits of native sulfur are found in the Gelasian sediments of the Baza Basin near the locality of Benamaurel (Fig. 3). These deposits could be produced by the action of sulfate-reducing bacteria in evaporitic zones with gypsum deposits. The sulfur compounds form stratiform deposits in the cavities and veins of the host rocks (evaporites and marls), as well as infillings in the hollows and cavities of the marly-evaporitic series, thus indicating the contribution of sulfate-rich hot springs (Holmberg, 1957; Gabrielle, 1993). This interpretation agrees with the environment deduced for the Baza Basin during the Gelasian, because the thermal fluids from deep zones would have dissolved a high concentration of sulfates from the Triassic formations (Keuper facies) of the Subbetic Domain. It is worth noting that the sulfur deposits found in Aptian coals from Teruel (Querol et al., 1993) represent a similar case. In this way, Dando et al. (1999) defined hydrothermal activity in the Mediterranean range as characterized by high CO_2 and sulfur contents, in the form of SO_2 and SH_2. Another type of sulfur anomaly linked to hydrothermal activity is found in the Cameros Basin from La Rioja (Alonso-Azcárate et al., 1995), where pyrite crystals in Cretaceous fluvio-lacustrine sediments are associated with a mobilization process during hydrothermal metamorphism.

Reolid et al. (2010) provided a more specific model for the reductive production of native sulfur in evaporitic lakes, indicating the inconsistency between the reductive nature of sulfur and the oxidative context of evaporitic environments. The absence of oxygen would result from the degradation of the organic matter in the lake bottom, as well as from restricted circulation and poor water renewal in a euxinic environment. This would lead to the precipitation of sulfur contents from plant matter, algae and plankton, a process mediated by the action of sulfur-reducing bacteria (Triborillard et al., 2006). The increase in the salinity of the lake waters would cause the cessation of bacterial activity, which would in turn put end to the production of sulfur and the precipitation of sulfates (gypsum). For this reason, the presence of sulfur deposits implies a relatively low salinity in the environment. Given that alluvial inputs were limited in the central sector of the Gelasian marly-evaporitic lacustrine system of the Baza Basin, being subject to astronomically-induced climatic cycles (García-Aguilar et al., 2013), sulfur deposits should be interpreted as resulting from hot springs.

A massive input of sulfates would have favored the precipitation of gypsum in the evaporitic Gelasian lacustrine environments of the Baza Basin (Fig. 4B). The anaerobic biogenic conversion of these sulfates would have resulted in the production of H_2S and its final oxidation to native sulfur (Gabrielle, 1993). In addition, crystalline gypsum is not limited to the Gelasian deposits, as the marly sediments of the Pliocene lacustrine units show variable proportions of microcrystalline gypsum and even mineralized beds with some lateral continuity.

However, we must recognize that although the evidence discussed above points to the presence of hot springs during the stages of lacustrine sedimentation, it is not possible to know how many of the modern hot springs were also active in the past, or the exact location of those that were active during the Plio-Pleistocene. In any case, it is worth noting that magnesium clays, celestine, strontium and native sulfur do not distribute homogeneously in the lacustrine sediments, but are concentrated in areas placed in the vicinity of hot springs that are active today, or in zones that can be parsimoniously interpreted as hot springs active during Plio-Pleistocene times.

The presence of travertine deposits in the lacustrine sedimentation of the Baza Basin provides additional evidence of hydrothermal activity. These calcareous formations are found as pseudo-stratiform, massive bodies of decimetric to metric thickness (Fig. 5) (García-Aguilar, 1997; Prado-Pérez, 2011) in the Late Pliocene, Gelasian, Calabrian and Middle-Late Pleistocene units, and/or as fragments reworked in pisolitic gravels and travertine microfacies in the Piacenzian and Calabrian units, which are frequently observed in the >100 thin sections of calcareous lacustrine facies analyzed. A remarkable feature of these deposits is their spatial relationship with the major tectonic fractures of the depression and with active hot springs (Figs. 3 and 4A).

