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# Revised isotopic ($^{40}Ar/^{39}Ar$) age for the lamproite volcano of Cabezos Negros, Fortuna Basin (Eastern Betics, SE Spain)

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**Abstract**

A new isotopic age of 7.71 ± 0.11 Ma (1$\sigma$) has been obtained with the $^{40}Ar/^{39}Ar$ incremental heating technique on phlogopites from the Miocene volcanic rocks (lamproites) of the Fortuna Basin in southeast Spain. This age is significantly older than earlier reported K/Ar ages, but confirms recent magnetostratigraphic ages on the sedimentary sequences of the eastern Betics. Because the volcanic rocks are intercalated in the stratigraphic sequence of the Fortuna Basin directly above the transition from evaporitic to continental sediments, it implies that the Fortuna evaporites are older than 7.71 Ma, and thus of Tortonian age. In addition, it shows that the volcanism in the Fortuna Basin must be attributed to a late Tortonian deformation phase and not to Messinian tectonics. Consequently, these results form an important step towards a consistent chronological framework for the sedimentary, tectonic and paleogeographic evolution of the Fortuna Basin during the late Miocene.


*Keywords:* $^{40}Ar/^{39}Ar$; Volcanism; Spain; Neogene; Evaporites; Lamproites

## 1. Introduction

The late Miocene sedimentary record of the Fortuna Basin, located in the eastern Betics of Spain (Fig. 1), shows a marked regressive sequence from marine marls, via an alternation of evaporites (predominantly gypsum) and diatomites, to continental deposits. The evaporite deposits were considered to be of late Tortonian age in the pioneering work of Montenat (1973), mainly based on planktonic foraminifera biostratigraphy. Absolute age control was not available until isotopic (K/Ar) dating on volcanic intercalations (lamproites) provided an age of 6.16 ± 0.30 Ma (Bellon et al., 1983). In the Fortuna Basin, these lamproites are located slightly above the transition from evaporitic to continental sediments and this dating result was used to infer a late Messinian age for the Fortuna evaporites. Consequently, it became very tempting to assume a direct relationship between the Fortuna evaporites and the widespread evaporite deposits of the Mediterranean Messinian Salinity Crisis (MSC) (Santisteban and Taberner, 1983; Lukowski et al., 1988). This correlation was supported by facies similarities, but never proven or substantiated by additional chronological data. Nevertheless, the supposed Messinian age for the Fortuna evaporites resulted in far-reaching hypotheses such as

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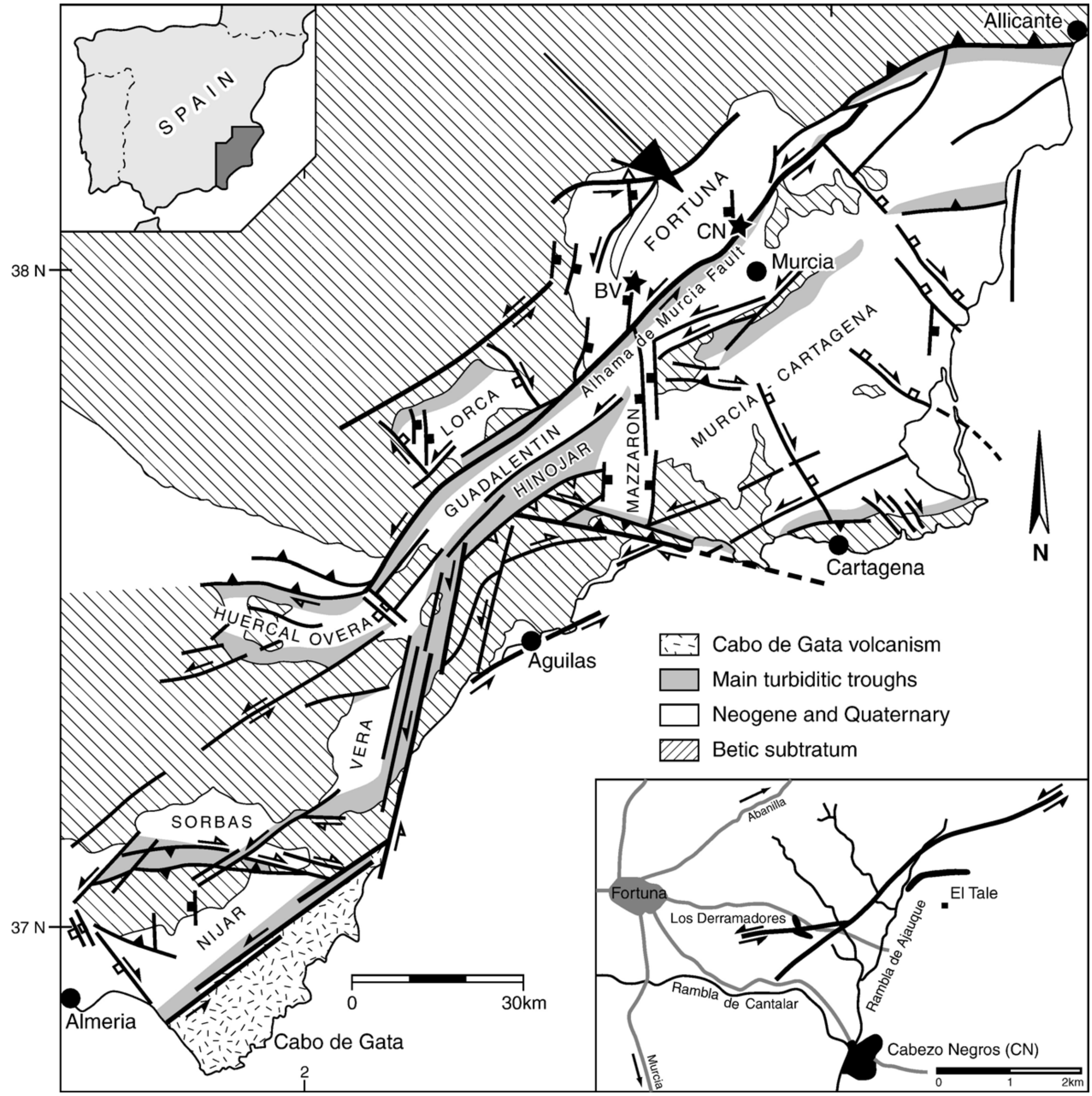


Fig. 1. Geological setting of the Fortuna Basin in the Betic Cordillera and location of the lamproites: CN = Cabezos Negros; BV = Barqueros volcano. Figure is modified after Montenat and Ott d'Estevou (1990) and Fuster et al. (1967).

the presence of a late Messinian Mediterranean–Atlantic gateway through Spain (Santisteban and Taberner, 1983; Müller and Hsü, 1987; Benson et al., 1991) and a diachronous onset of the MSC evaporites in the Mediterranean (Dinarès-Turell et al., 1999).

