Journal of
Iberian Geology
AN INTERNATIONAL PUBLICATION OF EARTH SCIENCES

Interaction between intra-continental sedimentary basins and small-volume monogenetic volcanism: Argamasilla and Calzada-Moral basins, Campo de Calatrava Volcanic Field, Spain

Interacción entre cuencas sedimentarias intra-continentales y volcanismo monogenético de pequeño volumen: Cuencas de Argamasilla y Calzada-Moral - Región Volcánica del Campo de Calatrava, España

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Abstract

We study the volcaniclastic lithofacies interbedded between siliciclastic and carbonate sediments of Cenozoic-Quaternary age (8.7 Ma to 7,000 BP) in Argamasilla and Calzada-Moral basins (Central Spain). The siliciclastic and carbonate deposits correspond to fluvio-lacustrine sedimentary environments. The volcanic materials consist of primary and reworked volcaniclastic successions sourced from the Campo de Calatrava Volcanic Field. Pyroclastic deposits are related to monogenetic and small-volume volcanic centres, such as scoria cones, tuff rings and maars, corresponding to Strombolian and phreatomagmatic eruptive styles.

Taking into account sedimentological constraints seven volcaniclastic lithofacies were distinguished. Type A corresponds to sub-aerial pyroclastic fall deposits, as is inferred by the common disorganization of the deposit, their breccia-like aspect with presence of large bombs, poor sorting and lack of tractional sedimentary structures. Types B1, B2, B3 and B4 have different volcanic sources and are interpreted to be the product of low-density (dilute) pyroclastic surges, with textural features indicative of fluctuations in flow regime. This interpretation is based on the fabric and grain size of pyroclasts, together with the size and geometry of the internal sedimentary structures. Type C represents a secondary volcanic deposit related to volcanic sediments reworked by transitional hyperconcentrated flows and dilute fluvial processes, having subsequently accumulated in braided fluvial systems. Finally, the Type D is interpreted as an intra-maar scoria/spatter cones related to the development of maars.

The most important factors that determined the sedimentation in these basins were orientation of basement faults, paleogeographic and sedimentological controls, style of eruption and volcaniclastic lithofacies type.

Keywords: Pyroclastic fall, dilute pyroclastic base surge, phreatomagmatic eruption, maar, tuff ring, sedimentary control

Resumen

Se presenta un estudio de las litofacies volcanoclásticas intercaladas entre sedimentos siliclásticos y carbonatados de edad Cenozoica y Cuaternaria (8,7 Ma a 7.000 BP) en las cuencas de Argamasilla y de Calzada-Moral (centro de España). Los depósitos carbonatados y siliciclásticos corresponden a ambientes sedimentarios fluvio-lacustres. Los materiales volcánicos se componen de sucesiones primarias y retrabajadas originadas en el Campo Volcánico del Campo de Calatrava. Los depósitos piroclásticos están relacionados con centros volcánicos monogenéticos y de pequeño volumen, como conos de escoria, anillos de tobas y maars, correspondientes a erupciones estrombolianas y freatomagmáticas.

Teniendo en cuenta el análisis sedimentológico se han distinguido siete litofacies volcanoclásticas. El Tipo A corresponde a depósitos de caída piroclástica subaérea, como se infiere por la desorganización común del depósito, su aspecto de brecha con presencia de grandes bombas, mala clasificación y la ausencia de estructuras sedimentarias de tracción. Los tipos B1, B2, B3 y B4 tienen diferentes fuentes volcánicas y se interpretan como productos de oleadas piroclásticas de baja densidad (diluidas), con características texturales indicativas de las fluctuaciones del régimen de flujo. Esta interpretación se basa en el tamaño de grano de los piroclastos, y el tamaño y la geometría de las estructuras sedimentarias internas. El Tipo C representa un depósito volcánico secundario relacionado con sedimentos volcánicos retrabajados por flujos hiperconcentrados de transición y procesos fluviales diluidos, habiéndose acumulado posteriormente en sistemas fluviales trenzados. Por último, el Tipo D se interpreta como un cono de escoria/salpicaduras intra-maar relacionado con el desarrollo de un maar.

Los principales factores que determinaron la sedimentación en estas cuencas fueron la orientación de las fallas del basamento, los controles sedimentológicos y paleogeográficos, así como el estilo eruptivo y el tipo de litofacies volcanoclástica.

Palabras clave: Piroclastos de caída, oleadas basales piroclásticas diluidas, erupción freatomagmática, maar, anillo de tobas, control sedimentario

1. Introduction

The eruption of basalts is the most common form of volcanism on the Earth's surface, especially in tectonically active zones and continental/intraplate zones (Valentine and Gregg, 2008). Cenozoic alkaline mafic magmas erupted in different regions of Europe defining the Tertiary Central European Volcanic Province (Wilson and Downes, 1991) and the Circum-Mediterranean Anorogenic Cenozoic Igneous Province (Lustrino and Wilson, 2007; Lustrino *et al.*, 2011). In both provinces different intra-continental volcanic fields were developed, namely in Eifel, Germany (e.g. Seib *et al.*, 2008), in the Pannonian Basin, in Central Europe (e.g. Kereszturi *et al.*, 2011), in the Eger Graben, Czech Republic (e.g. Cajz *et al.*, 2009), or in the Iberian Peninsula (Alborán Sea, Campo de Calatrava, Levante and the SE Volcanic Province, see López Ruiz *et al.*, 2002). Coevally with the Cenozoic volcanism it is not uncommon to found a continental sedimentation that occurred in basins formed during the Alpine Orogeny. This coexistence provides the occurrence of volcanic and non-volcanic deposits, as it has been reported in different geotectonic and paleoenvironmental settings, including large-volume stratovolcanoes, calderas and small-volume monogenetic volcanic fields (e.g. Smith, 1987, 1991; White, 1990, 1991; Haughton, 1993; Eriks-

son and Simpson, 1993; Hayes *et al.,* 2002; Gran and Montgomery, 2005; Kataoka, 2005; and Martina *et al.,* 2005; Manville *et al.,* 2009).

In the case of the Iberian Peninsula, different continental sedimentary basins were formed during the Alpine Orogeny, namely, Duero, Tajo, Ebro and La Mancha basins. In the latter, a number of associated depressions (Argamasilla and Calzada-Moral basins, Fig. 1) exhibit volcaniclastic deposits interbedded between continental deposits (Herrero *et al.*, 2004 a, b; Herrero *et al.,* 2009). Although abundant literature on volcaniclastic deposits exists regarding the transport processes and types of deposits (e.g., McPhie *et al.,* 2001; Németh *et al.,* 2009; Manville *et al.,* 2009), there is scarce information about the influence of volcanism on continental basins, being, therefore, an issue poorly understood, which is in line with the lack of systematic volcanological and sedimentological studies in the above basins.