The genetic association between travertine growths, hot springs and faulting is well documented (Khoury et al., 1982; Pentecost, 1990, 1993, 1995, 2005; Koban and Schweigert, 1993; Guo and Riding, 1994; Pentecost and Viles, 1994; Ford and Pedley, 1996; Pisarskii et al., 1998; Cerón et al., 2000; Pentecost et al., 2003; Echeveste, 2005; Kele et al., 2008). This model is similar to the one proposed here for the Guadix–Baza Depression: an increased geothermal gradient linked to intense tectonic activity, which generates the presence of hot springs where calcareous deposits are generated in an aquatic environment with a stable temperature, which is higher than in the atmosphere, and high HCO_3^- and Ca^{2+} concentrations. In these lacustrine environments, the precipitation of $CaCO_3$ is catalyzed by bacterial–algal activity.

From a genetic point of view, an autochthonous thermogene nature can be ascribed to the travertine deposits found in the lacustrine sediments of the Guadix–Baza Depression, under a context of high biological productivity reflected in calcareous growth layers of bacterial origin (Koban and Schweigert, 1993; Pentecost and Viles, 1994; Pentecost, 2005). However, the presence in some levels of travertine fragments reworked indicates allochtonous facies. The morphological criteria that allow differentiating thermogene travertines from meteogene ones include the presence of highly porous fabrics with concentric $CaCO_3$ growths and a limited spatial distribution (Pentecost, 1993, 2005; Pentecost and Viles, 1994). According to these criteria, the travertines of the Guadix–Baza Depression can be unequivocally classified as thermogenes. In addition, thermogene travertines are usually associated to hot springs which a predominant chemical composition of HCO_3^- and Ca^{2+} (Pentecost and Viles, 1994; Pentecost, 2005), as in the case of the Late Pleistocene to sub-recent travertines of the Baza Basin (Fig. 4A, Table 3) and probably also in the Plio-Pleistocene travertines. An additional evidence of the thermogenous nature of the Plio-Pleistocene travertines is their spatial association with magnesium- and strontium-rich deposits (Fig. 3) (Pentecost, 1993; Minissale et al., 2002; D'Alessandro et al., 2007; Kele et al., 2008). Therefore, an autochtonous thermogene model of sedimentation may be defined for the travertine deposits found in specific sectors of the lacustrine units of the Guadix–Baza Depression, linked to the presence of sub-recent and Plio-Pleistocene hot springs.

In this line of reasoning, Sanz de Galdeano et al. (2008) interpreted the uppermost Pliocene to Pleistocene travertine formations of 'Sierra de Gádor' (Almería) as resulting from hot springs. These travertines, not related to carbonate reliefs, resulted from inputs of carbonate waters originated in regionally active fractures, which is also the case of the travertines found in the Guadix–Baza Depression. Similarly, Cerón et al. (2000) interpreted the appearance of travertines as resulting from hot springs with elevated concentrations of dissolved CO_2 and HCO_3^-, which would favor the precipitation of carbonate deposits and their associated plant productivity. A similar model for travertine bodies is cited by Pisarskii et al. (1998) in the Rift Valley of Tanzania, related to thermal waters rich in CO_2, HCO_3^- and SiO_2, which produced Neogene-Quaternary travertine deposits up to 80 m thick with strontium and magnesium anomalies. Khoury et al. (1982) cited also Plio-Pleistocene travertines linked to magnesium-rich hot springs in the Amargosa Desert, Nevada. These models are fully compatible with the paleoenvironments deduced for the Baza Basin.

Travertine facies would indicate the occasional presence of high levels of organic productivity in the lacustrine deposits and the biological origin of a number of limestone facies sensu lato present in the sedimentary units (Freytet, 1975; Murphy and Wilkinson, 1980; Arribas et al., 1988; Bucziyski and Chafetz, 1991; Kempe and Kazmierczak, 1993). The correlation of these facies with those present in the sub-recent travertines of the Guadix–Baza Depression (García-Aguilar, 1997; Prado-Pérez, 2011), which are placed in the vicinity of hot springs that are nowadays active, supports this interpretation.

Finally, it is worth noting that the absence of both travertines and celestine deposits, as well as the moderate values recorded for the geochemical anomalies in the Middle Pleistocene unit, all suggest that hydrothermal activity was less intense during this stage than in previous ones.

