Geologica Acta, Vol.11, N° 3, September 2013, 295-310
DOI: 10.1344/105.000001860
Available online at www.geologica-acta.com

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Ultrapotassic volcanic centres as potential paleogeographic indicators: The Mediterranean Tortonian 'salinity crisis', southern Spain

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ABSTRACT

Dated peperites associated with ultrapotassic volcanic centres of the Neogene Volcanic Province of southeast Spain are of particular interest within the complex tectonomagmatic context of the Western Mediterranean because they show clear volcano-sedimentary interactions making them a valuable tool for correlating between Miocene sedimentary basins in the region. Detailed field mapping of two coeval, but geographically separate, ultrapotassic volcanic centres (Zeneta and La Aljorra), and comparison of sedimentary facies and radiometric ages with another at Fortuna, suggest that these centres apparently formed at approximately the same time, late Tortonian, by the same tectonomagmatic process, strike-slip, and in the same, shallow marine, paleogeographical context. Stratigraphic indicators in the Miocene basins suggest that basin-closure initiated in the region during the late Tortonian, prior to the main Mediterranean Messinian salinity crisis. Notably, many of the ultrapotassic volcanic centres are situated close to, and elongated along, the basin margins faults. We suggest, therefore, that movement of basin margin faults that closed the Miocene sedimentary basins causing drying out also facilitated the contemporaneous ascent of ultrapotassic magma. So, volcano-sedimentary interactions may be used to make inferences about both the tectonomagmatic and paleogeographic evolution of a region. In southeast Spain peperites provide evidence that the Tortonian 'salinity crisis' was geographically more widespread, extending to the southeast, than previously recognized.

KEYWORDS **Tortonian. Peperites. Lamproite. Basin-closure. Salinity crisis .**

INTRODUCTION

Correlation of geochronological and stratigraphic data of coexisting volcanic and sedimentary rocks (*cf.* Roger *et al.*, 2000) potentially gives insights into both how igneous rocks are emplaced and the paleogeographic conditions at the time of their formation. In the Neogene Volcanic Province of southeast Spain, Miocene sediments are cut by contemporaneous volcanic rocks of variable composition (Fig. 1) (López-Ruiz and Rodríguez-Badiola, 1980; Venturelli *et al.*, 1984; Cebriá and López-Ruiz, 1995; Prelevic *et al.*, 2008; Conticelli *et al.*, 2009). Recent publications have focused on the ultrapotassic volcanic rocks and, especially, on their geodynamic implications for the Mediterranean region (*e.g.* Turner *et al.*, 1999; Duggen *et al.*, 2005; 2008; Prelevic and Foley, 2007; Lustrino and Wilson, 2007; Álvarez-Valero and Kriegsman, 2008; Conticelli *et al.*,

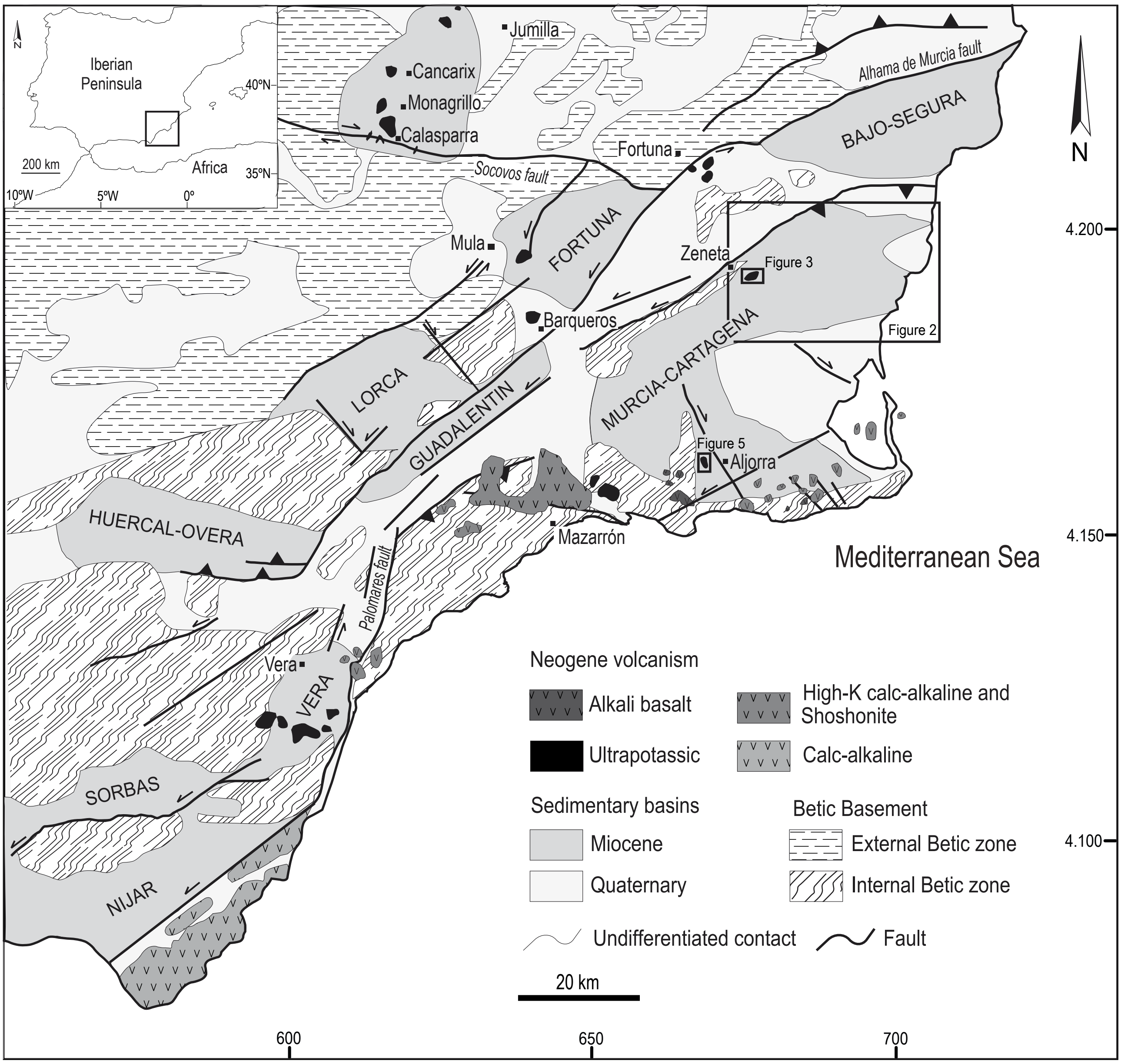

FIGURE 1 Schematic geologic situation of the Neogene Volcanic Province of southeast Spain. The Internal and External Betics zones are shown (modified from López-Ruiz and Bardiola, 1980), as is the distribution of the volcanic rocks (modified from Seghedi *et al.*, 2007), principal faults (modified from Kuiper *et al.*, 2006) and Neogene basins (modified from Soria *et al.*, 2008). The rectangles indicates the areas shown in detail in Figures 2, 3 and 5. Upper case names refer to basins, italic names refer to faults and lower case names to villages. Coordinates are expressed in km and UTM projection.

2009). These studies do not include descriptions of the different facies found in the volcanic outcrops. Detailed field studies, such as those for Jumilla, Cancarix and Calasparra (Seghedi *et al.*, 2007), are essential to attain a better understanding of how and why volcanic rocks erupt and the conditions of syn-emplacement sedimentation.

Sedimentological studies identify two regional drying out events in southeast Spain. The first one, which was less pronounced, was in the Tortonian (Krijgsman *et al.*, 2000; Playà and Gimeno, 2006; Tent-Manclús *et al.*, 2008) and the more pronounced and important second one, in the Messinian (Butler *et al.*, 1995; Reinhold, 1995; Riding *et al.*, 1998; Krijgsman *et al.*, 2000; Kouwenkoven *et al.*, 2003; Rouchy and Caruso, 2006; Braga *et al.*, 2010). The ultrapotassic volcanic centres that crop out in the Tortonian and Messinian sedimentary basins are potential paleogeographic markers. To assess this, two coeval but distinct volcanic centres Zeneta and La Aljorra were selected for detailed study from the various scattered lamproite outcrops of the southeast Spain Neogene Volcanic Province (Fernández and Hernández-Pacheco, 1972; Pellicer, 1973). These volcanic rocks have a similar age (8.08-8.20Ma, Duggen *et al.*, 2005) to the associated sedimentary rocks and are well correlated with them.