This work focuses on the description, interpretation and correlation of the volcaniclastic deposits of the Argamasilla and Calzada-Moral basins located in the Campo de Calatrava Volcanic Field, which will give us guidelines for establishing their relationship with the sedimentary and tectonic evolution of these basins. To achieve these goals we discuss twenty-two detailed stratigraphic profiles of selected outcrops, where volcaniclastic lithofacies have been identified. Data con-
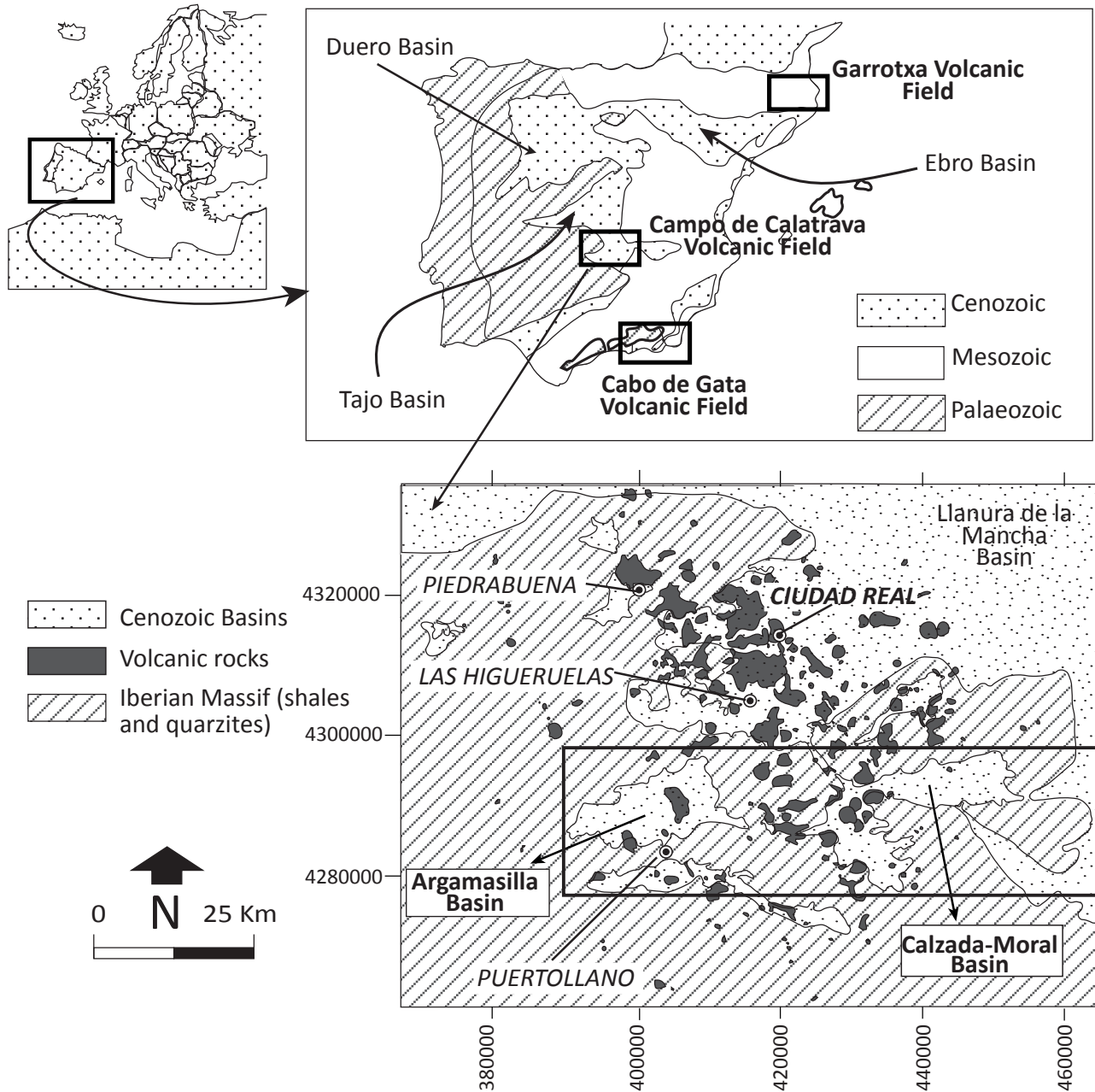
Fig. 1.- Location of the main Neogene basins and volcanic fields in the Iberian Peninsula. General geology of the Campo de Calatrava Volcanic Field, modified from Gallardo-Millán and Pérez-González (2000).

Fig. 1.- Localización de las principales cuencas neógenas y regiones volcánicas en la Península Ibérica. Geología general de la Región Volcánica del Campo de Calatrava, modificada a partir de Gallardo-Millán y Pérez-González (2000).

tain volcaniclastic successions, including classification of lithology, measurement of grain-size of particles, colour, bed thickness, overall rock texture, mean and maximum grain size, sedimentary structures and measurements of paleocurrent indicators. The analysis of the sedimentary processes that produced the volcaniclastic deposits interbedded between siliciclastic and carbonate sediments will provide a generalised facies model of intra-continental terrestrial sedimentation influenced by a monogenetic volcanism.

2. Geological setting

The sedimentary basins of Argamasilla and Calzada-Moral are located over the Variscan basement of the so-called Iberian Massif (Fig. 1). The most relevant works analysing the region are those of Molina (1975, 1980), Molina *et al.*, (1972), Crespo (1988, 1992) and Palero (1991). Basement structural features (folds and faults), with a general east-west trend, are conditioning the present regional relief. The reactivation of NNW-SSE

and ENE-WSW fault systems during the Alpine Orogeny is considered to have produced the subsidence recorded by its sedimentary filling. These basins are mainly surrounded by ranges of mountains consisting of Ordovician and Silurian metasediments, which constitute the supplies for the basin-filling process. Fossil-bearing deposits in Cenozoic basins located northwards of those analysed here, namely, at Piedrabuena and Las Higueruelas (Fig. 1), have led to an attempt at correlation and dating of Argamasilla and Calzada-Moral, obtaining similar ages to those obtained from absolute dating in volcanic rocks (8.7 to 0.7 Ma, e.g., Ancochea 2004). The deposits of these basins are related to fluvial, lacustrine and palustrine environments, soil alteration (calcretes) and a remarkable proportion to volcanic supplies from the so-called Campo de Calatrava Volcanic Field (CCVF). The eruptive style for the CCVF is dominated by small-volume explosive eruptions, typically Strombolian and phreatomagmatic (Di Traglia *et al.,* 2009). Two phases of volcanism have been distinguished in this area (Ancochea 2004): a first ultrapotassic episode occurring between 8.7 and 6.4 Ma (Upper Miocene), and a second episode, alkaline and ultraalkaline in composition, dated between 3.7 and 0.7 Ma (Plio-Pleistocene, e.g., Ancochea *et al.*, 1979; Ancochea and Ibarrola, 1982; Bonadonna and Villa 1984; Gallardo-Millán *et al.,* 2002; Gallardo-Millán, 2004). Finally, a late-stage phreatomagmatic has been dated at the mid-Holocene (Columba volcano, Fig. 1, see González-Cárdenas *et al.,* 2007, 2008). The volcanism in the CCVF was typically monogenetic according to its short live and small volumes (see e.g., Valentine and Gregg, 2008, Németh, 2010), producing small-volume volcanic edifices of scoria cones, tuff rings and maars. The most common eruption style is the Strombolian, showing 200 and 350 vents that are aligned NNW-SSE, generally in the preferential directions of N45-60W, N40E and N80-85E (Barrera, 1996; Rodríguez Pascua and Barrera, 2002 and Ancochea, 2004).