Recently, however, extensive paleomagnetic studies (Garcés et al., 1998, 2001; Krijgsman et al., 2000) provided a detailed magnetostratigraphic time frame for the late Miocene sedimentary sequence of the Fortuna Basin (Fig. 2). A remarkable result was that the entire Messinian was enclosed in the continental part of the depositional sequence. The latest marine sediments were deposited during Tortonian times, while evaporite deposition had taken place in the late Tortonian between 7.8 and 7.6 Ma, i.e. in agreement with the biostratigraphic results of Montenat (1973). This Tortonian scenario was also put forward for the Lorca Basin, based on integrated stratigraphic data (Krijgsman et al., 2000), and suggested that evaporite precipitation in the eastern Betics was related to a local tectonic phase of basin

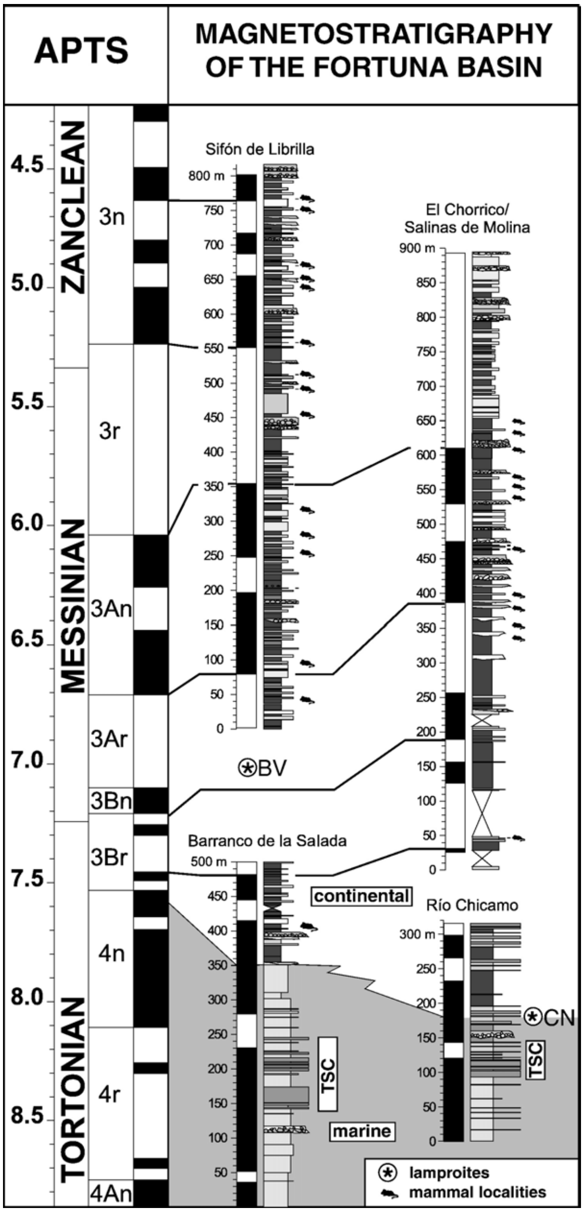


Fig. 2. Stratigraphy of the Fortuna Basin. Magnetostratigraphic time frame of the Fortuna Basin is after Garcés et al. (2001). The magnetostratigraphy relevant for this paper is established in the Chicamo section situated along the Rio Chicamo river. Location of the Chicamo section is indicated as CH in Dinarès-Turell et al. (1999) and CO in Krijgsman et al. (2000) and Garcés et al. (2001). The evaporites have been deposited in the late Tortonian during the time interval between 7.8 and 7.6 Ma. Consequently, this evaporitic phase was defined as the "Tortonian Salinity Crisis" of the eastern Betics, which took place 1.8 Myr earlier than the Messinian Salinity Crisis of the Mediterranean. The lamproites of the Fortuna Basin (CN) are located directly above the transition from evaporites to continental deposits, but have a K–Ar age of 6.1 Ma according to Bellon et al. (1983). The Barqueros volcano (BV) is positioned between the sections of Barranco de la Salada and Sifón de Librilla, which indicates an age between 7.4 and 6.8 Ma.

restriction (Garcés et al., 2001). Consequently, this evaporitic phase was defined as the Tortonian Salinity Crisis (TSC) of the eastern Betics, which took place 1.8 Myr earlier than the MSC of the Mediterranean (Krijgsman et al., 1999b, 2000). The magnetostratigraphic time frame for the Fortuna Basin furthermore proved to be in excellent agreement with continental biochronological (mammal fossils) data (Agustí et al., 2001), but showed a marked discrepancy of approximately 1.5 Myr with the K/Ar datings of the lamproites (Bellon et al., 1983).

In this paper, we present new isotopic dating results on the lamproites of the Fortuna Basin, which have been performed with the $^{40}Ar/^{39}Ar$ incremental heating technique. The importance of re-investigating the isotopic age of these lamproites derives from the significant controversy that still exists concerning the age of the evaporite deposits in the eastern Betics (e.g. Garcés et al., 1998, 2001; Rouchy et al., 1998; Krijgsman et al., 2000; Playà et al., 2000) and because the earlier K/Ar age of 6.16 Ma was often used as an important argument favouring a Messinian age for the Fortuna evaporites (Lukowski et al., 1988; Dinarès-Turell et al., 1999).

## 2. Geological background

The Betic Cordillera mountain belt of southern Spain constitutes the westernmost extension of the Mediterranean Alpine thrust-belt, which formed during the Cenozoic in response to the convergence between the African and European plates. This convergence caused thrusting and westward-directed migration of the Alboran domain units (Internal zones) over the autochthonous units of the Iberian plate (External zones) during the lower to middle Miocene. Following continental collision and blocking of the thrust kinematics, ongoing convergence between Africa and Iberia caused deformation along NE–SW and NW–SE strike slip faults and the formation of intramontane basins (Sanz de Galdeano and Vera, 1992). The Fortuna Basin is one of these intramontane basins that developed since the early Tortonian (Montenat, 1973; Sanz de Galdeano, 1990; Garcés et al., 2001), sealing the contact between the Internal and External zones in the eastern Betics (Fig. 1). The Fortuna basin is an elongated trough that has accommodated a thick (up to 2 km) sedimentary succession. The accommodation space was associated with a marked subsidence of the basin floor which agrees very well with a strike-slip structural setting of coalescent uplifting blocks and pull-apart basins (Garcés et al., 2001). The tectonic activity along the major strike slip faults evolved into a more transpressional component during the Pliocene as the direction of the local compression shifted from N–S to NNW–SSE and caused the recent uplift of the Fortuna Basin and its eastern margin (Montenat and Ott d'Estevou, 1990; Sanz de Galdeano and Vera, 1992).