In the present work we present detailed new maps of the Zeneta and La Aljorra volcanic centres. Here we report their field relations and petrography which, with X-ray diffraction (XRD) data (Cambeses and Scarrow, 2012), are used to define various facies in each outcrop. The most notable unit identified is that of basal peperites at Zeneta that indicate lava-wet sediment interaction. We combine these data with published stratigraphic data (Montenat, 1973; Krijgsman *et al.*, 2000; Playà and Gimeno, 2006; Tent-Manclús *et al.*, 2008) to discuss the paleogeographic context when the volcanoes formed, the controls on their emplacement and their possible role as markers of the Mediterranean Tortonian salinity crisis.

GEOLOGICAL SETTING

The Neogene Volcanic Province is located in southeast Spain in the Betic Cordillera (Fig. 1), a part of the Betic-Rif orogeny in western Mediterranean. This fragment of collisional mountain belt underwent late orogenic extension during the Miocene (Comas *et al.*, 1999; Platt *et al.*, 2003; Martínez-Martínez *et al.*, 2006). The Betic Cordillera is divided into two main zones: the External Zone (South Iberia paleomargin) and the Internal Zone (Alboran Domain). The External Zone comprises Triassic to Miocene continental margin sedimentary rocks (Vera, 2004 and references therein). The Internal Zone is made up of a stack of tectonic units, from base to top: the Nevado-Filábride Complex, the Alpujárride Complex and the Malágide Complex, it comprises Paleozoic to Mesozoic rocks which were affected by Alpine and Pre-Alpine metamorphism (Vera, 2004 and references therein).

Volcanism in the Neogene Volcanic Province consists of calc-alkaline, high-K calc-alkaline to shoshonitic, ultrapotassic (lamproite) and intraplate alkali rocks (Fig. 1) (López-Ruiz and Rodríguez-Badiola, 1980; Venturelli *et al.*, 1984; Cebriá *et al.*, 1995; Fernández-Soler, 1996). The igneous rocks were emplaced in the form of volcanoes, in general, plugs and dykes, especially the ultrapotassic rocks, cutting the late Tertiary sediment cover and Betic External and Internal Zones basement (Venturelli *et al.*, 1984; Venturelli *et al.*, 1988; Seghedi *et al.*, 2007).

The Zeneta volcanic edifice was emplaced at the contact of the post-orogenic Neogene Bajo-Segura and Murcia-Cartagena basins (Fig. 1, Soria *et al.*, 2008). The sediments that filled the basins were deposited after a significant paleogeographic change that took place at the middle-late Miocene boundary (Tent-Manclús *et al.*, 2005). The sediments which comprise marls, intercalated sandstones and, locally, conglomerates are part of the Torremendo unit (Fig. 2) (Montenat and Ott d'Estevou, 1999). These strata have been dated by planktonic foraminifera as Tortonian, 11.6-7.25Ma (Montenat and Ott d'Estevou 1999; Lancis, 1998). The paleogeographic situation prior to volcanic intrusion was, therefore, a pelagic basin that underwent changes in sedimentary conditions that have been interpreted to result from variations in sea level, recording stages of shallowing in the transition from the middle Miocene to the late Miocene (Montenat, 1975, Montenat and Ott d'Estevou 1999; Krijgsman *et al.*, 2006; Lancis *et al.*, 2010).

The La Aljorra volcanic edifice was emplaced, to the south of Zeneta, in the Murcia-Cartagena Basin (Fig. 1). The sedimentary rocks surrounding La Aljorra are somewhat different from the sediments at Zeneta: they are transitional in age from Tortonian to early Messinian, another difference is that they were deposited in deep water (Montenat, 1973, Montenat 1990, Montenat *et al.*, 1990; Krisjgsman *et al.*, 2006). They are Canteras Formation marls and limestones (Montenat, 1973). Despite these differences, in general terms the radiometric age, paleogeographical situation and associated sedimentary rocks were similar at La Aljorra and Zeneta (Colondrón *et al.*, 1993; Duggen *et al.*, 2005; Iribarren *et al.*, 2009).

MATERIALS AND METHODS

Detailed mapping was carried out of the Zeneta and La Aljorra volcanic edifices in the Bajo-Segura and Murcia-Cartagena basins (Figs. 3; 4; 5; 6). Volcanic rocks and associated sediments were sampled systematically at each outcrop. Standard thin sections of 20 samples were examined using a petrological microscope. X-ray diffraction (XRD) study identified the main minerals in approximately 90 samples (Cambeses and Scarrow, 2012). In addition to our work, we have included information from published petrographic descriptions of the Zeneta rocks (Fernández and Hernández-Pacheco, 1972; Toscani *et al.*, 1995) and the La Aljorra lamproites (Pellicer, 1973).

FIELD RELATIONS

Zeneta

The Cabezo Negro, Zeneta outcrop, (UTM coordinates: 678600-4207300, Fig. 3), is 1km long and 0.5km wide, with a maximum height of 203m in the central part, 190m in the western part and 150m in the eastern part of the outcrop (Fig. 3A). Both the dark colour of the volcanic rocks and their associated vegetation clearly differentiate them from the light-coloured Miocene sedimentary rock of the Bajo-Segura Basin through which the volcano erupted. The southern and western slopes of the outcrop are very steep, rising vertically from the sedimentary substrate and, locally show columnar joints. However, the morphology of the northern and eastern slopes is shallower.

Stratigraphic sequence

The stratigraphic sequence described below is based on the observed field and structural relationships. Four units have been identified, from bottom to top: volcano-sedimentary breccias of group Z-1; massive volcanic rocks of group Z-2 which, when they have intercalations of sedimentary rock, form group Z-3; fault-related breccias of group Z-4; and dykes of group Z-2 rocks that cut the whole series (Fig. 3B; 4).

Group Z-1 volcano-sedimentary breccias are the most widespread and thickest unit in the outcrop. They constitute the lowest unit in the sequence and are always overlain by the massive rocks of group Z-2 or by these rocks with alternating sedimentary layers of group Z-3 (Fig. 3B). Group Z-1 is not stratified and the blocks do not have a preferential orientation. The thickness of the breccia varies from 40m in the west to 15m in the east. The contact with the overlying rocks is concordant, in places the latter can be seen to drape the pre-existing undulating volcanic surface. Locally variations are observed in the abundance of the volcanic clasts in these breccias. In the west volcanic