Numerous hypotheses have been invoked to explain the mechanism triggering volcanism in the CCVF, namely, a transform fault located between the Betic Orogen and the Central Spanish Plateau (Doblas *et al.*, 1991), an extensional model associated with rifting processes (López Ruiz *et al.*, 1993) and lithospheric flexures that involved the mantle as a consequence of the Betic Orogen (Rincón and Vegas, 1996).

3. Sedimentary successions in the Argamasilla and Calzada-Moral basins

Besides volcaniclastic facies, described in detail below, the sedimentary succession in the Argamasilla

Basin mainly comprises gravels, sands, clays and limestones, with a maximum thickness of 50-70 m. The sedimentary environments correspond to braided river systems, with longitudinal and transverse gravel bars within low-sinuosity fluvial channels and a moderate-to-high braided component (Monteserín *et al.,* 2011; Martín-Serrano *et al.,* 2011 and Martín Banda *et al.,* 2011). Flood plain deposits are mainly formed by sands and were generated by overbank deposition. The channel network is interpreted to be ephemeral and mobile, as it can be deduced from the pattern of channel and overbank facies, with a maximum of one or two superimposed sequences of conglomerates surrounded by flood plain deposits. Flood plains show evidences of subaerial exposures and processes of soil alteration (calcretes). In the southeast of the basin, carbonate-rich lacustrine and palustrine environments occur, with different marginal, littoral, and open lake facies (profiles 1 and 2, Fig. 3).

Complementary information about Neogene sediment thickness has been provided from the ARG-1 borehole, located close to Argamasilla de Calatrava (Figs. 3 and 4A), obtaining a minimum thickness of 105 m for this basin.

Calzada-Moral Basin is constituted by fine-grained terrigenous material, namely, clays and sands, as well as calcretes, conglomerate beds, marls and scarce limestones. The coarse sediments were deposited in low-sinuosity, mono-episodic, and ephemeral fluvial channels. The existence of sigmoidal lateral accretion units in some bars indicates high-sinuosity channels. Fine-grained materials represent the sedimentation in a flood plain, where pedogenic processes occurred (profiles 3, 9, 10, 11 and 12; Fig. 5).

Using available subsoil data, two depocentres were identified in the Calzada-Moral Basin. The shallowest depocentre is placed close to Moral de Calatrava (Fig. 5), having a maximum depth of 150 m. The deepest one is close to Aldea del Rey, where its maximum depth has been estimated to be around 300 m (Fig. 2). The thickness of Neogene sediments decreases towards the NE, as it is inferred from the 811/1 borehole (Fig. 2A), where a maximum thickness of 184.50 m was reached in these sediments (Fig. 4 B).

4. Sedimentological analysis of the volcaniclastic deposits

In this section, volcaniclastic deposits interbedded with siliciclastic and carbonate sediments of the Argamasilla and Calzada-Moral basins are described and interpreted, the description of volcaniclastic lithofacies and sequences being summarized in Table 1.
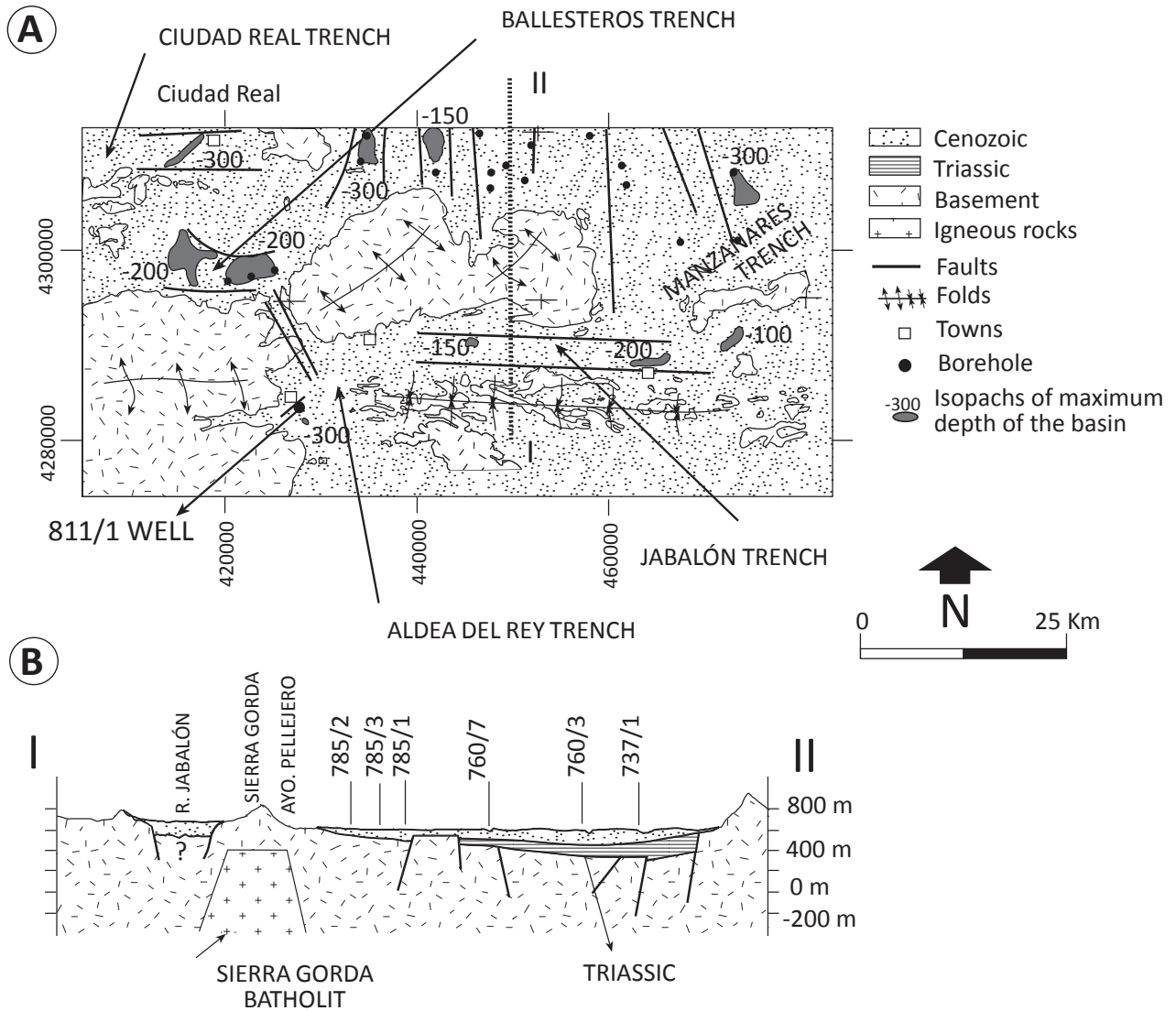
Fig. 2.- Isobaths and structural maps of the Campo de Calatrava. Modified after Rosales et al. (1988). A) Structural map of the Campo de Calatrava region. B) N-S geological sections.