All data discussed above suggest the hydrological feeding by hot springs of the lacustrine systems of the Baza Basin. Specifically, the highest ratios of inherited clay minerals to neoformed clay minerals are recorded in the Early Pliocene and Calabrian units, which suggest a more intense contribution of thermal waters to the lacustrine systems during these intervals (Table 2). In contrast, intermediate ratios are found in the Latest Miocene and Late Pliocene units, while the lowest ones correspond to the Gelasian and the Middle Pleistocene, which indicate greater alluvial inputs for these units (Table 2).

The origin and physico-chemical features of these hot waters would be extrapolated from those of the modern hot springs of the depression. In fact, the distribution of the hot springs that are active today in the depression shows a clear relation with the faulting network (Fig. 4A). Moreover, the ionic composition of these hot waters (calcium sulfates) relates to the gypsiferous sediments and other less abundant rocks (ophites) of the Triassic Keuper facies present in the depression substrate, which could explain the SiO_2, magnesium, sulfur and strontium anomalies detected in both the modern hot springs and the lacustrine deposits.

5. Paleoenvironmental and paleoecological implications of hydrothermal activity

The huge vertebrate assemblages unearthed from the important paleontological localities of the Calabrian lacustrine unit in the Baza Basin, including Venta Micena, Barranco León and Fuente Nueva-3 (Martínez-Navarro and Palmqvist, 1995; Turq et al., 1996; Agustí et al., 1997; Martínez-Navarro et al., 1997, 2010, 2011; Crêgut-Bonnoure, 1999; Eisenmann, 1999; Martínez-Navarro and Rook, 2003; Martínez-Navarro, 2004; Madurell-Malapeira et al., 2011; Ros-Montoya et al., 2012; Toro et al., 2013), indicate that a rich and well-diversified large mammal community, similar to those of modern African savannas with bush and tree patches, developed in the lake surroundings and maintained a high standing crop biomass (Palmqvist et al., 1996, 2003, 2008a, 2008b, 2011; Palmqvist and Arribas, 2001; Mendoza et al., 2005).

As discussed before, the mineralogical and geochemical anomalies of the Calabrian unit suggest the possibility of an important contribution of thermal waters to the lake. This would have certainly represented a milder ecological habitat for the large mammal community that lived in the basin compared to present day conditions, which are characterized by intense climatic oscillations between the warm and cold seasons, with frequent frosts in winter and a low mean annual rainfall ($\sim$350 mm). In contrast, the climate during Calabrian times was warmer and more stable than today through the whole year, as suggested by the presence of abundant fossil remains of hippos (Martínez-Navarro, 2004). These exotic animals, known in recent times only from Africa, indicate that climate was milder than today in the basin, as they could not have inhabited a lake that froze in winter and desiccated completely in summer. In fact, the elevated δ^{15}N values measured in bone collagen recovered from fossil remains of the extinct hippo (*H. antiquus*) that inhabited the Baza Basin during the Calabrian (Palmqvist et al., 2003, 2008a) suggest that this species was more adapted to the aquatic environments than the extant one (*Hippopotamus amphibius*), as it fed predominantly on aquatic plants, which do not fix atmospheric N_2, instead of consuming terrestrial grasses as do living hippos. This implies that the lake waters did not freeze during winter, as would happen today in the region. In addition, the very arid conditions of the present landscape in the basin are clearly incompatible with the paleoenvironmental inferences obtained from the isotopic contents of bone collagen (δ^{13}C, δ^{15}N) and hydroxylapatite (δ^{18}O) samples from the large mammals identified at Venta Micena, which indicate the presence of some water dependent, leaf-browsing species that inhabited a forested habitat, and megaherbivores with elevated water requirements, such as hippos, rhinos and proboscideans (Palmqvist et al., 2003, 2008a, 2008b).