A confined period of Neogene magmatic activity developed within the eastern Betics, closely related to the major strike slip faults (Montenat, 1973; Bellon et al., 1983; Hernandez et al., 1987). Five types of Neogene volcanism can be recognized: (1) rhyolitic tuffs of late Burdigalian age, located northeast of Malaga and west of Lorca; (2) the Cabo de Gata group of Langhian to Tortonian age, located east of Almeria, consisting of calc alkaline volcanic sequences derived from orogenic processes; (3) a peraluminous group, located in the El Hinojar-Mazarron area and at some places at Cabo de Gata, representing anatectic derived extrusives; (4) the lamproites of supposed Messinian age, spread from the Vera and Mazarron Basins in the south as far north as 100 km land inward parallel to Alicante, originating from the deep mantle and (5) the final alkali basalts, mainly situated near Cartagena, resulting from intracontinental distensive activity.

## 3. Lamproites of the eastern Betics

Lamproites, like kimberlites, are crystallised from magmas that originate from the deep astenospheric mantle and commonly include fragments of rocks from the Earth's mantle, large phenocrysts, and a crystallised groundmass that glues the mixture together. The magmas are very rich in magnesium and volatile compounds such as water and carbon dioxide. As the volatiles dissolved in the magma are exsolved to gas near the Earth's surface, explosive eruptions may create the characteristic carrot- or bowl-shaped pipes.

The lamproites of the eastern Betics have been the subject of several earlier studies, and their particular petrographic character has lead to a variety of different local names such as "jumillites" and "fortunites" after the villages of Jumilla and Fortuna (e.g. Fuster et al., 1967; Montenat, 1973). The lamproite rocks are porphyritic and some are very glass-rich (e.g. in Fortuna). The most abundant mafic phases are olivine and phlogopite (Venturelli et al., 1988). Orthopyroxene as a consequence of high silica content occurs in several outcrops as microlites in the groundmass (e.g. in Fortuna). Sanidine is the most abundant groundmass phase in the glass-poor and glass-free rocks. The presence of Mg-rich olivine in combination with other geochemical data (e.g. high Ni and Cr contents) suggests that these lamproites can be considered as the effusive expression of near-primary, mantle derived magmas (Venturelli et al., 1988). They are dispersed on an area of approximately 150 km in SE Spain, between the cities of Vera and Jumilla. Other important localities are within the Mazarrón group west of Cartagena (De Larouzière et al., 1988), the Barqueros volcano north of Librilla (Montenat et al., 1975), the Cabezo Negro de Zeneta east of Murcia and–the subject of this study–the "fortunites" (= Cabezos Negros) of Fortuna.

Previous dating on rocks from the Fortuna Basin includes the lamproites of the Cabezos Negros located 3 km south of Fortuna village, with a reported age of 6.16±0.30 Ma (Bellon et al., 1983). These volcanic rocks are located in the uppermost part of the marine–continental transitional interval (Montenat, 1973; Dinarès-Turell et al., 1999). The volcanic rocks are thought to be almost coeval with the country rock sedimentation because geological observations in the lamproites and in the country rock indicate that the volcanic emplacement took place under a thin and soft sediment layer (Playà, 1998). According to the magnetostratigraphic time frame of the Fortuna Basin (Garcés et al., 2001), however, this would suggest an age of approximately 7.6 Ma for the lamproite deposition.

## 4. $^{40}Ar/^{39}Ar$ dating

### 4.1. Methods

New samples were collected at several sites in the largest volcanic outcrop of the Cabezos Negros, south of Fortuna village (Fig. 1). The bulk samples were washed and sieved. The fractions of 400–500 μm were used for standard magnetic and heavy liquid separations for micas. Subsequently, all samples were handpicked. The samples were wrapped in Al-foil and loaded in a 5 mm ID quartz vial. Fish Canyon Tuff (FC-2) sanidine was wrapped in Cu-foil and loaded at the top and bottom positions and between each set of 3 samples. The vial was irradiated in the Oregon State University TRIGA reactor in the cadmium shielded CLICIT facility for 7 h. After irradiation, samples and standards were loaded in 2 mm diameter holes of a copper planchet and placed in an ultra-high vacuum extraction line. Samples and standards were stepwise heated or directly fused. The gas was analysed with a Mass Analyzer Products LTD 215-50 noble gas mass spectrometer.

Two multiple grain fractions of the phlogopite sample of Fortuna have been measured by stepwise heating with a 24 W argon-ion laser. The FC-2 standards have been preheated using a defocused laser beam with an output of 2 W (samples did not glow and gas was pumped away) to remove undesirable atmospheric argon. After the preheating step the standards were analysed by total fusion. Experiments were replicated 7 to 10 times for single crystals of FC-2. Beam intensities were measured in a peak-jumping mode over the mass range 40–36 on a secondary electron multiplier. For data collection, the mass spectrometer is operated with a modified version of standard MAP software. Data reduction was carried out using the in-house developed ArArCalc(v2.2) software (Koppers, 2002). Each analysis was corrected for mass discrimination and system blanks. System blanks were measured every 3 steps. The total system blanks were in the range of $5.0\times10^{-17}$ mol for mass 40, $4.0\times10^{-18}$ mol for mass 39, $2.6\times10^{-18}$ mol for mass 38, $2.6\times10^{-17}$ mol for mass 37 and $2.0\times10^{-18}$ mol for mass 36. Mass discrimination (1.002–1.010 per atomic mass unit) was monitored by frequent analysis of $^{40}Ar/^{38}Ar$ reference gas pipette aliquots. The irradiation parameter $J$ for each unknown was determined by interpolation using a second-order polynomial fitting between the individually measured standards.