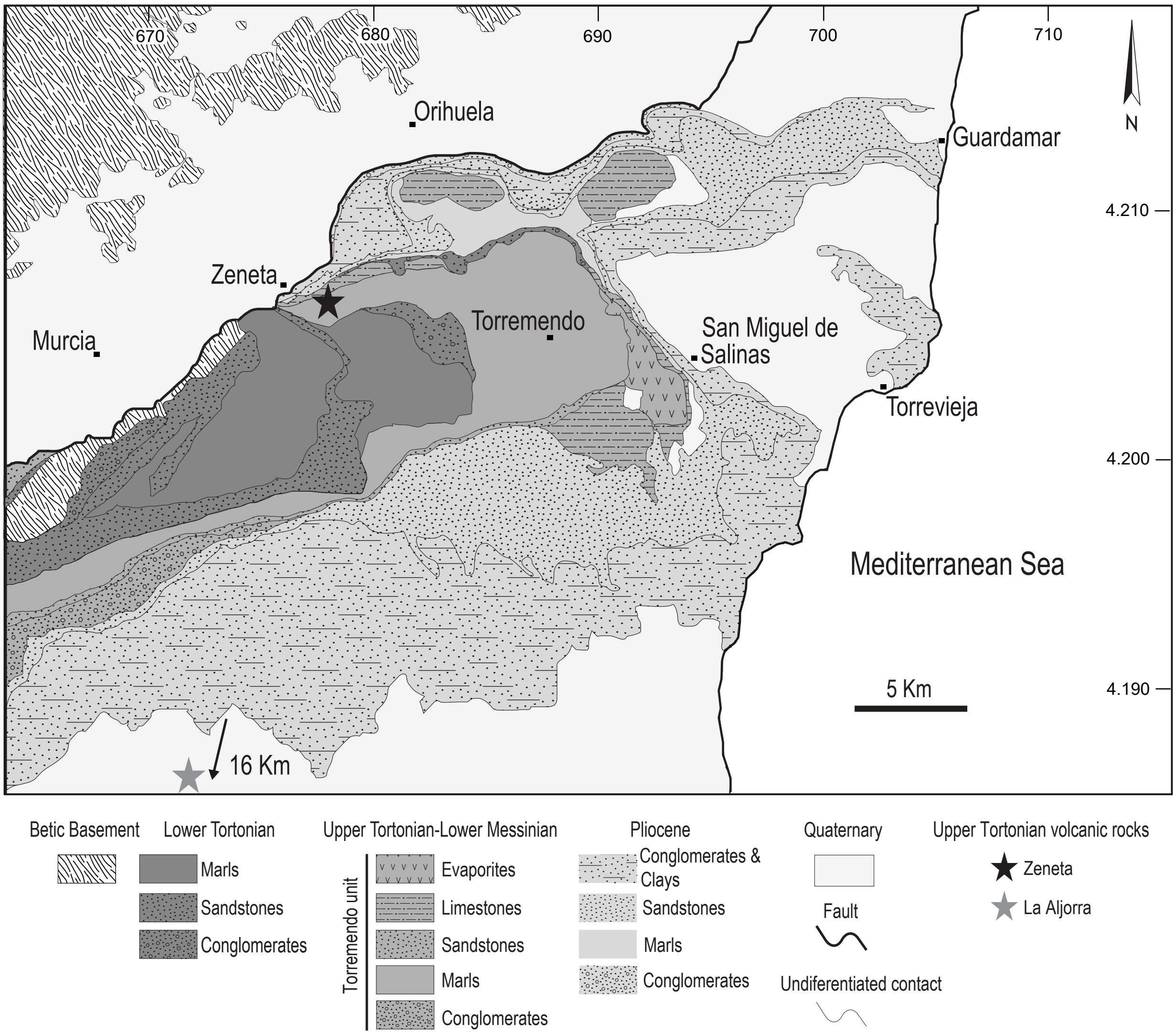

FIGURE 2 | Distribution of sediments in the pre-volcanic basin situation (modified from Soria *et al.* (2008)) and the location of volcanic centres. Coordinates are expressed in km and UTM projection.

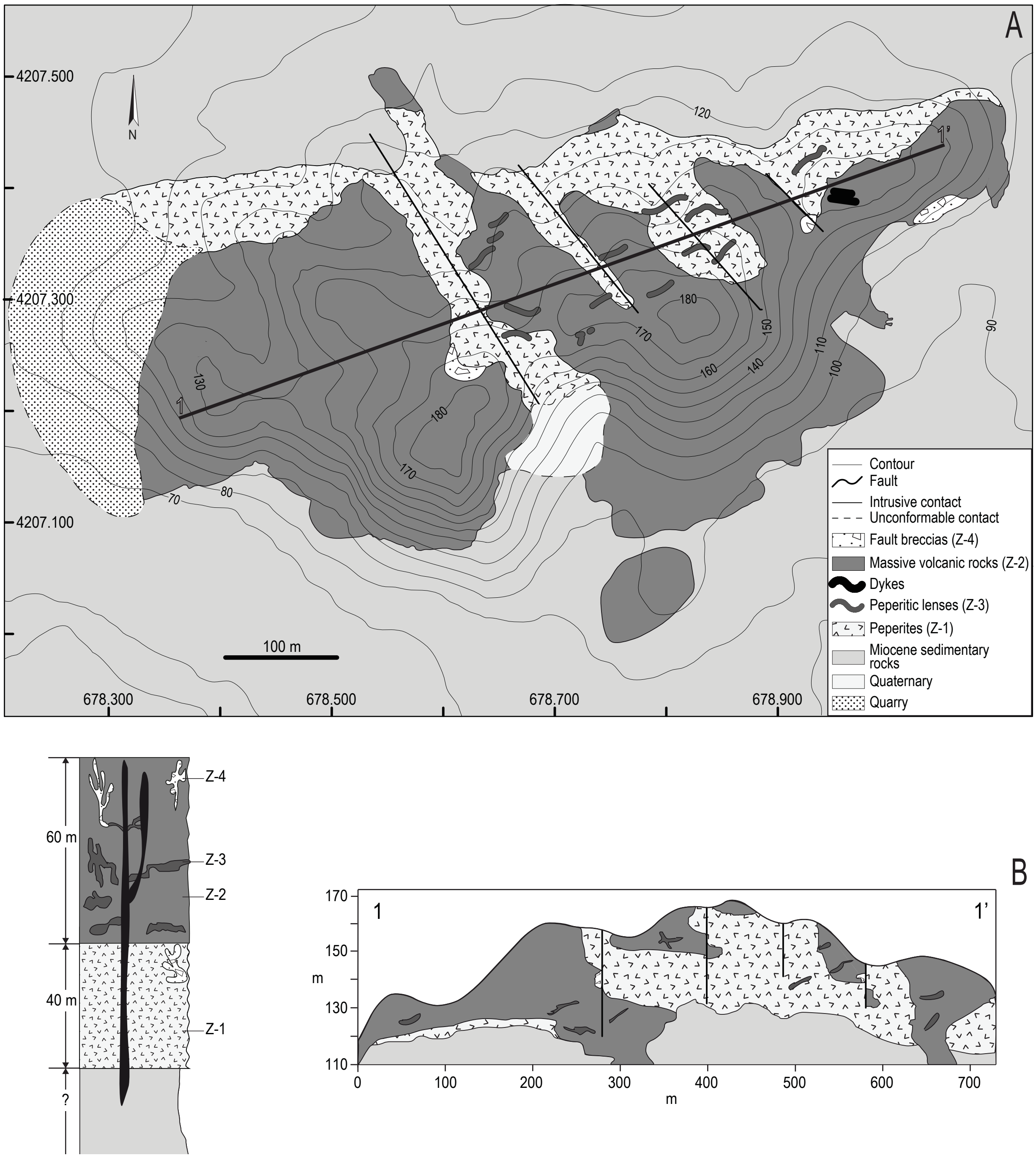

FIGURE 3 | A) Map of Zeneta volcanic outcrop showing all rock types described in the text. B) Stratigraphic sequence of the volcanic edifice and cross section showing the distribution of the different rock types. Coordinates are expressed in m and UTM projection.

blocks are abundant, up to 30-60%, however, in the east and in the upper part of the unit there are fewer blocks, 5-15%, and the sedimentary matrix dominates. The size of the group Z-1 breccia clasts is variable, from centimetre-sized blocks up to large metre-sized blocks (Fig. 4B). The volcanic blocks have a particular alteration in their central part with a bleaching in the interior that is not observed in the exterior (Fig. 4B). They have phenocrysts of phlogopite or biotite in a dark coloured, fine grained, groundmass. Chilled margins are not observed. In hand specimen the matrix sediment is difficult to identify because it is very fine grained but Toscani *et al.* (1995) described it as a marlstone. Significantly, we identified planktonic foraminifera that are comparable to those defined by Montenat (1973) in marls of the Tortonian Torremendo unit in the peperite sediments (Pérez-López, 2010, personal communication). Such volcano-sedimentary field relations are typical of peperites (*cf*. White *et al*., 2000; Skilling *et al*., 2002; Brown and Bell, 2007).