It is worth considering also the possibility of calculating the relative contribution of water feeding from hot springs to the total water volume of the Calabrian lacustrine system in the Baza Basin. For doing so, the surface area estimated for the lake ($\sim$600 km^2) and its mean depth ($\sim$2 m) can be used (García-Aguilar, 1997). These estimates provide a total water volume close to 1200 Hm^3. Taking into account the measurements of water volume supplied by the hot springs that are today active in the Baza Basin ($\sim$930 L s^{-1}, $\sim$29 Hm^3 year^{-1}; Table 3), the total water volume of the lake would be reached in around forty years if thermal fluids were the only contributing mechanism and other hydrological factors (i.e., rainfall on the lake surface, runoff waters, evaporation and infiltration) are not considered. In contrast, the annual rainfall recorded today in the region ($\sim$350 mm) would represent 210 Hm^3 year^{-1} of direct precipitation on the lake surface, which would result in a period of 5.7 years for recharging the lake waters. These precipitations could not support any kind of permanent water pool in the Baza Basin, because a negative water balance of 440 mm/yr has been computed for the basin (Rivas-Martínez and Rivas-Sáenz, 1996-2009).

These estimates, however, need qualifying. On the one hand, the tectono-sedimentary context of the Calabrian unit indicates that hydrothermal activity was far more intense than today, which suggests a greater volume of hot waters and thus a shorter lake recharge time. On the other, the values of precipitation on the lake surface, runoff waters and evapotranspiration certainly played relevant roles in the hydrological balance and, as discussed below, these values have probably changed since the Calabrian. Reasonable estimates for them can be derived from data of 'Fuente de Piedra' (Rodríguez-Rodríguez et al., 2006), a pool in the province of Málaga with (to a certain extent) similar climatic, environmental and hydrological conditions to those present during the Calabrian in the Baza Basin. However, although 'Fuente de Piedra' is probably the only modern analog for the Baza Basin, the hydrological regime of this pool shows some striking differences with the conditions inferred for the Calabrian Lake, as discussed below, which means that this comparison would only be partially valid.

'Fuente de Piedra' is a temporally atalassohaline endorheic system placed at 410 m above sea level that extends over a surface of 13.5 km^2 and has a drainage basin of 152.3 km^2. The pool is very shallow, with a maximum depth of 1.8 m. Annual meteorological values in the pool's basin between the years 1965 and 1996 (Rodríguez-Rodríguez and Benavente, 2008: Table 1) average 16.8 °C for temperature, 462 mm for rainfall, 1321.5 mm for evaporation and 362 mm for transpiration (which represents 42% of the potential value). The hydrological balance of the pool is defined by 6.5 Hm^3 $year^{-1}$ of precipitation on the pool's surface, 6.4 Hm^3 $year^{-1}$ of runoff waters, 6.6–8.8 Hm^3 $year^{-1}$ of groundwater inflow, and 19.3–21.5 Hm^3 $year^{-1}$ of evaporation. This results in a negative balance for water accumulation in the pool, which is dry during several months of the year and is very shallow during others (for instance, the pool was not desiccated during the period 1962–1971). The submerged biomass of macrophytes, at the end of the spring-early summer, is very high, with values from 50 to 150 g dry weight m^{-2} (Conde-Álvarez et al., 2012). It is noteworthy that the net annual primary production, based on macrophytes, is ca 0.8 kg C m^{-2}, higher than the values recorded in temperate forests but lower than those from rainforests (Woodwell and Whittaker, 1968).

The conditions of 'Fuente de Piedra' could illustrate the hydrological and ecological landscape of the lake developed in the Baza Basin during Calabrian times, especially for the Orce-Fuente Nueva-Venta Micena sector. As explained below, high $\delta^{15}N$ values have been estimated in the bone collagen of aquatic mammals from Venta Micena, which is interpreted as resulting from feeding on aquatic vegetation grown in saline waters (Palmqvist et al., 2003, 2008a, 2008b), and very high $\delta^{15}N$ values are also recorded in the feathers of greater flamingo (*Phoenicopteus roseus*) from 'Fuente de Piedra' (Amat et al., 2009). Such an environment would have experienced frequent periods of desiccation, although it is worth noting that they are not reflected in the sedimentary record, with some exceptions such as Venta Micena (Arribas and Palmqvist, 1998). In the excavation quarry of this locality, the fossil mammal assemblage is embedded in micrite sediments that rest on a paleosol, evidence of the lowering of the water table of the lake and the emersion of a plain in the north-eastern sector of the Baza Basin. This allowed the emerged plain to be a habitat for ungulates and large carnivores, as happened in the case of the Venta Micena excavation quarry, which has been interpreted as a feeding area for giant, short-faced hyenas (*Pachycrocuta brevirostris*). In this area surrounding the lake, the hyenas transported carcasses and portions of the scavenged large mammals to the vicinity of their denning sites, accumulating the skeletal remains after dismembering and fracturing the bones to access the marrow (Palmqvist and Arribas, 2001; Palmqvist et al., 2011). Subsequent rise of the water table resulted in the precipitation of carbonates, which capped the bone assemblage (Arribas and Palmqvist, 1998).