### 4.2. Results

All $^{40}Ar/^{39}Ar$ ages in this study have been calculated using the decay constants of Steiger and Jäger (1977). The age for the Fish Canyon Tuff sanidine neutron fluence monitor used in the age calculations is 28.02 Ma (Renne et al., 1998). Errors are quoted at the 1$\sigma$ level. The results of the incremental heating experiments are presented in age spectra diagrams (Fig. 3 and Table 1a,b). An age is accepted as an accurate estimate of the crystallisation age when the following criteria are fulfilled. There should be a well-defined, high temperature plateau for more than 50% of the $^{39}Ar$ released formed by three or more concordant, contiguous steps. A well-defined isochron should be obtained from the results of the gas fractions on the plateau, while also the $^{40}Ar/^{36}Ar$ intercept for the trapped argon derived from the isochron should not be significantly different from the atmospheric ratio of 295.5 (McDougall and Harrison, 1999).

In sample 01m0436, the first two steps are excluded from the calculation of a plateau age, because they contain abundant atmospheric argon (<20% radiogenic $^{40}Ar$) and have relatively large uncertainties, although

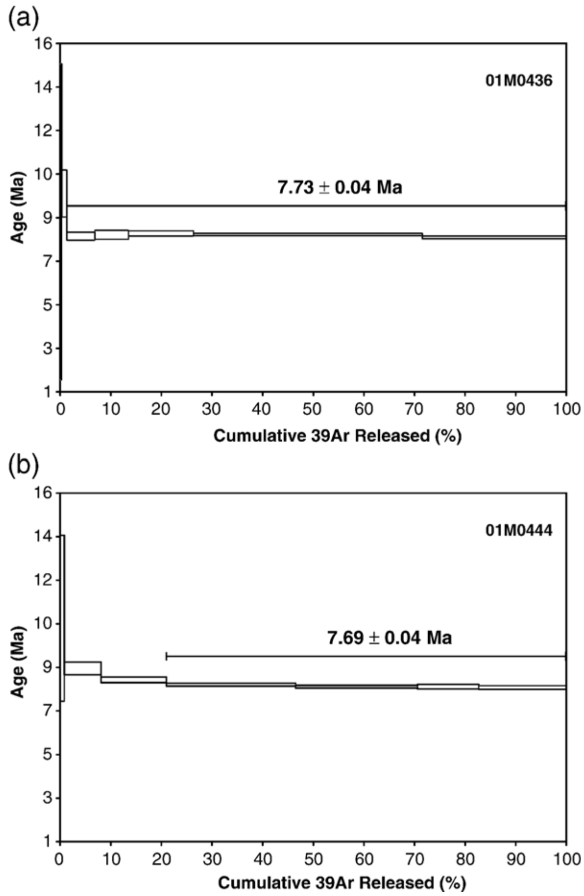


Fig. 3. Two incremental heating spectra of phlogopite from the Fortuna lamproite: (a) sample 01M0436, (b) sample 01M0444.

these steps are not significantly different from the other steps in the spectrum at the 95% confidence level, but they do differ at the 68% significance level. Further, the plateau age has a MSWD value of 0.77, which means that the analytical error slightly overestimates the observed scatter. In sample 01m0444, the first three steps are excluded from the plateau because of their higher atmospheric argon content compared to the remaining four steps (<60% radiogenic $^{40}Ar$ versus >80% $^{40}Ar$ for the steps in the plateau). The MSWD value is 0.61 and the error overestimates the observed scatter. Including the omitted steps in the plateaus will result in an increase of the MSWD values to >1.7. This means that the observed scatter cannot be explained by the analytical error alone, supporting the decision to discard the first steps in the plateau ages. In both cases the plateaus comprise more than 70% of the released $^{39}Ar_K$, no age difference can be detected between any of the two plateau steps at the 68% confidence level and the trapped $^{40}Ar/^{36}Ar$ component is atmospheric. Because the normal and inverse isochron ages are

Table 1
Summary of $^{40}Ar/^{39}Ar$ data

a

| Incremental heating | | | $^{36}Ar_{(a)}$ | $^{37}Ar_{(Ca)}$ | $^{38}Ar_{(Cl)}$ | $^{39}Ar_{(K)}$ | $^{40}Ar_{(r)}$ | Age ± 1σ (Ma) | $^{40}Ar_{(r)}$ (%) | $^{39}Ar_{(K)}$ (%) | K/Ca ± 1σ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 01M0436A | 0.30W | | 0.02599 | 0.01021 | 0.00035 | 0.05346 | 0.13102 | 8.32 ± 6.80 | 1.68 | 0.30 | 2.3 ± 0.6 |
| 01M0436B | 0.50W | | 0.00986 | 0.00647 | 0.00005 | 0.17783 | 0.50007 | 9.54 ± 1.01 | 14.65 | 1.01 | 12 ± 5 |
| 01M0436C | 0.65W | * | 0.00806 | 0.00811 | 0.00074 | 0.97859 | 2.22087 | 7.70 ± 0.17 | 48.25 | 5.55 | 52 ± 17 |
| 01M0436D | 0.80W | * | 0.00912 | 0.00779 | 0.00009 | 1.17153 | 2.67933 | 7.76 ± 0.19 | 49.84 | 6.64 | 65 ± 24 |
| 01M0436F | 1.0W | * | 0.00888 | 0.01101 | 0.00041 | 2.27109 | 5.23054 | 7.82 ± 0.11 | 66.57 | 12.87 | 88 ± 15 |
| 01M0436G | 1.5W | * | 0.02165 | 0.02800 | 0.00000 | 7.97814 | 18.26951 | 7.77 ± 0.05 | 74.04 | 45.21 | 123 ± 9 |
| 01M0436J | Fuse | * | 0.01452 | 0.02455 | 0.00139 | 5.01713 | 11.31179 | 7.65 ± 0.06 | 72.48 | 28.43 | 88 ± 8 |
| | | ∑ | 0.09809 | 0.09613 | 0.00302 | 17.64777 | 40.34312 | *J* value = 0.001885 | | | |

| Phlogopite 01m0436 | Weighted plateau | Normal isochron | Inverse isochron |
|---|---|---|---|
| $^{40}Ar*/^{39}Ar_K$ | 2.2789 ± 0.0101 | 2.2758 ± 0.0267 | 2.2769 ± 0.0265 |
| *N* | 5 | 5 | 5 |
| MSWD | 0.77 | 1.04 | 1.02 |
| $^{39}Ar_K$ (% included in plateau) | 98.69 | – | – |
| Isochron intercept | – | 296.2 ± 7.6 | 296.2 ± 7.5 |
| Age (Ma) | 7.73 ± 0.04 | 7.72 ± 0.09 | 7.73 ± 0.09 |