Fig. 2.- Mapas de isobatas y estructural del Campo de Calatrava. Modificado a partir de Rosales et al. (1988). A) Mapa estructural de la región del Campo de Calatrava. B) Cortes geológicos en dirección N-S.

4.1. Type A volcaniclastic deposit (A)

This deposit is recorded at Granátula de Calatrava (Calzada-Moral Basin) (Fig. 6) and is composed of two distinct stratigraphy horizons covered by the Type B3 deposits (described below). The lower part of the deposit is a volcanic breccia (formed of lapilli, blocks and bombs) (Fig. 7A) sometimes joined at one or two points between particles (Table 1). These materials are polymodal, with a main size of 20-25 cm. They show clast-supported texture, with matrix (sometimes open framework) of coarse ash and reddish fine lapilli, without any orientation of blocks. The deposit is poorly sorted and shows a non-uniform distribution of grain sizes. Outsized blocks, of up to 1 m^3, are arranged sparsely between the rest of the clasts (Fig. 7B). Most of the pyroclasts are welded in this lithofacies and form an indurated level (Fig. 7B). Internally, materials are disorganised, massive to weakly bedded and normal graded. The lateral extension of this volcaniclastic deposit is less than 500 m.

The components are primary juvenile clasts, most of them with angular to irregular shapes. Slightly vesiculated blocks and angular shapes, locally showing subrounded rims, are abundant, being mainly formed by plagioclase-rich basalts and limburgites (Martín-Serrano *et al.,* 2011).

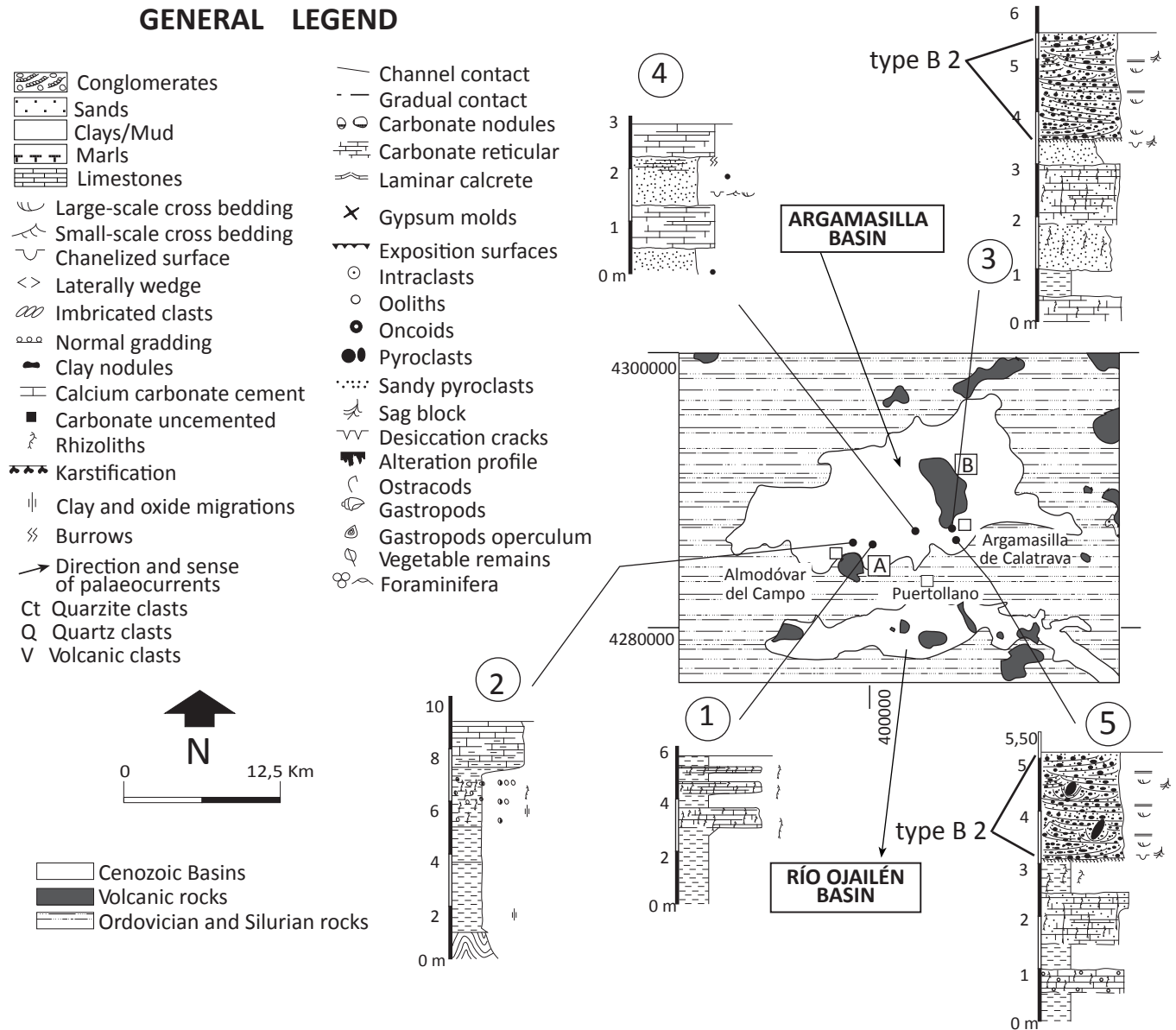The upper part is made up of red clays (10 R 4/6) with ash, together with scattered blocks and bombs. These

Fig. 3.- Stratigraphic sections of the Argamasilla Basin. A- Laguna Blanca maar and Cerro de Cabeza Parda volcano; B- Almodóvar del Campo maar.