The absence of sedimentary evidence for recurrent periods of total desiccation in the Calabrian lake of the Baza Basin may be explained by: (1) a greater input of runoff waters than in the 'Fuente de Piedra' pool; (2) a higher rainfall on the lake surface; and/or (3) a significant contribution of endogenous waters of minero-thermal origin. The lack of detritic facies in the sedimentary record of this unit (Arribas and Palmqvist, 1998) allows the first explanation to be discarded. Neither does the second account for the generalized absence of periods of total desiccation, given that this would imply an annual rainfall substantially higher than today. As discussed below, this contradicts the estimates based on the abundance of nitrogen isotopes in the fossil mammals from Venta Micena, which point to precipitations during the Calabrian that merely doubled those recorded today in the region. The third explanation, however, is in agreement with the tectonic, sedimentary, mineralogical and geochemical evidence presented here, as well as with the presence of hot springs that are nowadays active in the basin. Such an endogenous water input would have avoided the total desiccation of the Calabrian lacustrine system during the dry season, in spite of a negative hydrological balance between inputs of meteoric waters and evaporation. This would result in a relatively constant water table for the lake, except for some periods with partial desiccations during the dry season (e.g., Venta Micena), which would have important consequences for its hydrochemical and ecological parameters.

The negative correlation between rainfall and nitrogen isotope ratios in mammalian herbivores allows estimating annual precipitations in the Baza Basin during the Calabrian (Fig. 7). Specifically, $\delta^{15}N$ values measured in bone collagen retrieved from fossils of herbivorous mammals from Venta Micena (range: 1.2–7.7‰; data from Palmqvist et al., 2003, 2008a) are consistently lower than the ones measured in the herbivores of Amboseli, Kenya (range: 6.4–14.2‰; data from Koch et al., 1991), a game reserve with a