b

| Incremental heating | | | $^{36}Ar_{(a)}$ | $^{37}Ar_{(Ca)}$ | $^{38}Ar_{(Cl)}$ | $^{39}Ar_{(K)}$ | $^{40}Ar_{(r)}$ | Age ± 1σ (Ma) | $^{40}Ar_{(r)}$ (%) | $^{39}Ar_{(K)}$ (%) | K/Ca ± 1σ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 01M0444A | 0.30W | | 0.02065 | 0.00876 | 0.00027 | 0.08551 | 0.2649 | 10.61 ± 3.57 | 4.20 | 0.83 | 4.2 ± 1.12 |
| 01M0444B | 0.50W | | 0.01085 | 0.01127 | 0.00023 | 0.74656 | 1.86061 | 8.46 ± 0.27 | 36.71 | 7.25 | 28 ± 6 |
| 01M0444D | 0.70W | | 0.00863 | 0.01589 | 0.00024 | 1.32772 | 3.11774 | 7.97 ± 0.12 | 55.01 | 12.90 | 36 ± 6 |
| 01M0444E | 0.90W | * | 0.00488 | 0.02169 | 0.00000 | 2.62713 | 6.00766 | 7.76 ± 0.06 | 80.63 | 25.52 | 52 ± 6 |
| 01M0444G | 1.1W | * | 0.00303 | 0.00682 | 0.00066 | 2.48109 | 5.60971 | 7.67 ± 0.06 | 86.20 | 24.10 | 156 ± 51 |
| 01M0444J | 5.0W | * | 0.00115 | 0.00239 | 0.00092 | 1.24025 | 2.80416 | 7.67 ± 0.10 | 89.13 | 12.05 | 223 ± 234 |
| 01M0444L | Fuse | * | 0.00325 | 0.00073 | 0.00030 | 1.78494 | 4.01544 | 7.63 ± 0.08 | 80.66 | 17.34 | 1046 ± 3557 |
| | | ∑ | 0.05244 | 0.06755 | 0.00261 | 10.29320 | 23.68280 | *J* value = 0.001885 | | | |

| Phlogopite 01m0444 | Weighted plateau | Normal isochron | Inverse isochron |
|---|---|---|---|
| $^{40}Ar*/^{39}Ar_K$ | 2.2789 ± 0.0101 | 2.2386 ± 0.0478 | 2.2355 ± 0.0477 |
| *N* | 4 | 4 | 4 |
| MSWD | 1.10 | 0.68 | 0.66 |
| $^{39}Ar_K$ (% included in plateau) | 79.02 | – | – |
| Isochron intercept | – | 314 ± 31 | 314 ± 31 |
| Age (Ma) | 7.69 ± 0.04 | 7.60 ± 0.16 | 7.59 ± 0.16 |

All errors are given at the 1σ level. The error represents the error due to uncertainties in the $^{40}Ar*/^{39}Ar_K$ ratio of the sample and the analytical error in the *J*-value, but ignores uncertainties in the age of the standard and decay constants. *N* is the number of steps included in the plateau, MSWD is the Mean Square Weighted Deviate. For comparison of the data presented here with the K/Ar age of Bellon et al. (1983) or the magnetostratigraphic age, a slightly extended error propagation method has to be applied (see text and Tables 2a,b). * = step included in age spectrum.

Table 2a
Age and error calculation for comparison with an independent dating method

| Absolute | Age (Ma) | Internal error ($1\sigma$) | External error ($1\sigma$) | $^{40}K/K$ error (%) | $R$ error (%) | $^{40}Ar_e$ error (%) | $^{40}Ar_\beta$ error (%) | $^{40}Ar_P*$ error (%) | $K_P$ error (%) | $N_0$ error (%) | Atw K error (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 01m0436 | 7.73 | ±0.04 | ±0.11 | 0.0 | 13.2 | 71.4 | 0.0 | 13.3 | 2.2 | 0.0 | 0.0 |
| 01m0444 | 7.69 | ±0.04 | ±0.11 | 0.0 | 15.3 | 69.5 | 0.0 | 12.9 | 2.3 | 0.0 | 0.0 |

The internal error represents the analytical error of the unknown and the error in $J$. The external error includes the internal error and the uncertainties in the radiogenic $^{40}Ar$ and K content of the primary standard, the uncertainty in the intercalibration between the primary (GA1550) and secondary (FC-2) standard (both from Renne et al., 1998), the errors in the activity data for the decay of $^{40}K$ to $^{40}Ar$ ($^{40}Ar_e$) and the decay of $^{40}K$ to $^{40}Ca$ ($^{40}Ar_\beta$), the error in the $^{40}K/K$ abundance ratio ($^{40}K/K$), the uncertainty in Avogadro's number ($N_0$) and the uncertainty in the atomic weight of potassium ($^{40}K$) (see Min et al., 2000). The contribution of the different parameters required for age calculations is also shown (in %).

concordant with the plateau ages at the 68% level (Table 1) and the trapped $^{40}Ar/^{36}Ar$ component is atmospheric, we can consider our plateau ages as reliable age estimates of the Fortuna lamproites.

The error propagation for the $^{40}Ar/^{39}Ar$ data (Table 2a) includes all uncertainties associated with the decay constants (i.e. also the errors in the atomic $^{40}K/K$ abundance, in the atomic weight of K), primary standards (GA1550), intercalibration between primary and secondary standards (FC-2–GA1550) and analytical errors in $J$ and in the unknown. Incorporating all the errors, the combined weighted mean of the two plateaus for the Fortuna lamproite arrives at an age of 7.71 ± 0.11 Ma. In addition, Table 2a assesses the influence of the different parameters to the final error. Evidently, the total error is dominated by the uncertainty in the activity of the decay of $^{40}K$ to $^{40}Ar$ and the uncertainty in the amount of radiogenic $^{40}Ar$ in the primary standard.

## 5. Discussion

### *5.1. Comparison between $^{40}Ar/^{39}Ar$ age and K/Ar age*

The only radiometric date for the Cabezos Negros is a K/Ar age of 6.16 ± 0.30 Ma for the Fortuna lamproite (Bellon et al., 1983), which was recalculated from Bellon (1976) with the decay constants as recommended by Steiger and Jäger (1977). Since the recommendations of the IUGS Subcommission on Geochronology were summarised (Steiger and Jäger, 1977), longstanding acceptance was reached on the value of the decay constants of $^{40}K$. However, a number of recent publications (e.g. Min et al., 2000) draw attention to possible uncertainties in the decay constants, which are not accounted for in the publication of Steiger and Jäger (1977). Therefore, Min et al. (2000) propose a more realistic error propagation to obtain more reliable absolute ages and errors. The ArArCalc software (Koppers, 2002) includes an option to calculate this more realistic error propagation method based on Min et al. (2000).