Group Z-2 comprises structureless massive volcanic rocks that form the main part of the volcanic edifice (Fig. 4A). These dark grey massive rocks have a compact appearance (Fig. 4C), they contain large, up to 0.5mm, phenocrysts of phlogopite or biotite and, in places, altered olivine and clinopyroxene. This massive group marks the highest peaks in the outcrop. It also crops out as a lava

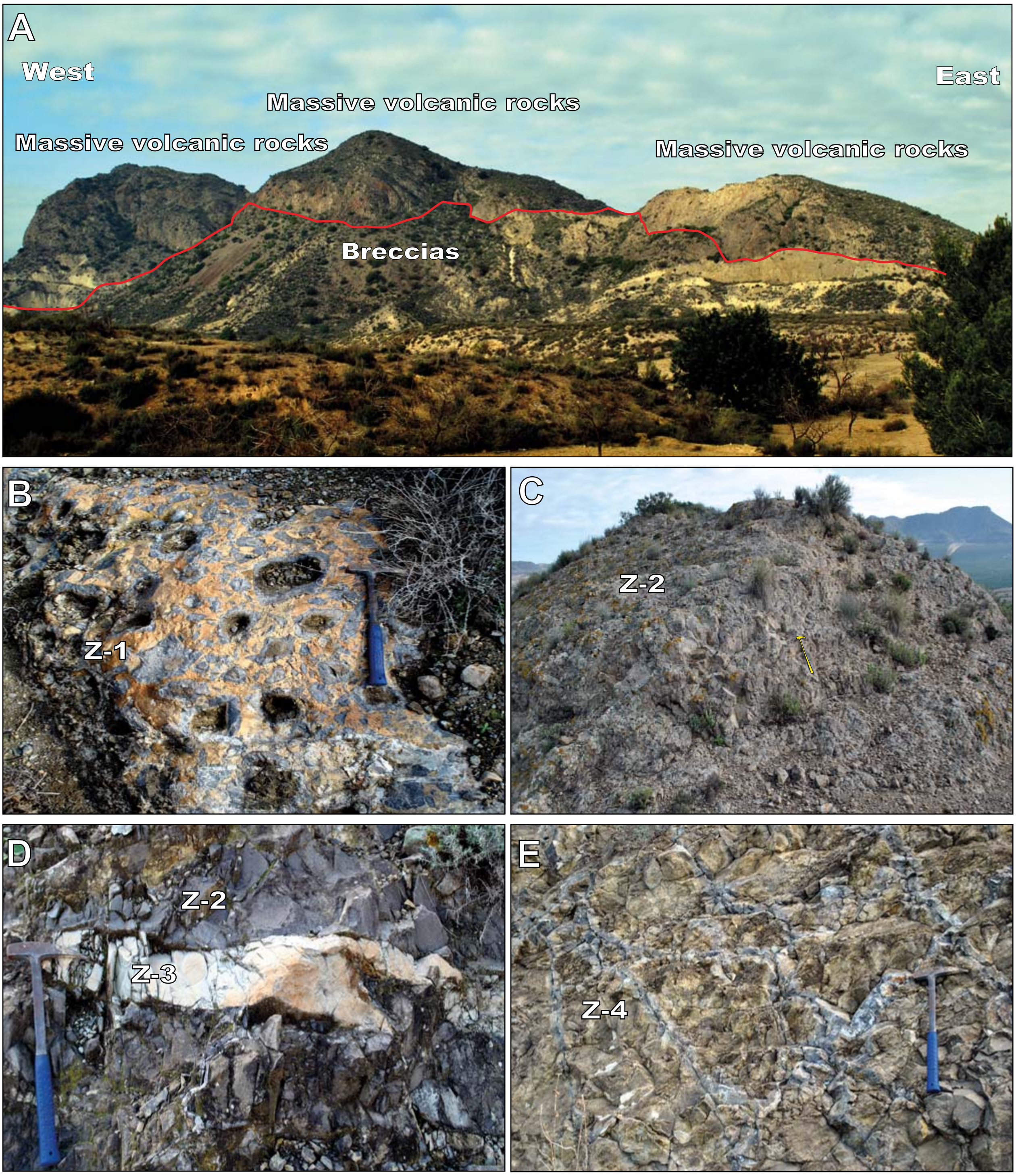

FIGURE 4 | Types of rocks present at Zeneta. A) Panoramic view of the outcrop. B) Breccias of group Z-1, with a sedimentary matrix, and blocks of massive volcanic rocks, classified in this work as peperites. C) Massive volcanic rock of group Z-2. D) Sedimentary rocks, group Z-3, between massive volcanic rock. E) Fault breccias, of group Z-4, cutting the massive volcanic rocks of group Z-2.

flow in which flow lineation is observable marked by alternating dark and light layers orientated parallel to the slope where it solidified. The lava flow is extensive and can be seen on both sides of the volcanic centre although, notably, the inclination of the flow varies: in the southern sector it is slightly inclined whereas in the northern sector it is almost vertical (Fig. 3A). This is the first identification of a lava flow at this volcanic centre and constitutes one of the few known potassic lava flows in the whole southeast Spain Neogene Volcanic Province, the other one being at Barqueros to the southwest (Fuster, 1956).

Group Z-3 is most clearly represented in the eastern and central parts of the outcrop (Fig. 3A). It is formed of sedimentary marlstone inter-layered in the massive volcanic rocks of group Z-2 (Fig. 3B). The marlstone is similar to the sediments that form the matrix of the group Z-1 volcano-sedimentary breccias, but is found in this unit as discrete lenses. These lenses are not very thick, reaching a maximum of around half a metre (Fig. 4D). There is a gradation in this unit: in some areas, at the base of the volcanic edifice, there are thin, up to 15cm, but repetitive layers of sediments, higher up, other sectors have less repetitive, but thicker, up to 50cm, sediment layers. The lenses vary in their orientation from horizontal to vertical.

Group Z-4 fault breccias are much less widespread than group Z-1 breccias, (Fig. 3A). The group Z-4 breccias are made up of fractured blocks which, in places, preserve their original larger block morphology indicating that they are preserved in situ. In addition, the fault breccias are cut by veins of secondary, fault-related, hydrothermal quartz (Fig. 4E). Although not strictly a stratigraphic unit, this rock type was considered separately because lithologically it is quite distinct from the other groups. Group Z-4 cuts the other rock types, usually the group Z-2 massive volcanic rocks but also the group Z-3 breccias (Fig. 4E). The fault breccias are poorly exposed in the field, only being visible along fault zones (Fig. 3A). They are easily confused with the group Z-1 block-rich sedimentary breccias, because the composition of clasts is igneous in both cases.

The whole outcrop is cut by a set of repetitive irregularly spaced vertical joints with a strike of N170ºE. In addition, vertical normal faults, with a strike of N160ºE, cut the central part of the outcrop (Fig. 3A). In the east vertical dykes of group Z-2 composition have a strike of N135ºE.