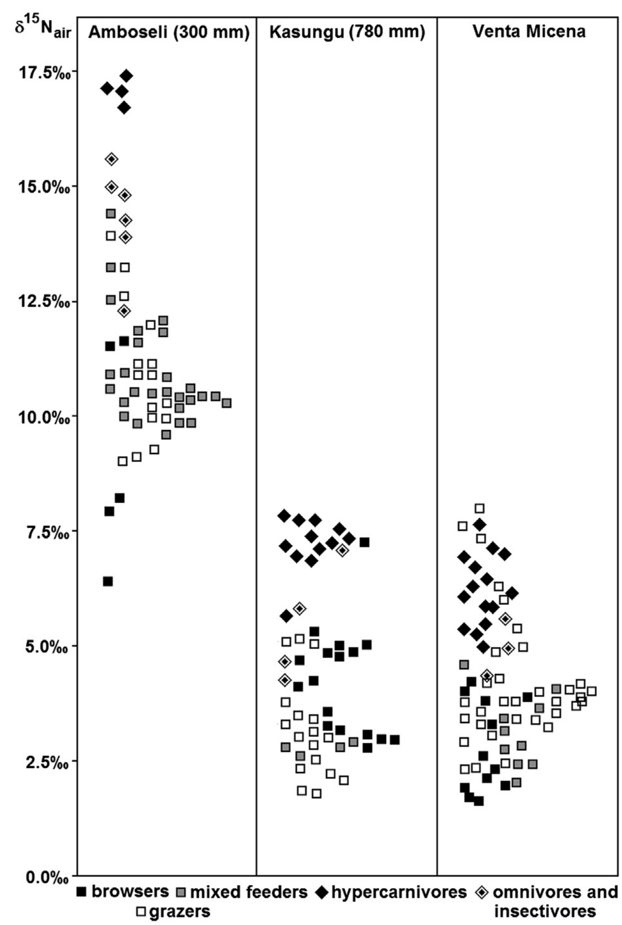

Fig. 7. Comparison of nitrogen isotope ratios ($\delta^{15}N_{air}$, in ‰) measured in bone collagen of mammals from Amboseli Game Reserve, Kenya (data from Koch et al., 1991), Kasungu National Park, Malawi (data from Sealy et al., 1987) and the Calabrian site of Venta Micena, Baza Basin (data from Palmqvist et al., 2008a). Mean annual rainfall values (in mm) are provided for both natural parks. Among the grazing ungulates of Venta Micena, unexpectedly high $\delta^{15}N$ values, similar to those of hypercarnivores, were measured in the bone samples from hippo *H. antiquus*, which indicates that this species fed on non-N_2-fixing, aquatic vegetation growing in moderately saline waters (see text).

mean elevation of 1140 m that has a mosaic of habitats, including grasslands, bushlands, swamps, seasonal lakes and woodlands. The mean rainfall of Amboseli is 300 mm/yr, a value close to the one recorded today in the Venta Micena sector of the Baza Basin (350 mm), which has an altitude of 970 m, although it is worth noting that Amboseli is continuously supplied with spring waters fed by melting snow from Mount Kilimanjaro (Koch et al., 1991). In contrast, the $\delta^{15}N$ values of the Venta Micena mammals (Fig. 7) are similar to those recorded at Kasungu, Malawi (range: 1.6–7.2‰; data from Sealy et al., 1987), a National Park with a mean elevation of 1165 m that has a mosaic of vegetation, including open country and medium height 'miombo' woodland, with grasslands bordering the rivers. The average rainfall of Kasungu is 780 mm yr, a value that doubles present-day precipitations in the Baza Basin.

This comparison indicates that the climate of the Baza Basin was more humid during the Calabrian than today, which is in agreement with the inferences obtained from the study of the assemblages of small vertebrates from the paleontological localities of the Orce-Venta Micena sector (Agustí et al., 2009, 2010; Blain et al., 2011), as discussed below. However, such increase in annual rainfall does not account for the absence of periodic desiccations of the lake during the dry season, as happens now in the 'Fuente de Piedra' pool. Specifically, if we assume a mean annual rainfall of ~780 mm for the Baza Basin during the Calabrian, this would result in a period of two and a half years for recharging the lake with the precipitations on its surface (468 Hm^3 $year^{-1}$). Although this contribution is comparatively higher than the one recorded today in the 'Fuente de Piedra' pool, it would not probably compensate for the losses by evapotranspiration, as happens in 'Fuente de Piedra', where direct rainfall on the pool's surface and runoff waters represent ~50% of the losses by evaporation. For this reason, the hydrological balance of the lacustrine systems of the Baza Basin would have probably required of continued water supplies from hot springs to avoid their total desiccation during the warm season.

Finally, it is worth noting that a recent study of fossil remains of water-associated amphibians and reptiles from Barranco León and Fuente Nueva-3 (Blain et al., 2011), two archaeo-paleontological localities of the Baza Basin dated in ~1.4 and ~1.2 Ma, respectively (Duval et al., 2012; Toro et al., 2013), has also provided estimates of mean annual temperature (16.0–16.9 °C) and precipitation (741–753 mm) for the Calabrian that are higher than those recorded today in the region (12.0 °C and 370 mm for the nearby village of Orce, respectively) and agree with those obtained from the large mammal isotopes (Fig. 7). Specifically, the presence of this herpetofauna, which requires a permanent aquatic environment through the whole year, indicates that, compared to present-day conditions, continentality (i.e., the contrast between summer and winter temperatures) was less pronounced, mainly due to a warmer winter, and precipitations were greater in every season except summer.

It is worth noting here that a recent study (Domingo et al., 2013) of $\delta^{18}O$ and $\delta^{13}C$ values in the tooth enamel of different large herbivorous mammals from Spain, which includes a number of sites in the Guadix–Baza Depression, has provided estimates of mean annual temperatures and precipitations from the interval between the Late Miocene and the Middle Pleistocene. Specifically, mean annual temperatures and precipitations changed from 23.8–22.0 °C and 410–390 mm/yr in the latest Miocene (biozones MN12 and 13) to 20.9–19.6 °C and 790–800 mm/yr in the Zanclean and Early Piacenzian (MN14 and 15), which reflects the more humid conditions of the Pliocene Warm Period, and then dropped to 17.6 °C and 400 mm/yr in the Late Piacenzian (MN16), 16.8 °C and 490 mm/yr in the Gelasian (MN17), and 18.3 °C and 390 mm/yr in the Middle Pleistocene, as a result of the onset of the Northern Hemisphere glaciation at 2.6 Ma (Domingo et al., 2013).