A relative comparison of the K/Ar age of Bellon et al. (1983) and our data (Fig. 3 and Table 1a,b) requires an error assessment, where the analytical errors, the analytical error in $J$, the errors of two decay constants ($\lambda_e$ and $\lambda_\beta$) as in Steiger and Jäger (1977), the errors in the radiogenic $^{40}Ar$ and K contents for the primary standard GA1550 and the error in intercalibration factor between FC-2 and GA1550 (adapted from Renne et al. (1998)) are included in the error propagation (Table 2b). This results in an age estimate of 7.73 ± 0.08 Ma for sample 01m0436 and 7.69 ± 0.08 Ma for 01m0444. The

Table 2b
Age and error calculation of the two plateau ages of the Fortuna lamproite for comparison with the K/Ar age of Bellon et al. (1983)

| Absolute | Age (Ma) | Internal error ($1\sigma$) | External error ($1\sigma$) | $R$ error (%) | $\lambda_e$ error (%) | $\lambda_\beta$ error (%) | $^{40}Ar_P$* error (%) | $K_P$ error (%) |
|---|---|---|---|---|---|---|---|---|
| 01m0436 | 7.73 | ±0.04 | ±0.08 | 23.6 | 48.9 | 0.0 | 23.7 | 3.8 |
| 01m0444 | 7.69 | ±0.04 | ±0.08 | 24.8 | 48.1 | 0.0 | 23.3 | 3.8 |

The internal error represents the analytical error of the unknown and the error in $J$. The external error includes the internal error and the uncertainties in the radiogenic $^{40}Ar$ and K content of the primary standard, the uncertainty in the intercalibration between the primary (GA1550) and secondary (FC-2) standard (both from Renne et al. (1998)) and the errors in the decay constant as in Steiger and Jäger (1977). The contribution of the different parameters required for age calculations is shown for the analytical error and error in $J$ ($R$), the decay constants ($\lambda_e$ and $\lambda_\beta$), the radiogenic $^{40}Ar$ ($^{40}Ar_P^*$) and K ($K_P$) content of the primary standard (all contributions in %).

error is slightly smaller than the previous mentioned ±0.11, because the uncertainty in the Steiger and Jäger (1977) decay constants is slightly underestimated (see Min et al., 2000). Clearly, the mean value of 7.71±0.08 Ma for the Fortuna lamproite in this study is significantly different from the 6.16±0.30 Ma of Bellon et al. (1983). Furthermore, Table 2b shows that the total error is dominated by the analytical uncertainty ($R$), the uncertainty in the decay constant of $^{40}K$ to $^{40}Ar$ and by the amount of radiogenic $^{40}Ar$ in the primary standard.

It is difficult to explain why both ages show a more than 1.5 Myr discrepancy, because detailed information about the original K/Ar determination is lacking. The younger age of Bellon et al. (1983) might be explained by several reasons. Incomplete extraction of argon in the K/Ar method results in underestimation of the amount of the daughter isotope in a sample, which gives rise to younger apparent ages. In the $^{40}Ar/^{39}Ar$ method, incomplete extraction of argon would underestimate the amount of daughter and parent isotopes equally (because $^{39}Ar$ is a function of the parent isotope $^{40}K$) and will thus not result in underestimation of the age (apart from differential diffusion out of low retention phases where the lighter isotopes might escape more easily, which will also result in slightly younger ages). Moreover, Bellon et al. (1983) give a radiogenic $^{40}Ar$ component of only 28.1% for the Fortuna lamproite. In our study the total amount of released gas contains an amount of ~ 60% radiogenic $^{40}Ar$. Furthermore, we discard all steps containing less than about 40% argon. Potential errors, introduced by the atmospheric and blank correction, influence the K/Ar age of Bellon et al. (1983) to a much larger extent than the data presented in this study. The high atmospheric $^{40}Ar$ content may also point to more weathered samples used by Bellon et al. (1983). A third point of concern involves the possibility of heterogeneity in the sample. In K/Ar dating, the potassium and argon are measured separately. Potassium is generally measured with flame photometry, atomic absorption spectrometry or isotope dilution. Argon is normally determined using isotope dilution with $^{38}Ar$ as a tracer with extraction of the gas from the sample by fusion in an ultra high vacuum system (McDougall and Harrison, 1999). These analyses are performed on two different, relatively large sample splits. Heterogeneity in the sample immediately introduces errors, which are impossible to account for in error propagations.

Too old $^{40}Ar/^{39}Ar$ ages can be produced by the occurrence of $^{39}Ar$ recoil during irradiation of the samples. $^{39}$Ar-recoil results in lower amounts of $^{39}$Ar in the sample, and thus results in older apparent ages. However, $^{39}$Ar recoil artefacts in age spectra of coarse grained (>100 μm in diameter) mineral separates seem to be unimportant (Huneke and Smith, 1976), and can certainly not explain the 1.5 Myr difference.

### 5.2. Comparison between $^{40}$Ar/$^{39}$Ar age and magnetostratigraphic age

When isotopic ages are compared with magnetostratigraphic ages, two entirely independent systems for age determination are compared. This requires a complete error assessment for both systems. Principally, magnetostratigraphic ages largely depend on the reliability of the correlation of the magnetic polarity pattern to the geomagnetic polarity time scale (GPTS). Assuming that the correlation is correct, ages can be estimated by linear interpolation between two magnetic reversals, inferring a constant sedimentation rate. The age of the reversals in the conventional GPTS is again based on an interpolation between two isotopically dated tie-points with their own statistical error. The minimum error in magnetostratigraphic age is therefore that of the isotopically dated tie-points with superposed on it the uncertainty in the determination of the sedimentation rate. Consequently, it is virtually impossible to calculate a meaningful error for a magnetostratigraphic age. The astronomical dating technique, however, has caused a breakthrough in dating the geological record (e.g. Hilgen et al., 1997). This resulted in the development of an astronomical polarity time scale (APTS) in which all magnetic reversals are astronomically dated, i.e. completely independent of isotopic dating. Errors in astronomical dating are considered to be very small, in the order of 5 to 10 ky, providing that the tuning itself is correct (see Krijgsman et al., 1999a). Additionally, as ages can be assigned to individual sediment layers, dating with the APTS is independent of uncertainties in sedimentation rate. In the case of the Fortuna lamproites, however, the largest uncertainty is related to the exact stratigraphic position of the volcanic deposits, since they are not located in the magnetostratigraphically sampled Chicamo section. Based on field studies it could be established that they roughly (within ±100 m) correspond to the transition from marine to continental sedimentation (see also Fig. 2 of Dinarès-Turell et al., 1999). Regarding the relatively high and constant sedimentation rate of approximately 100 cm/ky (Garcés et al., 2001), we expect the error in the magnetostratigraphic age to be not higher than 0.1 Myr. Therefore, we can calculate a good estimate of the magnetostratigraphic age for the Fortuna lamproites as 7.6±0.1 Ma. Clearly, this is not significantly different from the mean $^{40}$Ar/$^{39}$Ar age of 7.71±0.11 Ma.