La Aljorra

The Cerro Cabezuela La Aljorra outcrop, (UTM coordinates 667650-4173280, Fig. 5), is 600m long by 350m wide, and has a maximum height of 145m. It has an elliptical morphology, with smooth shallow slopes (Fig. 5A; 6). The volcanic rocks are in contact with Betic Basement Paleozoic shales and Tortonian-Messinian sedimentary marls, clays and sandstones from the Campo de Cartagena Basin (Pellicer, 1973; Montenat, 1975, Fig. 5A). The dark reddish grey colour of the volcanic rocks clearly differentiate them from the sedimentary rocks through which they erupted. Capping the

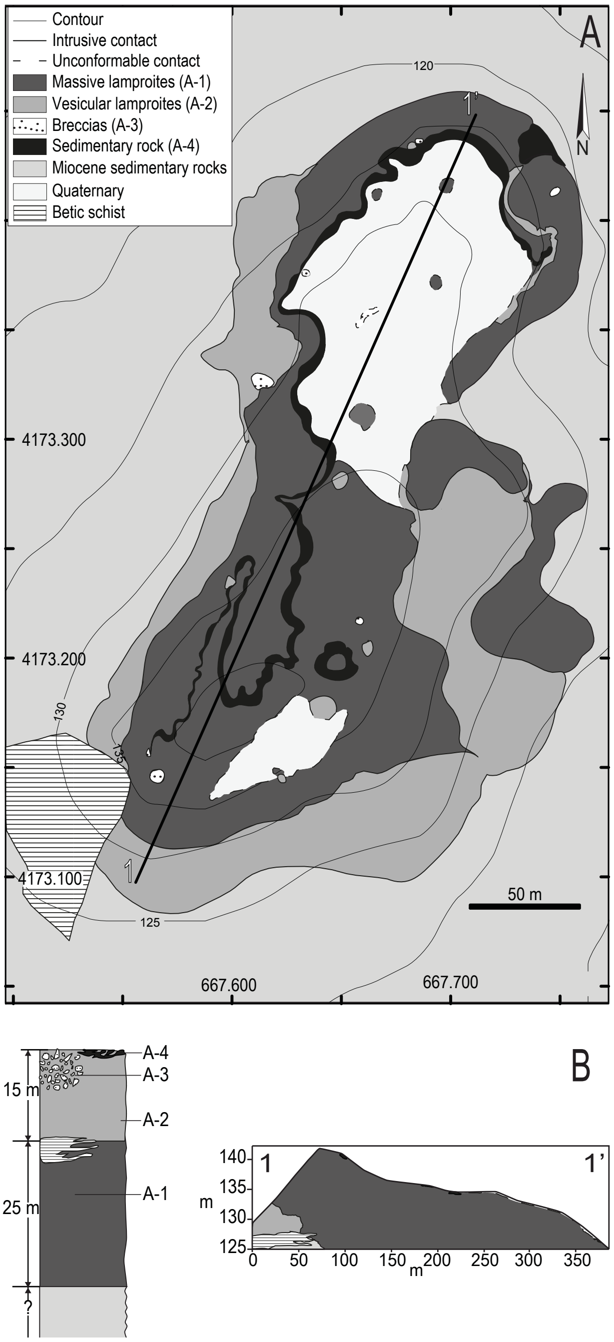

FIGURE 5 | A) Map of La Aljorra volcanic outcrop showing all rock types described in the text. B) Stratigraphic sequence of the volcanic edifice and cross section showing the distribution of the different rocks types. Coordinates are expressed in m and UTM projection.

outcrop is a soil formed of altered lamproites and Quaternary marine sedimentary rocks which cover the dome.

Stratigraphic sequence

The field relations allow a stratigraphic sequence to be established. Four units have been identified, from bottom to top: massive lamproites of group A-1, in which a raft of metamorphic rock is present; vesicular lamproites of group A-2; lamproite breccias of group A-3 which shows a lateral transition to group A-4 lamproite with sedimentary intercalations (Fig. 5B; 6).

Group A-1 massive lamproites are dark grey to red, they contain mafic phenocrysts, olivine and clinopyroxene

FIGURE 6 | Types of rocks present at La Aljorra. A) Panoramic view of outcrop (modified from Del-Ramo, 2010). B) Massive lamproites, from group A-1. C) Massive vesicular-amigdaloydal lamproites, group A-2, in contact with massive lamproites. D) Breccia, from group A-3 located above the massive lamproites. E) Sedimentary intercalations, between massive lamproite blocks, group A-4.

(Fig. 6A, B). Alteration is very marked, indicated by iron oxides, showing stains, and secondary minerals such as zeolites and carbonates. These massive lamproites are the most widespread rock type, they form the core of the outcrop and are typically overlain by group A-2 vesicular lamproites (Fig. 5A). Contacts with the other units of the outcrop indicate lateral changes. A large, 75m by 50m, block of Betic basement schist is present in the south of this unit (Fig. 5A). Columnar joints are observed in places. In contrast to Zeneta, no flow directions are observable, suggesting that the volcanic body was emplaced in situ as a dome.

Group A-2 are vesicular and amygdaloidal lamproites, similar to group A-1, they are dark grey to red and contain mafic phenocrysts, olivine and clinopyroxene (Fig. 6C). This group is well exposed in the western sector of the outcrop where it overlies group A-1 massive lamproites. These rocks are also recognizable in the eastern sector, although there they are less abundant. The contact with group A-1 lamproites is diffuse, and the thickness of this unit is variable, it increases towards the west (Fig. 5A).

Group A-3 are breccias of group A-1 lamproites. The best exposed section of these breccias is in the northern sector (Fig. 5A) where they crop out above group A-1 massive lamproites (Fig. 6D).

Group A-4 is formed of blocks of group A-1 massive and group A-2 vesicular lamproites infilled by marls in the upper section of the outcrop (Fig. 5A). The marls are principally located in the northern and eastern parts of the outcrop, they have a variable thickness but never exceed a metre (Fig. 6E). The contact between this unit and the underlying lamproites is usually sharp though in some sectors of the outcrop it is diffuse because of soil formation or thin cover (Fig. 6E).

PETROLOGY OF THE VOLCANIC ROCKS

Zeneta

The samples selected for detailed petrographic study from the Zeneta volcanic centre are representative of the main rock units described in the current study. In general the rocks are porphyritic with a hypocrystalline texture, they are altered by secondary processes. The main minerals, both as phenocrysts and in the matrix, are olivine (in most cases entirely altered), clinopyroxene, phlogopite and biotite (up to 0.5mm) and alkali feldspar. Zircon, apatite, magnetite and monazite are accessory minerals (Fig. 7A). The rocks also present minerals that are not typical in lamproites such as orthopyroxene, sillimanite, Al-rich spinel and plagioclase, plus xenocrysts of quartz (Cambeses, 2011).

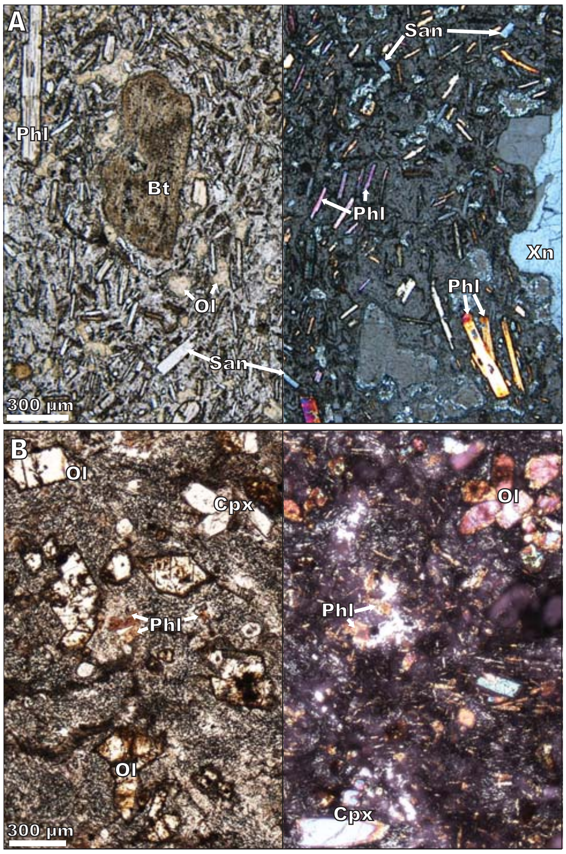

FIGURE 7 | Representative photomicrographs from A) Zeneta and B) La Aljorra volcanic rocks. The left parts of the figure are in ppl while the right parts are in xpl. Ol: olivine, Cpx: clinopyroxene, Phl: phlogopite, Bt: biotite, San: sanidine and Xn: xenolith. Olivine is entirely altered in the Zeneta rocks.

The modal proportions of the main minerals, as determined by XRD, are: olivine ~5%, clinopyroxene ~8%, phlogopite and biotite ~47%, sanidine ~32% and secondary and accessory minerals ~8% (Cambeses, 2011; Martín-Ramos *et al.*, 2012; Cambeses and Scarrow, 2012).