Fig. 3.- Columnas estratigráficas de la Cuenca de Argamasilla. A- Maar de la Laguna Blanca y volcán de Cerro de Cabeza Parda; B- Maar de Almodóvar del Campo.

clays show a polyhedral texture, relict bedding and fine root traces. This paleosoil has been dated by radiocarbon analysis yielding an age less than 7,000 BP (Middle Holocene) (González-Cárdenas *et al.,* 2007 and 2008).

Interpretation

This volcaniclastic facies is inferred to be formed in a proximal setting around a small-volume volcano, as indicated by its coarse-grained nature, matrix pure texture and uncharacteristic grading, providing a massive nature to the deposits. These physical features, together with the composition and the shape of the pyroclasts suggest that this facies is dominated by the accumulation of fallout deposits, which were formed close to a vent in the rim surrounds the crater of a Strombolian style scoria cone (Fisher and Schmincke, 1984; Vespermann and Schmincke, 2000; Valentine *et al.,* 2005). The disorganised lower part consisting of coarse breccia-like, together with the poor sorting and the absence of sedimentary structures also indicates proximity to the vent. It seems likely that pyroclasts were ejected following a ballistic trajectory during outbursts of hot and vesiculated magma from a vent that formed a ring around the vent and built a scoria cone. These deposits are inferred to be part of a flank of a scoria cone.

The material in the upper part has been weakly modified by pedogenesis and has the characteristics of a paleosoil (less than 7,000 years BP, dated by González-Cárdenas

et al., 2007, 2008), indicating an interruption in volcanic activity.

This lithofacies is related to the well-preserved Columba Volcano (Fig. 8) whose volcanic edifice has a conical shape and a circular depression with a preserved crater. This edifice is composed of different stratigraphic episodes, indicating distinct eruptive episodes that began with lava-flows spreading out to the northeast and to the northwest in the base of the volcanic edifice. The Type A volcaniclastic deposits are mainly distributed to the southeast part, forming part of a Strombolian cone edifice from a pyroclastic succession. Some pedogenic textural modifications occurring in this lithofacies were used to dating the activity of Columba volcano, yielding an absolute age of $6,560 \pm 130$ and $6,590 \pm 200$ years B.P. (González-Cárdenas *et al.,* 2007, 2008).

4.2. Type B 1 volcaniclastic deposit (B1)

This deposit occurs close to Calzada de Calatrava (Calzada-Moral Basin) being composed of a fining-upward sequence of several volcaniclastic lithofacies repeated over a thickness of several tens of metres (Fig. 9D). The base of this deposit is flat, sharp and erosive to centimetre scale. Materials show a decrease in grain size and an increase in fine materials towards the top.

The lower part consists of strongly consolidated breccia and coarse lapilli-tuff, with a matrix-supported texture of coarse tuff (Figs. 7C and D). These materials were very poorly sorted, containing clasts in subrounded and locally subangular shapes and a maximum diameter size of 20 cm. The main clast components were juvenile and lithic (sandstones and shales). On average, the thickness of the lower part varies between 2 and 3 m and occupies a volume of 70-90% of the total. Internally, this part is massive, horizontally stratified or in tangential beds. They frequently show normal grading and rarely inverse grading.

This part grades upward into fine lapilli-tuff and coarse-medium tuff. Similarly, it comprises flat and parallel laminations (dunes and megaripples) with millimetre-thick cross-laminae, highlighted in most cases by variations in grain size. Paleocurrents are directed to the SE.

Interpretation

This type of deposit can be interpreted as a product of low density (dilute), highly turbulent pyroclastic surges that were generated in phreatomagmatic eruptions (Sparks and Walker, 1973; Sparks, 1976; Sheridan and Wohletz, 1981 and 1983; Fisher and Schmincke, 1984; Cas and Wright, 1987). The sedimentological characteristics, geometry and size of the sedimentary beds indicate
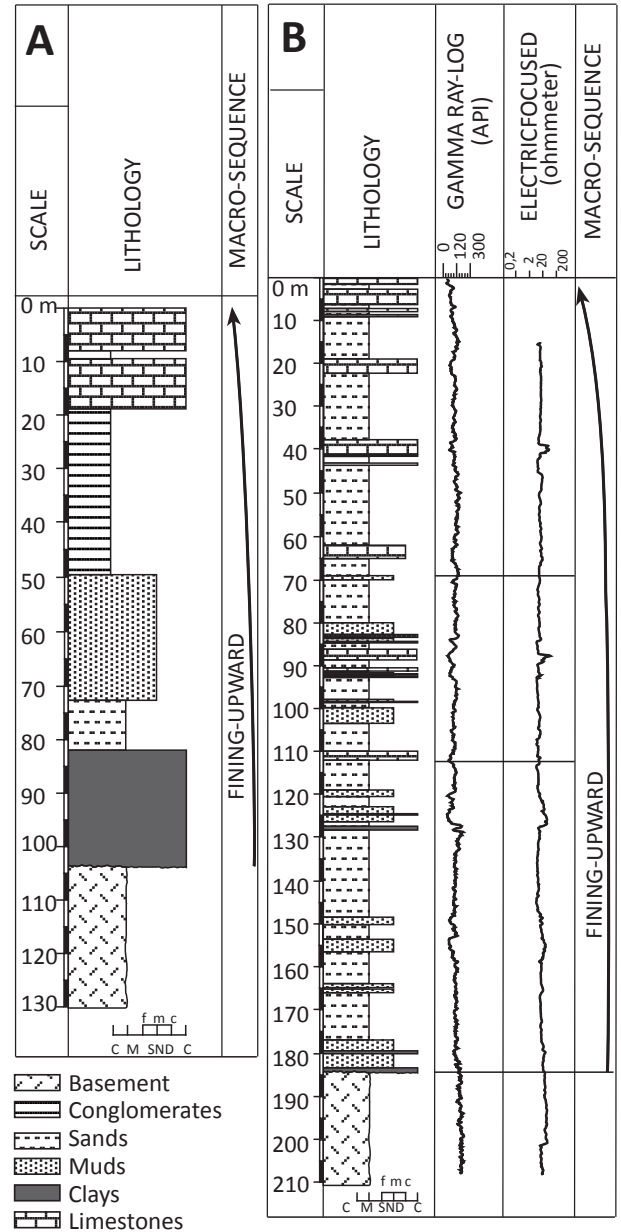

Fig. 4.- A) ARG-1 borehole drilled in the vicinity of Argamasilla de Calatrava. B) Main characteristics of the 8/11 borehole drilled to the south of Aldea del Rey, modified after Rosales et al. (1988).

Fig. 4.- A) Sondeo ARG-1 perforado en los alrededores de Argamasilla de Calatrava. B) Principales características del sondeo 8/11 perforado al sur de Aldea del Rey, modificado a partir de datos de Rosales et al. (1988).

that a high-energy tractional flow deposited the base of the sequences. A decrease in tractional energy and flow speed occurred at the top of the sequence, as it is inferred by the decrease in the grain size, the transport of finer materials and a lesser amount of material.