### 5.3. Towards more consistent age constraints in the Fortuna Basin

Our new isotopic age of 7.71±0.11 Ma for the volcanic intercalations in the sedimentary sequence of the Fortuna Basin is in good agreement with the estimated magnetostratigraphic age of 7.6±0.1 Ma. In addition, it confirms the hypothesis that the main phase of basin restriction, resulting in the deposition of diatomites and evaporites, already took place in the late Tortonian (Montenat, 1973; Krijgsman et al., 2000; Garcés et al., 2001). It was suggested that this “Tortonian Salinity Crisis” of the eastern Betics was related to a local phase of basin restriction caused by uplift of the metamorphic complexes at the basin margin, probably in concert with strike-slip activity along SW–NE trending fault systems (Fig. 1). Regarding the open marine character of the late Tortonian to Messinian sediments of the Murcia-Cartagena Basin, located directly southeast of Fortuna, it suggests that the Betic substratum southeast of Murcia (Carrascoy and La Alberca Massifs) has been uplifted along the Alhama de Murcia Fault during the late Tortonian. Hence, we consider it most likely that the volcanic deposits of the Fortuna Basin are related to the same tectonic phase of strike-slip activity. These tectonic movements formed an important part of the evolutionary history of basin configuration in SE Spain. Differential uplift of the basement units caused major changes in the depositional environment and created large accumulation space in the subsiding basins.

In the southwestern part of the Fortuna Basin, another significant exposure of lamproitic deposits is found at the Barqueros volcano (BV), which is related to the same Alhama de Murcia fault system (Fig. 1). Four whole rock samples from different localities of the Barqueros volcano have earlier been dated with the K–Ar technique and yielded ages of 6.2±0.3 Ma, 6.45±0.1 Ma, 6.79±0.03 Ma and 7.00±0.03 Ma, where this last uncertainty seems to be underestimated (Montenat et al., 1975). The authors questioned if these ages could be translated into a hypothesis that the Barqueros volcano has been active during a period of approximately 800 ky, or that the small variations in age are related to the different quality of the samples, or to the limitations of the dating analyses. Fuster and

Gastesi (1965) already showed that the Barqueros volcano contained at least two episodes. But Montenat et al. (1975) proposed that the oldest age is likely the best representation of the "real" eruption age since rock alteration and/or Ar loss from the glass fraction are prone to yield younger ages. The volcanic deposits in the Barqueros area are intercalated into the magnetostratigraphically dated sections of Barranco de la Salada and Sifón de Librilla, which indicates that the Barqueros volcano was formed between 7.4 and 6.8 Ma. Consequently, it can be concluded that the Barqueros volcano contained more than 1 episode and that whole rock K/Ar analyses seem to be affected by Ar loss. Further, the Barqueros volcano is younger than the Fortuna lamproites, which would indicate that several different volcanic episodes have occurred during the late Tortonian–early Messinian time span in the Fortuna Basin.

## 6. Conclusions

Samples from the volcanic (lamproite) outcrops of the Cabezos Negros in the Fortuna Basin have been dated with the $^{40}Ar/^{39}Ar$ incremental heating technique. The combined weighted mean of the plateau ages results in an isotopic age of 7.71±0.11 Ma for the Fortuna lamproites. This is approximately 1.5 Myr older than the earlier reported K/Ar age of 6.16±0.30 Ma for the same deposits (Bellon et al., 1983). Possible explanations for this marked discrepancy are: (1) incomplete extraction of argon in the K/Ar method, (2) lower radiogenic $^{40}Ar$ contents in the sample studied by Bellon et al. (1983) point to possible advanced alteration, causing uncertainties in the atmospheric argon correction, or (3) heterogeneity of the samples. These three factors may all produce too young apparent ages in the K/Ar method. The new $^{40}Ar/^{39}Ar$ age is, however, in very good agreement with the estimated magnetostratigraphic age of 7.6±0.1 Ma and indicate that the lamproites of the Fortuna Basin are Tortonian in age.

The lamproite deposits are located in the uppermost part of the marine to continental transition zone of the sedimentary sequence of the Fortuna Basin, but clearly at a younger stratigraphic position than the well-known evaporites (Montenat, 1973). Consequently, the new $^{40}Ar/^{39}Ar$ age confirms the hypothesis that the main phase of evaporite deposition in the Fortuna Basin took place in the late Tortonian (Krijgsman et al., 2000). These results form an important step towards a consistent chronological framework for the sedimentary, tectonic and paleogeographic evolution of the Fortuna Basin during the late Miocene.

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## References

Agustí, J., Cabrera, L., Garcés, M., Krijgsman, W., Oms, O., Parés, J.M., 2001. A calibrated mammal scale for the Neogene of western Europe. State of the art. Earth-Sci. Rev. 52 (4), 247–260.

Bellon, H., 1976. Séries magmatiques néogènes et quaternaires du pourtour de la Méditerranée occidentale, comparées dans leur cadre géochronométrique. Implications géodynamiques, thesis, Univ. Orsay, Paris Sud. 367 pp.

Bellon, H., Bordet, P., Montenat, C., 1983. Chronologie du magmatisme neogène des Cordillèeres bétiques (Espagne méridionale). Bull. Soc. Géol. Fr. 25, 205–217.

Benson, R.H., Rakic-El Bied, K., Bonaduce, G., 1991. An important current reversal (influx) in the Rifian corridor (Morocco) at the Tortonian–Messinian boundary: the end of Tethys Ocean. Paleoceanography 6, 164–192.

De Larouzière, F.D., Bolze, J., Bordet, P., Hernandez, J., Montenat, C., Ott d'Estevou, P., 1988. The Betic segment of the lithospheric Trans-Alboran shear zone during the Late Miocene. Tectonophysics 152, 41–52.