According to these studies, the terrestrial landscape in the surroundings of the permanent lacustrine system of Calabrian age that can be inferred from both the herpetofauna and the small mammals was composed of a predominance of open environments, including dry meadows, rocky-stony areas and Mediterranean shrubland, together with patches of wooded areas (Agustí et al., 2009, 2010; Blain et al., 2011). This paleoenvironmental reconstruction is in agreement with the paleosinecology inferred from the large mammal community (Mendoza et al., 2005) and paleobotanical studies (González-Sámperiz et al., 2010), in which the predominance among ungulates of medium-to-large sized grazing species suggests an environment similar to those of African savannas with tree patches and bush areas. However, it is worth

Fig. 8. Reconstruction of the landscape of the Orce-Venta Micena sector in the Baza Basin during Calabrian times. A saber-toothed cat (*Homotherium latidens*) lies in the shade (foreground), while a group of elephants (*Mammuthus meridionalis*) and horses (*Equus altidens*) take mud baths and drink in the ponds that surround the lake (background). Drawing by Mauricio Antón.

noting that all attempts to extract pollen from diverse lithological material in the Orce-Venta Micena sector of the Baza Basin have been unsuccessful (Agustí and Julià, 1990) and, for this reason, the vegetation is basically inferred from a paleosinecological approach based on the composition of the vertebrate assemblages.

The existence of hot springs in the Plio-Pleistocene lacustrine systems of the Baza Basin had important paleobiological consequences. One would be that the water-mass was warmer and more stable during the whole year; as a result of the continued supply of hot waters (the average value of the temperature is $\sim$26 °C for the alkaline hot springs that are now active). In addition, the contribution of high amounts of CO_2, sulfur and magnesium to the lake environments would have resulted in an increased population density for primary producers (i.e., aquatic macrophytes, benthic algae and plankton). Moreover, these lakes would represent 'ecological islands' of hot waters in an environmental context of lower temperatures, which would attract many species. It has been proposed for hot springs that the emissions of CO_2 can result in mass deaths of scavengers attracted by carcasses of large mammals, which would represent a natural trap for carnivores (García-Romero, 2004). This could explain a number of taphonomic attributes of some vertebrate assemblages, for example in the case of Fuente Nueva-3, a locality with an abundant record of proboscideans that preserves evidence for the competition between hominins and hyenas for an elephant carcass (Espigares et al., 2013). This means that the Baza Basin was a refugium during the Plio-Pleistocene (Fig. 8), with warmer and more humid conditions than in the surrounding environments of the Iberian Peninsula, and probably also than in other regions of Europe. Such inference is corroborated by the finding of a pathological specimen of the hypercarnivorous, extinct painted dog *Lycaon lycaonoides*, which shows a number of skull anomalies (e.g., absence of teeth and a high degree of cranial fluctuating asymmetry) resulting from inbreeding, which suggests genetic isolation from other populations (Palmqvist et al., 1999). For this reason, we must be cautious before extrapolating these environmental and faunal conditions to other areas of the European Mediterranean context (Rodríguez et al., 2012).