B1 lithofacies features, namely, accretionary lapilli, oversteepened foresets and/or backsets, load structures and/or convolutions, and poor sorting are conclusive with a cool and moist deposit (less or equal to 100 ºC), in
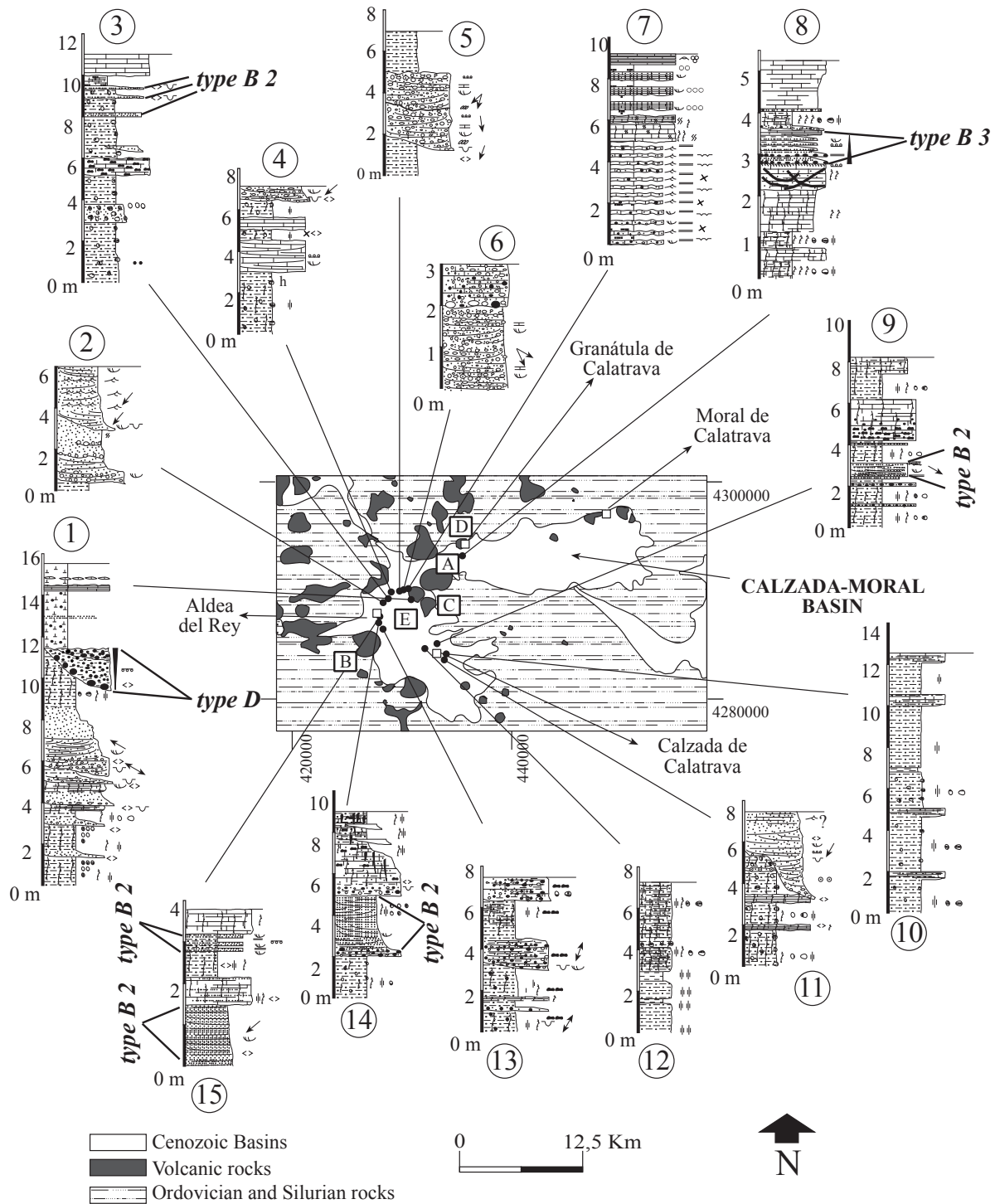
Fig. 5.- Stratigraphic profiles of the Calzada-Moral Basin. A- Columba volcano, B- El Cortijillo volcano, C- Cabezuelo volcano, D- Granátula maar, and E-Casablanca maar.

Fig. 5.- Columnas estratigráficas de la Cuenca de Calzada-Moral. A- Volcán Columba; B- volcán El Cortijillo; C- volcán Cabezuelo; D- maar de Granátula; E-maar de Casablanca.

agreement with Branney and Kokelaar (2002).

B1 deposit is vertically repeated (Fig. 9) and consists of successive pyroclastic single-surges showing a decrease in the grain size and an increase in fine materials at the top. It is inferred to be a medial-to-distal base surge suc-cession accumulated in the "ring-plain" around a maar or tuff ring volcano about several hundreds to few kilo-metres from their source. Bearing in mind the direction of the paleocurrents observed, this deposit is possibly re-lated to the poorly preserved El Cortijillo Volcano.
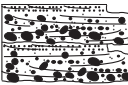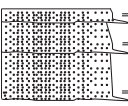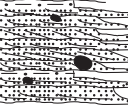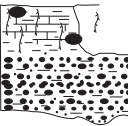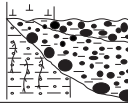
TYPE OF DEPOSIT		SEDIMENTARY STRUCTURES	COLOUR	GEOMETRY lateral extent / thickness	LIMIT	OTHER CHARACTERISTICS	INTERPRETATION
A		disorganized, without sedimentary structures	dark brown and black (5 YR 3/4)	lenticular <300 m/>7 m	not visible	Outsize bombs of up to 1 m3 are sometimes seen (Fig. 7 B). Calcium carbonate coats the pyroclasts.	Pyroclastic fall deposits with ballistic projection bombs
B1		massive, horizontally stratified, tangential bedding, flat and parallel laminations, dunes and megaripples, normal-graded stratification.	brown (5 YR 6/ 1) ochre (10 YR 7/4)	tabular >100 m/<3 m	flat, well visible, and small-scale erosive	The colours of the pyroclasts are of two types: green and dark (10 GY 5/ 2), the most frequent type, and light in colour (N9), forming the minority. The directions of the paleocurrents obtained reveal flows towards the SE. Locally there may be veins of calcium carbonate.	Low-density (dilute) pyroclastic surges with decrease in tractional energy in the upper interval.
B2		small to medium-scale cross-bedding, dunes and flat-parallel lamination and sag block	blackish and green (10 GY 5/ 2), light in colour (N 9).	wedge >100 m/0,45-3,00 m	planar, or locally sharply erosive	The colours are green and light brown, normally superimposed by a reddish colour due to soil alteration.	Low-density (dilute) pyroclastic surges. Fall of bombs with ballistics projection.
B3		millimetre-thick parallel lamination and normal grading	yellow (10 YR 6/ 6)	U-shaped channel <60 m/ 4 m	erosive, channelized	The direction and sense of the paleocurrents provided by this channel is N 30°.	Low-density (dilute) pyroclastic surges with high flow regime.
B4		parallel lamination, dunes and ripple cross-lamination, massive or with a horizontal lamination	brown (10 YR 7/4) to (5 YR 3/2)	tabular >100 m/5-25 cm	irregular and slightly erosive	The laminations are highlighted by variations in grain size and colour.	Low-density (dilute) pyroclastic surges. Air fall deposits in the upper interval.
C		normal grading with a massive base or with horizontal stratification.	reddish brown (5 YR 5/6 to 10 R 4/ 6)	lenticular, channelized <50 m/various m	erosive at metric scale, and is somewhat channelized	The shape of the clasts is subrounded and the more angular ones have worn sides.	Secondary volcanic sediments were reworked by fluvial streams.
D		both intervals show inverse grading	lower red interval (10 R 4/ 6) and a green upper interval (5 Y 6/ 4 to 10 Y 6/ 2).	lenticular <3 m/<10 m	planar, or locally sharply erosive	Deposits interbeded between lacustrine marls and limestones and fluvial red siltstones and clays	Deposits of scoria/spatter cones