Dinarès-Turell, J., Ortí, F., Playà, E., Rosell, L., 1999. Palaeomagnetic chronology of the evaporitic sedimentation in the Neogene Fortuna Basin (SE Spain): early restriction preceding the "Messinian Salinity Crisis". Palaeogeogr. Palaeoclimatol. Palaeoecol. 154, 161–178.

Fuster, J.M., Gastesi, P., 1965. Estudio petrologico de las rocas lamproiticas de Barqueros (prov. de Murcia). Estud. Geol. 20, 299–314.

Fuster, J.M., Gastesi, P., Sagrado, J., Fermoso, M.L., 1967. Las rocas lamproiticas del S.E. de Espana. Estud. Géol. 23, 35–69.

Garcés, M., Krijgsman, W., Agustí, J., 1998. Chronology of the late Turolian deposits of the Fortuna basin (SE Spain): implications for the Messinian evolution of the eastern Betics. Earth Planet. Sci. Lett. 163, 69–81.

Garcés, M., Krijgsman, W., Agustí, J., 2001. Chronostratigraphic framework and evolution of the Fortuna basin (Eastern Betics) since the late Miocene. Basin Res. 13, 199–216.

Hernandez, J., De Larouzière, F.D., Bolze, J., Bordet, P., 1987. Le magmatisme néogène bético-rifain et le couloir de décrochement trans-Alboran. Bull. Soc. Géol. Fr. 8 (III), 257–267.

Hilgen, F.J., Krijgsman, W., Langereis, C.G., Lourens, L.J., 1997. Breakthrough made in dating of the geological record. Eos 78 (28), 285,288–285,289.

Huneke, J.C., Smith, S.P., 1976. The realities of recoil; 39Ar recoil out of small grains and anomalous age patterns in 39Ar–40Ar dating.

In: Merrill, R.B., Morris, R.V., Rhodes, J.M., Usselman, T.M. (Eds.), Proceedings of the Seventh Lunar Science Conference. Petrogenetic Studies of Mare and Highland Rocks, vol. 2. Pergamon Press, New York, NY, United States, pp. 1987–2008.

Koppers, A.A.P., 2002. ArArCALC-software for 40Ar/39Ar age calculations. Comput. Geosci. 28, 605–619.

Krijgsman, W., Hilgen, F.J., Marabini, S., Vai, G.B., 1999a. New paleomagnetic and cyclostratigraphic age constraints on the Messinian of the Northern Apennines (Vena del Gesso Basin, Italy). Mem. Soc. Geol. Ital. 54, 25–33.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999b. Chronology, causes and progression of the Messinian salinity crisis. Nature 400, 652–655.

Krijgsman, W., Garcés, M., Agustí, J., Raffi, I., Taberner, C., Zachariasse, W.J., 2000. The "Tortonian salinity crisis" of the eastern Betics (Spain). Earth Planet. Sci. Lett. 181, 497–511.

Lukowski, P., Wernli, R., Poisson, A., 1988. Mise en évidence de l'importance des dépôts messiniens dans le bassin Miocène de Fortuna (Province de Murcia, Espagne). C. R. Acad. Sci. Paris 307, 941–947.

McDougall, I., Harrison, M.T., 1999. Geochronology and Thermochronology by the 40Ar/39Ar Method. Oxford University Press, Inc. 269 pp.

Min, K., Mundil, R., Renne, P.R., Ludwig, K.R., 2000. A test for systematic errors in 40Ar/39Ar geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite. Geochim. Cosmochim. Acta 64 (1), 73–98.

Montenat, C., 1973. Les formations néogènes et quaternaires du Levant espagnol (Provinces d'Alicante et de Murcia). These Sci. Univ. Orsay: 1170.

Montenat, C., Ott d'Estevou, P., 1990. Eastern Betic Neogene basins —a review. Doc. Trav. IGAL 12–13, 9–15.

Montenat, C., Thaler, L., Van Couvering, J.A., 1975. La faune de rongeurs de Librilla. Corrélations avec les formations marines du Miocène terminal et les datations radiometriques du volcanisme de Barqueros (Province de Murcia, Espagne méridional). C. R. Acad. Sci. Paris 281, 519–522.

Müller, D.W., Hsü, K.J., 1987. Event stratigraphy and paleoceanography in the Fortuna basin (Southeast Spain): a scenario for the Messinian salinity crisis. Paleoceanography 2, 679–696.

Playà, E., 1998. Les evaporites de les conques bétiques marginals (Fortuna-Lorca, Miocè superior): Comparació amb altres conques mediterrànies. PhD thesis, Univ. Barcelona. 248 pp.

Playà, E., Ortí, F., Rosell, L., 2000. Marine to non-marine sedimentation in the upper Miocene evaporites of the Eastern Betics, SE Spain: sedimentological and geochemical evidence. Sediment. Geol. 133, 135–166.

Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., DePaolo, D.J., 1998. Intercalibration of standards, absolute ages and uncertainties in 40Ar/39Ar dating. Chem. Geol. 145, 117–152.

Rouchy, J.M., Taberner, C., Blanc-Valleron, M.-M., Sprovieri, R., Russell, M., Pierre, C., Stefano, E.D., Pueyo, J.J., Caruso, A., Dinares-Turell, J., Gomis-Coll, E., Wolff, G.A., Cespuglio, G., Ditchfield, P., Pestrea, S., Combourieu-Nebout, N., Santisteban, C., Grimalt, J.O., 1998. Sedimentary and diagenetic markers of the restriction in a marine basin: the Lorca Basin (SE Spain) during the Messinian. Sediment. Geol. 121, 23–55.

Santisteban, C., Taberner, C., 1983. Shallow marine and continental conglomerates derived from coral reef complexes after desiccation of a deep marine basin: the Tortonian–Messinian deposits of the Fortuna Basin, SE Spain. J. Geol. Soc. (Lond.) 140, 401–411.

Sanz de Galdeano, C., 1990. Geological evolution of the Betic Cordilleras in the Western Mediterranean, Miocene to present. Tectonophysics 172, 107–119.

Sanz de Galdeano, C., Vera, J.A., 1992. Stratigraphic record and palaeogeographical context of the Neogene basins in the Betic Cordillera, Spain. Basin Res. 4, 21–36.

Steiger, R.H., Jäger, E., 1977. Subcommission on geochemistry: convention on the use of decay constants in geo- and cosmochronology. Earth Planet. Sci. Lett. 36, 359–362.

Venturelli, G., Mariani, E.S., Foley, S.F., Capedri, S., Crawford, A.J., 1988. Petrogenesis and conditions of crystallization of Spanish lamproitic rocks. Can. Mineral. 26 (1), 67–79.