La Aljorra

The samples selected for detailed petrographic study from the La Aljorra volcanic centre are representative of the main rock units described in the current study. In general, the rocks are holocrystalline with a porphyritic texture with typical lamproite phenocrysts of olivine (up to 0.25mm), diopside and sanidine (Fig. 7B). The main minerals, both as phenocrysts and in the matrix, are olivine (most abundant), diopside, sanidine, phlogopite and matrix carbonates. Accessory minerals are apatite and opaques. Secondary minerals include iron oxides, iddingsite-serpentine, carbonates and clay minerals.

The modal proportions of the main minerals, as determined by XRD, are: olivine ~33%, clinopyroxene

~21%, phlogopite ~11%, sanidine ~30% and secondary and accessory minerals ~5% (Cambeses and Scarrow, 2012).

DISCUSSION

Interpretation of the volcanic centres

Zeneta

Combining the results of previous work (Fernández and Hernández-Pacheco, 1972; Toscani, *et al*., 1995) with studies on comparable rocks (Montenat, 1973; Playà and Gimeno., 2006; Seghedi, *et al*., 2007) we use field data, stratigraphic relationships and petrographic information to develop a model for the generation of this outcrop. The starting point for our model is the available age data: the Zeneta sedimentary rocks have been dated as middle–late Miocene (Montenat and Ott d'Estevou 1990; Montenat, 1990; Soria, *et al*., 2001, 2005), and the volcanic rocks have been dated by Ar-Ar, on phlogopite, at 8.08 ± 0.03Ma (late Miocene, Tortonian) (Duggen *et al*., 2005).

The model presented here explains three stages in the formation of the volcanic centre.

i) First stage – phreatomagmatic episode and formation of peperites: The field relations presented above indicate that the first intrusive phase formed the group Z-1 volcano-sedimentary breccias, which are located in the lower part of the sequence (Fig. 2). The volcanic blocks in the breccias are randomly orientated and their sizes are very variable (Fig. 4B), all of which suggest that they were transported as a mixture of sediment and volcanic blocks that were subsequently cemented.

Peperites are rocks formed, essentially in situ, although potentially transported after their formation, by fragmentation of lava intruding and mingling with unconsolidated or poorly consolidated, typically wet, sediments. They are often formed at the margins of intrusions and at the base of lavas, as noted by Playà and Gimeno (2006). Such lithofacies only form in shallow water within poorly lithified sediments. Where they are found, peperites are a key indicator of contemporaneity of magma extrusion and sediment deposition. They provide valuable information about phreato-magmatic processes and environments of eruption, thus giving important insights into the evolution of volcanic intrusion (White *et al*., 2000; Brown and Bell, 2007).

The Zeneta volcano-sedimentary breccias are classified here, for the first time, as peperites because they show distinctive sedimentary and magmatic textures typical of such facies: sediment surrounding irregular bodies of lava and the presence of lava and/or phenocrysts surrounding sediments. They are, in fact, in our opinion, a spectacular text book example of such rocks (Fig. 4B, *cf*. Kokelaar, 1982; White *et al*., 2000; Skilling *et al*., 2002; Brown and Bell., 2007). So, the group Z-1 breccias are apparently phreatomagmatic, related to interaction between magma and water-rich, in some cases marine, sediments, the Tortonian marls of the Torremendo unit (Fig. 8A) (*cf*. Lorenz, 1987). According to Skilling *et al*. (2002), breccias such as those of group Z-1 from Zeneta, peperites with irregular volcanic clasts, indicate that the sedimentary component was dominant. Foraminifera fossils identified in the peperite sediments are typical of a shallow, near coast, marine environment. The importance of this setting in terms of paleogeographic reconstructions is considered below.

ii) Second stage – formation of massive volcanic rocks and peperite lenses: After the formation of the group Z-1 peperites, group Z-2 massive volcanic rocks show

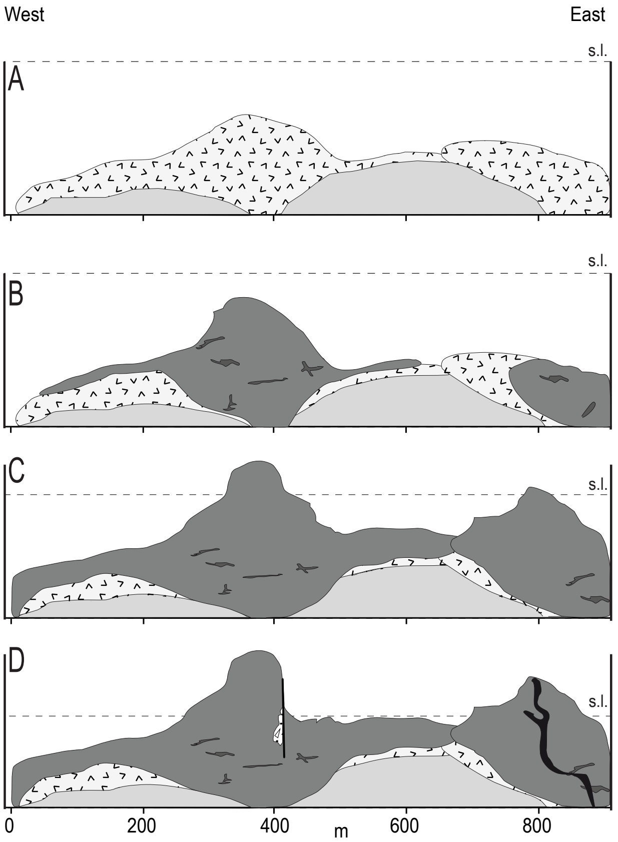

FIGURE 8 | Schematic interpretative model explaining the generation of the Cabezo Negro, Zeneta, volcanic edifice. A) First intrusive stage: phreatomagmatic episode, forming volcano-sedimentary peperites of group Z-1. B) Second intrusive stage: submarine intrusive episode, forming the initial massive intrusion and peperite lenses of group Z-3. C) Third intrusive stage: main subaereal episode, forming the massive volcanic rock dome with columnar joints group Z-2. D) Finally, intrusion of dykes and formation of fault breccias of group Z-4. s.l.: sea level. The vertical scale is exaggerated for clarity in all sections. Legend explained in Figure 3.

little evidence of interaction with water-rich sediment. Based on the field evidence, this suggests that formation of Z-1 peperites produced a conduit or conduits that isolated subsequent magma emplacement from significant interaction with wet sediment. So, group Z-2 massive volcanic rocks passed through the sedimentary formations and were deposited on the sea floor. However, during this massive episode, the group Z-3 peperite lenses also formed. This association of massive volcanic rocks and peperite lenses indicates that the volcanic system was more established than during the formation of group Z-1 and that the phreatomagmatic activity had significantly decreased (*cf.* Skilling *et al.*, 2002). Evidence for interaction between sediments and volcanic rocks decreases towards the top of the outcrop (Fig. 8B).

iii) Third stage – main subaereal episode: This episode is the most important: it formed the main body of the group Z-2 as a large volcanic dome (Fig. 8C). We suggest that it was a multiphase intrusion because two large bodies are recognized in the field. The dome comprises massive rocks, with no interbedded sediments, in which columnar jointing and joints are present. Related to this intrusion are the aforementioned lava flows that apparently originated in the dome and now reach the edge of the outcrop (Fig. 3A). When the lava was erupted below sea level it intercalated with layers of sediment, forming peperite lenses, the absence of such features in the lava flows suggest that when they formed the volcanic activity was subaereal (Fig. 8C).

The field relations presented above indicate that, at the end of the magmatic episode, fault movements disrupted the original sequence favouring the intrusion of dykes of group Z-2 composition, with a strike of N135ºE, along lines of weakness during the late stages of the evolution of the volcano (Fig. 8D).