From a paleoanthropological point of view, a lacustrine system with supplies of hot waters was probably advantageous for hominin settlements, as evidenced by a number of Plio-Pleistocene sites in the African Rift Valley found in similar paleoenvironmental contexts. In fact, there is an association between fossil sites with hominid remains and sedimentary deposits indicative of intense hydrothermal and/or volcanic activity linked to tectonic landscapes. At least 54 out of 70 sites with hominin fossils of ages between the Late Miocene and the Middle Pleistocene are placed in the vicinity of areas that show evidence of intense hydrothermal activity, following a tectonic axis along South Africa, Ethiopia and Israel, and also in the Indonesian islands (S. Jones et al., 1994; Stringer and Andrews, 2005; Henke and Tattersall, 2007). Some of these sites, for example Laetoli and Olduvai (Tanzania), Koobi Fora, Olorgesailie and Lake Turkana (Kenya), Usno (Ethiopia), 'Ubeidiya and Gesher Benot Ya'aqov (Israel), provide key evidence for addressing the major milestones in human evolution. Other important localities are located also in zones with noticeably tectono-hydrothermal activity, for example Dmanisi in the Caucasus (Georgia), a site dated at 1.77 Ma, which records the first human settlement out of Africa (Ferring et al., 2011). The evidence presented in this study suggests a similar geological context for the fossil localities of the NE sector of the Baza Basin, which provide the earliest evidence of human presence in Western Europe (Martínez-Navarro et al., 1997; Arribas and Palmqvist, 1999; Oms et al., 2000b; Palmqvist et al., 2005), including the recent finding of a human tooth associated with Oldowan tool assemblages and cut marks on large mammal bones in Barranco León (Toro et al., 2013) and a partial skeleton of an elephant surrounded by flint flakes and coprolites of hyena in Fuente Nueva-3 (Espigares et al., 2013).

The explanation for the association of hominins and hot springs would be the causal link between a hydrothermal environment and the proliferation of plant and animal communities with high values of both standing crop biomass and diversity (Fig. 8). Such an environment would provide abundant trophic resources, for example the carcasses of ungulate prey killed and defleshed only in part by saber-toothed carnivores (Palmqvist et al., 1996, 2007, 2008b), which could be subsequently exploited by the hominins in competition with the scavenging hyenas (Palmqvist et al., 2011; Espigares et al., 2013). Without any doubt, the environmental conditions of the lacustrine systems of the Baza Basin (i.e., a warm and stable climate with high organic productivity) were optimal for the first human settlements in Western Europe.

6. Conclusions

The sedimentary record of the Baza Basin shows six lacustrine units for the period of continental sedimentation between the latest Miocene and the Middle-Late Pleistocene. These units are characterized by a dynamic tectonic landscape that resulted in a number of depositional troughs, which allowed the development of lacustrine systems with sedimentation rates between 2 and >40 cm ka^{-1}. The distribution of the outcrop areas of the lacustrine units shows that they are aligned with the major regional fractures, particularly those with a 50°N–70°E direction in the case of the sedimentary units deposited from the Piacenzian to the Calabrian.

Mineralogical analyses of the lacustrine units show geochemical anomalies for magnesium, strontium and sulfur, as well as deposits of celestine and travertine formations, all of which suggest that the lakes were subject to a variable contribution of hot waters. Hydrothermal activity was more intense in the Baza Basin during a number of intervals, particularly during the Piacenzian and the Calabrian. These hot waters would contribute to the partial feeding of the lacustrine systems, which helps to explain the rise of the water table above the level that would result from the relatively limited input of runoff waters that can be deduced from the scant record of detritic facies during prolonged time intervals. In addition, the contribution of hot waters would result in a milder environment for the basin compared to present-day conditions. Evidence for this hydrothermal activity of tectonic origin is that 13 localities in the basin show now hot springs with waters that have a predominant hydrochemistry of calcium sulfates and a mean output temperature of 26 °C.

The existence of a permanent and relatively constant water table for the Pleistocene lake allowed the development in the basin of a rich and well diversified mammalian community that included a number of water-dependent species such as a variety of grazing and mixed-feeding ungulates, rhinos, hippos and elephants, as well as the first hominins that inhabited Western Europe.

Acknowledgments

This study, developed by the Research Groups RNM-146 "Paleobiology, Paleoclimatology and Paleogeography" and RNM-115 "Biodiversity, conservation and plant resources", has been sponsored by the Dirección General de Bienes Culturales (Council of Culture, Junta de Andalucía, Spain) and funded by project HUM-7248 (Council of Economy, Innovation and Science of Junta de Andalucía, Spain) and projects CGL2012-38358, CGL2011-30334, CGL2010-15326 and CGL2008-04896 (Spanish Ministry of Science and Innovation). Dr Eric C. Henry kindly revised the English style and usage. We gratefully acknowledge constructive remarks and suggestions from two anonymous reviewers.

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