Table 1.- Description of the volcaniclastic deposits.
Tabla 1.- Descripción de los depósitos volcanoclásticos.

4.3. Type B 2 volcaniclastic deposit (B2)

This type of volcaniclastic lithofacies occurs interbedded between terrigenous materials (profiles 3 and 5 in Fig. 3 and profiles 3, 9, 14 and 15 in Fig. 5) and is widely represented in the Argamasilla and Calzada-Moral basins. This volcaniclastic deposit is composed of a centimetre-thick alternation of coarse- to medium-grained lapilli to coarse- to medium-grained ashes (Table 1) with a fining- and thinning-upwards sequence with thickness between 0.45 and 3.00 metres (Figs. 7 E and F). Frequently, it presents a wedge geometry pinching out laterally. The base is planar or sharply erosive and occasionally displays an ash-coloured bed (grey) almost 30 cm thick. The deposit is matrix-supported with a predominance of juvenile over lithic fragments. The colours of the lithofacies are green and light brown, normally superimposed by a reddish colour. They are well sorted and show sub-rounded to rounded, sometimes subangular, shapes.

The Type B 2 volcaniclastic deposit contains sedimentary structures including small to medium-scale cross-bedding, with troughs up to 4 m amplitude and heights up to 1 m. Frequently, the bedforms show an asymmetric geometry (Fig. 7 E) where the sets show a sigmoidal aspect with truncated low-angle laminae. These structures may also show dunes and flat-parallel lamination, with millimetre-thick laminae, where normal grading is not uncommon. Likewise, low-angle laminae with a leaning opposite to the flow direction occur, in a similar way to the antidunes of fluvial environments.

Lithic fragments (mainly palaeozoic sandstones), bombs and blocks up to 30 cm in size often break the stratification (Fig. 7 F) forming bomb sags. This structure is emplaced ballistically into deformable materials and it is mainly found in alternating beds of fine-grained ash and lapilli, causing a depression with deranged laminae.

B2 deposit has a very broad distribution in these sedimentary basins. It was observed in profiles 3 and 6 in the Argamasilla Basin (Fig. 3). Flow directions measured in sedimentary structures and in deformation tails left by the sag block structures (N 10º E) are coincident, pointing to the same source, namely, Laguna Blanca Maar and Cabeza Parda Volcano.

B2 deposits were also identified in profiles 13, 14 and 15 in the proximities of Aldea del Rey in the Calzada-Moral Basin (Fig. 5). Their sources could be some of the vents identified in the neighbourhood. This kind of deposit was also observed in the vertical profile number 9 at Calzada de Calatrava (Fig. 5), where paleocurrents measured point to the El Cortijillo Volcano. Finally, in the vertical profile number 8, close to Granátula de Calatrava (Fig. 5), this type of deposit reaches a thickness of less than 1.00 m, and the best candidate for the source, due to its proximity, is the Granátula Maar.

Interpretation

The abundance of current structures, well-developed bedding, fining and thinning-upwards sequences, well-sorted particles and small to medium-scale cross-bedding in these deposits is evidence of a pyroclastic density current (base surge) (Fisher and Schmincke 1994; Walker, 1983; Carey, 1991; Druitt, 1998). So, this lithofacies was formed as a consequence of a turbulent and low-density pyroclastic density current such as base surges (Sparks and Walker, 1973; Cole, 1991 and Dellino *et al.,* 2004 a and b). Facies sequences and deposit structures suggest that these pyroclastic base surges had a phreatomagmatic explosive origin from a nearby maar or tuff ring (see Fisher and Schmincke, 1984; Cas and Wright, 1987).

The occurrence of bomb sags (impact structures) distorting the previously deposited materials indicates that the deposit is located close to the vent and represents a strong evidence of a contemporaneous explosive and subaerial volcanism that influenced the intra-continental fluvio-lacustrine sedimentation in the basin.

4.4. Type B 3 volcaniclastic deposit (B3)

This volcaniclastic deposit has been only observed in Granátula de Calatrava (Calzada-Moral Basin, Fig. 6). This lithofacies shows channel geometry, with a lateral extension up to 60 m and a maximum thickness of 4 m. The paleocurrent directions provided by this channel are N 30º. The above mentioned A deposit is underlying B3, as it can be observed in the eastern side of the Columba Volcano (Fig. 8).