La Aljorra

Combining the result of previous work (Pellicer, 1973; Duggen *et al.*, 2005; Conticelli *et al.*, 2009) with our field results we develop a model for the emplacement evolution of these rocks. The starting point, as in the case of Zeneta, is the temporal connection between the volcanic activity (8.02 ± 0.04Ma, Ar-Ar, on matrix chips, Duggen, *et al.*, 2005) and the associated Tortonian to Messinian sedimentary rocks (Martínez Díaz, 1969; Montenat, 1973; Montenat, 1990; Montenat *et al.*, 1990; Colondrón *et al.*, 1993).

The model presented here explains two stages in the formation of the volcanic centre.

i) First stage – massive intrusion: The first intrusive phase formed the group A-1 massive lamproites, which, as described above, are located in the lowest part of the sequence. There was apparently no peperite formation as seen in Zeneta, probably because of the increased hydrostatic pressure of the deeper water conditions (Montenat, 1973; Montenat, 1990; Montenat *et al.*, 1990; Krisjgsman *et al.*, 2006), but then at La Aljorra the base of the volcanic centre is not observed (Fig. 9A).

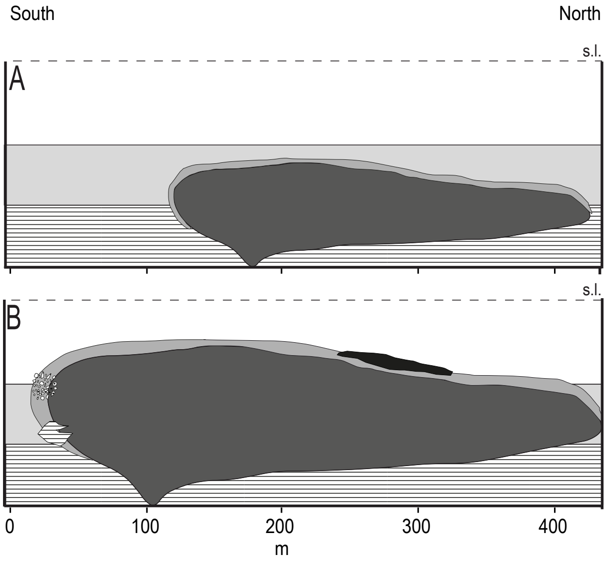

FIGURE 9 | Schematic interpretative model explaining the generation the Cerro La Cabezuela, La Aljorra, volcanic edifice. A) First intrusive stage: massive intrusion. B) Second intrusive stage. s.l.: sea level. The vertical scale is exaggerated for clarity. Legend explained in Figure 5.

ii) Second stage – emplacement process: During this stage the magma body rose to the surface and, as a result of rapid ascent, the massive lamproites exolved volatiles and vesicles were formed. In these group A-2 rocks stretched vesicles can be observed at the border of the massive intrusion. We suggest that, as it rose, the massive intrusion entrained the block of metamorphic rock that is present in the southern part of the outcrop (Fig. 9B).

At a later stage and unrelated to the emplacement of the La Aljorra volcanic dome, the Murcia–Cartagena Basin Quaternary sediments infilled the blocky lava surface.

Paleogeographic implications

Age and stratigraphic position: preliminary correlations

Volcanic rocks from southeast Spain have been the subject of detailed geochronological study (*e.g.* Duggen *et al.*, 2005) to establish the relationships between the different types (*e.g.* López-Ruiz and Rodríguez-Badiola, 1980) (Fig. 1). These geochronological data represent an excellent source of information to establish stratigraphic and paleogeographic relationships in particular when, such as at Zeneta, interactions between volcanic and sedimentary rocks are identified (*e.g.* Playà *et al.*, 2000, Playà and Gimeno, 2006; Caracuel *et al.*, 2004). Ultrapotassic magmas are well suited to such a study because they are typically geographically restricted, furthermore, they are characterized by fast, fault-related ascent (Mitchell and Bergman, 1991), which potentially allow them to interact with unconsolidated sedimentary rocks, and, most importantly, to preserve this interaction in the stratigraphic record, typically as peperites.

The southeast Spain Miocene sedimentary basins, specifically those around Murcia and Almeria, have a very well defined stratigraphic sequence (Montenat, 1973) in which different stages of regression and transgression have been identified (Montenat and Ott d'Estevou, 1990; Montenat and Ott d'Estevou, 1999; Montenat, 1990). The well-known Messinian salinity crisis has been the focus of detailed study (*e.g.* Krijgsman *et al.*, 2000; Duggen *et al.*, 2003; Roveri *et al.*, 2008). Nevertheless, other important stages of shallow and deep water sediment deposition have been described in these basins, although the age of these stages is not always clear because of the lack of specific chronological indicators.

Ultrapotassic volcanic rocks from southeast Spain have an age interval of 6.7 to 8.6Ma (Ar-Ar on mineral separates, Duggen *et al.*, 2005), middle Tortonian to very early Messinian. This is significant because the greatest regression identified in the region was during this time, when the Mediterranean sea dried out (Butler *et al.*, 1995; Reinhold, 1995; Riding *et al.*, 1998; Krijgsman *et al.*, 2000; Rouchy and Caruso, 2006; Braga *et al.*, 2010). Some authors suggest that the ultrapotassic volcanic centres formed as a result of the same convergence that is proposed to have provoked the Messinian regression (Duggen *et al.*, 2003, 2005). Sediments within the peperites are typically shallow-marine *e.g.* gypsum or marls (White *et al.*, 2000; Playà and Gimeno, 2006; Brown and Bell, 2007; the present work), which supports the idea of a convergence-related basin-closure and subsequent drying out. Such an event is potentially datable by the peperite volcanic component.

The Tortonian 'salinity crisis': ultrapotassic volcanic rocks as a record

It is not always possible to identify the initiation of a basin drying out stage, to do so it is necessary to understand the stratigraphic sequence of the basin and also to make lateral correlations between basins in the same region. As described above, the middle to late Tortonian volcanic rocks from Zeneta were emplaced into the marls from Torremendo unit of the Bajo-Segura Basin (Montenat, 1973; Montenat and Ott d'Estevou, 1999; Soria *et al.*, 2008). Notably, the sedimentary unit associated with the late Tortonian-early Messinian La Aljorra lamproites are also marls, from the Canteras unit of the Murcia-Cartagena Basin (Montenat, 1973; Montenat and Ott d'Estevou, 1999).

A relationship between strike-slip fault movement and ultrapotassic magma generation is well established worldwide (*cf.* Mitchell and Bergman, 1991; Vaughan and Scarrow, 2003; Scarrow *et al.*, 2011 and references therein) and specifically in recent regional studies of strike-slip related ultrapotassic bodies, e.g, the Socovos fault lamproites dyke, in the Neogene Volcanic Province of southeast Spain (Pérez-Valera, 2010; Pérez-Valera *et al.*, 2010). Consideration of the regional geological map shows that many of the ultrapotassic volcanic centres are situated close to basin margins (Fig. 1) which are marked by strike-slip faults (Montenat and Ott d'Estevou, 1990). What is more, some centres show evidence of elongation with a strike that is comparable to the regional faults (Fig. 3; 5). As noted above these rocks are characterized by rapid rise and emplacement, allowing correlation of their emplacement process with sediments that were being deposited in the Neogene basins. So, the precise geochronological age of the volcanic rocks can be used to constrain the timing of the stratigraphic sedimentary section.

The Zeneta and La Aljorra volcanic rocks can be related temporally and compositionally to other ultrapotassic volcanic outcrops in the region such as Fortuna (Fuster, 1967). Lamproites at Fortuna have an age of 8.21 ± 0.17Ma (Ar-Ar on mica, Duggen *et al.*, 2005) and 7.71 ± 0.11Ma (Ar-Ar on mica, Kuiper *et al.*, 2006). Many authors link the Fortuna Basin and the Bajo-Segura and San Miguel de Salinas basins, (Fig. 1) by lateral stratigraphic correlations relating the gypsums and marls of the Gypsum units in the former (Playà and Gimeno, 2006) to the marls of the Torremendo unit in the latter (Playà *et al.*, 2000; Soria *et al.*, 2005; Tent-Manclús *et al.*, 2008) (Fig. 2). Very few works have been published regarding the stratigraphic sequence further to the south in the Murcia-Cartagena Basin at La Aljorra (Montenat, 1973; Colodrón *et al.*, 1993) (Fig. 1). Nevertheless, based on the comparable radiometric ages of the volcanic rocks between Fortuna, Zeneta and La Aljorra (Duggen *et al.*, 2005) a lateral correlation may be drawn between the sediments of these three localities. These correlations link the compositionally similar ultrapotassic volcanic rocks in the three centres as being apparently formed at approximately the same time, by the same tectonomagmatic process and in the same paleogeographical context.

The Fortuna Basin sediments have been interpreted to be the result of a regressive episode in the Tortonian based on magnetostratigraphy, palaeontology and sedimentary and igneous petrology (*e.g.* Dinarès-Turell *et al.*, 1999; Playà *et al.*, 2000; Playà and Gimeno, 2006; Krijgsman *et al.*, 2000; Kuiper *et al.*, 2006; Tent-Maclús *et al.*, 2008; Lancis *et* *al*., 2010). A Tortonian 'salinity crisis' has been defined by the above authors as a significant regression stage during which the Fortuna Basin evaporite facies were deposited. Some of these evaporite units are associated with marls that form peperites as a result of interaction with lamproitic lavas (Playà and Gimeno, 2006), although these are not as spectacular as those described in the present work.

Even though the Tortonian 'salinity crisis' was more apparent in the Fortuna Basin it was still detectable in the Bajo-Segura Basin. The basins located further to the south, such as Murcia-Cartagena, although they may have been involved in the same closure process, were more submerged and so did not dry out (Fig. 10). Evidence of the greater marine depth further south is provided in the current study by the apparent shallow-marine transitional to subaereal situation of the more northerly Zeneta volcanic centre during its formation, peperite emplacement, and its emergent, subaereal lava flows, and marine sediment-free situation since formation. This contrasts with the submarine situation of the La Aljorra volcanic centre further south as indicated by the volcanic edifice being almost completely covered by Miocene marine sediments (Fig. 9B). We suggest that detailed consideration of interactions between sedimentary and volcanic rocks, for example the pillow lavas observed to the south at Vera and subaereal lava flows found at Barqueros to the north (Fig. 10C), may be an interesting line of investigation for future paleogeographical studies.

Ultrapotassic volcanic rocks can apparently be used to constrain basin margin fault movement that led to the start of basin-closure which subsequently resulted in drying out leading, eventually, to the Mediterranean salinity crisis in southern Spain in the Miocene. Our observations support the idea that basin-closure actually started in the middle-late Tortonian and became more pronounced as it continued through the Messinian (*cf.* Butler *et al*., 1995; Reinhold, 1995; Riding *et al*., 1998; Krijgsman *et al*., 2000; Kouwenkoven *et al*., 2003; Rouchy and Caruso, 2006; Braga *et al*., 2010). Clearly, the processes leading to the Tortonian 'salinity crisis' were temporally and spatially more widespread than previously thought, as shown by ultrapotassic volcanic rocks which, being typically geographically restricted and characterized by fast, fault-related, ascent, are potentially excellent paleogeographic indicators that may be applied where clear volcano-sedimentary interactions are identified.

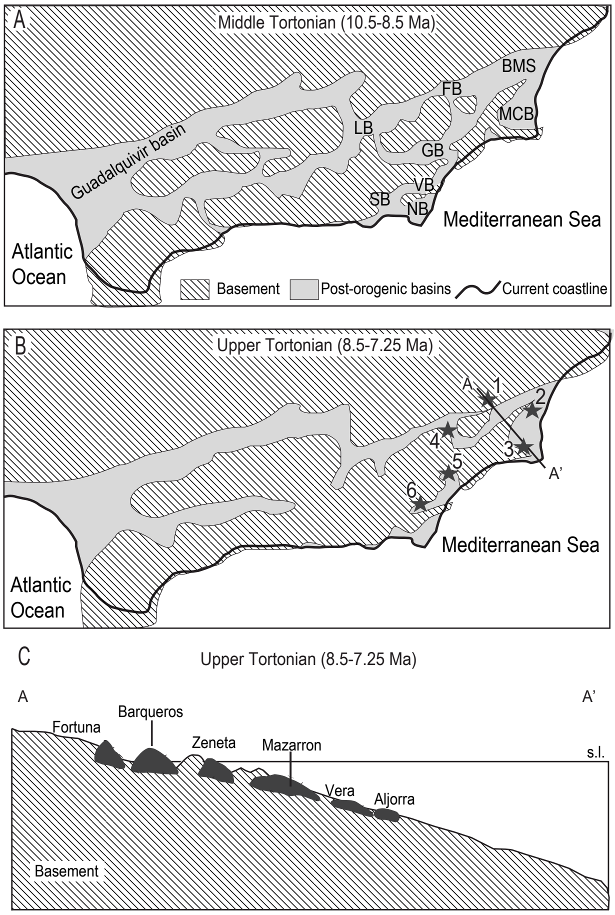

FIGURE 10 | A) and B) Schematic evolution of the Neogene basins during the Tortonian stage in which the Fortuna, Zeneta, La Aljorra, Barqueros, Mazarron, and Vera ultrapotassic volcanic centres formed. The figure shows basin-closure that is more marked in the north during this stage (modified from Viseras *et al*., 2004). C) Model, this work, of relative positions of ultrapotassic volcanic centres and the relationship with the late Tortonian situation. s.l.: sea level. The volcanoes are projected onto the line AA'. Basins nomenclature; LB: Lorca Basin, FB: Fortuna Basin, BMS: Bajo-Segura and San Miguel de Salinas Basins, MCB: Murcia-Cartagena Basin, GB: Guadalentin Basin, VB: Vera Basin, SB: Sorbas Basin and NB: Nijar Basin. Volcano outcrops are indicated by stars and their nomenclature is; 1: Fortuna, 2: Zeneta, 3: La Aljorra, 4: Barqueros, 5: Mazarron and 6: Vera.

CONCLUSIONS

i) In the present work detailed mapping revealed that at Zeneta, to the north, at the contact of the Bajo-Segura and Murcia-Cartagena basins, peperites formed during the early stages of volcanic activity when lava interacted with unconsolidated shallow-marine sediments, the subsequent activity resulted in an emergent volcanic edifice. By contrast, at La Aljorra, some 20km to the south, in the Murcia-Cartagena Basin, a volcanic dome was covered by marine sediments syn- and post-formation.

ii) Emplacement of ultrapotassic volcanic rocks, forming peperites, at Fortuna and Zeneta, 8–8.2Ma, allows lateral correlation of gypsum and shallow marine marls sediments that were deposited during a drying out event in the late Tortonian. At this time basin closure initiated in southeast Spain prior to the main Messinian salinity crisis.

iii) The Zeneta and La Aljorra outcrops indicate that the processes leading to the Tortonian 'salinity crisis' were temporally and spatially more widespread throughout the area of the Neogene Volcanic Province of southeast Spain than previously thought.

iv) We propose that the process that resulted in closure of the Miocene basins was related to the ultrapotassic rock generation, most obviously it may be suggested, by movement on basin margin strike-slip faults.

Knowledge of the field relations and emplacement style of the ultrapotassic volcanic centres and their connection with associated sediments can be used to constrain paleogeographic setting and to make inferences about the tectonic evolution of a region.

ACKNOWLEDGMENTS

We are grateful to Dejan Prelevic, Elisabet Playà, and an anonymous referee for their detailed revisions which helped us to improve the manuscript. Insightful comments by Alan Vaughan clarified many points. We acknowledge the editorial work of Emilio Ramos and Montserrat Liesa is thanked for her editorial handling and suggestions. This study has been financially supported by the Andalusian grant RNM1595, the Spanish grant CGL2008-02864, and a Masters grant awarded to AC by the Departamento de Mineralogía y Petrología, Universidad de Granada, Spain.

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Manuscript received May 2012;
revision accepted January 2013;