B3 is composed of fining -upwards sequences of fine- to medium-grained lapilli-tuff, changing to   fine- to me-
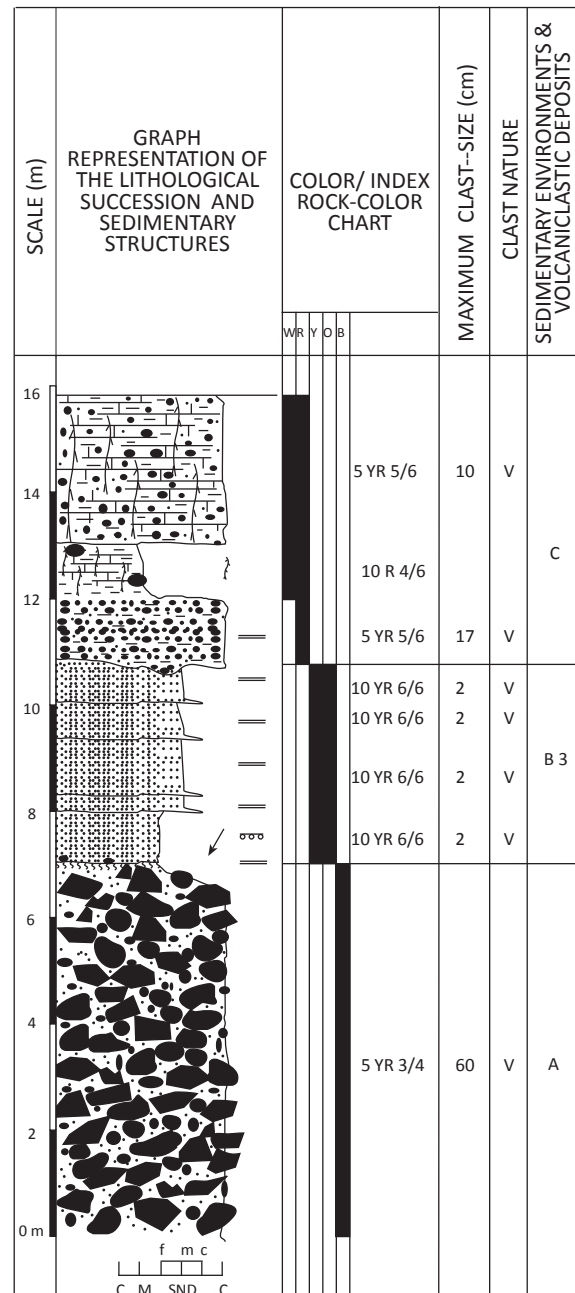

Fig. 6.- Stratigraphic section close to the Columba volcano in the Calzada-Moral Basin.
Fig. 6.- Columna estratigráfica cerca del volcán Columba en la Cuenca de Calzada-Moral.

dium-grained tuffs at the top. Both intervals are strongly lithified and finely stratified in beds of less than 15 centimetres thick and yellowish in colour (Figs. 10 A and B). Occasionally, the base of the deposit contains bombs with sizes up to 15 cm, that could correspond to the A deposit subsequently re-incorporated into B3. In this latter case, the sedimentary structures were readapted. Clasts in B3 are commonly primary juvenile. The particle shapes are from subrounded to strongly rounded, very homogeneous and well sorted.

Internally, the lower and upper parts of these sequences display a millimetre-thick parallel lamination and normal grading (Fig. 10 B).

Interpretation

The well-developed parallel lamination of B3 is interpreted to be a traction deposit from a high-flow regime. This kind of deposits is consequence of low-density pyroclastic surges generated by energetic explosive phreatomagmatic eruptions (Wohletz and Sheridan, 1979; Sheridan and Wohletz, 1981 and 1983; Cas and Wright, 1987; Cole, 1991; Wohletz, 1993, 1998).

Moreover, the vertical and lateral relationships between both intervals of the sequence indicate turbulent conditions together with transportation in upper and lower flow-regime conditions. The bedding with centimetre-scale fining-upwards sequences and the well-sorted texture indicate warm and dry surges (cf. Fisher and Schmincke 1994; and Walker, 1983).

4.5. Type B 4 volaniclastic deposit (B4)

This deposit is composed of a variety of lithofacies outcropping near Calzada de Calatrava (Calzada-Moral Basin) (Fig. 9). It comprises fining-upward sequences of tuff beds of 5 to 25 cm thick (Figs. 10 C and D). Estimates of volcaniclastic fragment sizes indicate that these sequences grade from fine- to medium-grained lapilli-tuff to coarse- to medium-grained ash. The lower limit of the sequences is well-defined, irregular and slightly erosive. The deposit shows tabular bedding and the individual beds predominantly consist of juvenile fragments.

The basal beds are up to 20 cm thick. They are strongly lithified, brown in colour and internally contain a variety of primary sedimentary structures, such as parallel lamination, dunes and ripple cross-lamination, and other very extended laminations indicating paleocurrents coming from the S and SE. The layer displays scattered and isolated lithic fragments of pyroclasts up to 15 cm.

The upper interval of the sequence is light brown in colour, with thickness up to 5 cm and appears to be unconsolidated. It is massive or with a horizontal lamination, highlighted by variations in grain size and colour (Figs. 10 C and D).

Interpretation

Paleocurrent directions allowed the provenance of B4 to be established (i.e., El Cortijillo Volcano, Calzada-Moral Basin).

The fine- to very fine-grained size together with some sedimentary structures occurring at the base indicate a low-speed tractional flow. All these features are in line with low-velocity, dilute and turbulent phreatomagmatic surges, similar to those of B2. Textural differences between this lithofacies and other similar ones were interpreted in terms of different sources, variations in fragmentation styles and geographical location in relation with their source areas (e.g., proximal to distal facies).

The horizontal mantle bedding lamination of the upper part of B4 is clearly a separate facies and was interpreted as a pyroclastic-air fall deposit (see: Walker 1983; Cas and Wright 1987).

Occasionally, recurrences of fining-upward and cyclic sequences were found (Fig. 9), which are typical for a succession composed of deposits accumulating formed from pyroclastic surges and intermittent pyroclastic air-fall events. Such superposition of processes in vertical can occur in short periods of time (days to weeks) and can be considered geologically instantaneous. This succession is considered proximal to its volcanic source area (e.g., to the poorly preserved El Cortijillo Volcano).

4.6. Type C volcaniclastic deposit (C)

This deposit has only been observed in Granátula de Calatrava (Calzada-Moral Basin) (Fig. 6). The base of this lithofacies is erosive at the metre scale and is somewhat channelized over B3 (Fig. 10 F).

At the base, it comprises particles larger than 2 cm (pebble-boulder conglomerate and breccias) and a clast-supported texture. Maximum grain size is 17 cm, with a main of 4-8 cm. The deposit is reddish brown in colour, with clasts of olivine basalt (90%) and volcaniclastic clasts, e.g., pieces of tuff or lapilli tuff (10%). (Figs. 10 E and F). The matrix consists of coarse-grained ashes and fine-grained lapillis with a superimposed weak cementation of calcium carbonate rimming pyroclasts. Deposits show a poor sorting at the base and it is well sorted at the top (Fig. 10 E). Pyroclasts are subrounded in shape and the most angular show abraded margins.

The deposit exhibits normal grading, massive stratification at the base and a diffuse horizontal stratification at the top. Laterally, it has an extent of 75-100 m and a few metres thick.

Towards the top, the deposit passes gradually to red terrigenous clays (10 R 4/6) with cementation of calcium carbonate, a low content in fine-grained sands and abundant pedogenic modifications, such as carbonate root traces and clay and carbonate migrations.

Interpretation

The composition of clasts suggests diverse sources from eroded lavas and volcaniclastic materials. Sedimentological characteristics indicate that transportation pre-

ceded the deposition, supporting a resedimented volcaniclastic deposit with a secondary origin.

The secondary origin of the Type C deposit can be explained in terms of two contrasting scenarios, namely, eruptive and sedimentation. Regarding the former, the deposit could have been formed when rain soaks loose fine-grained volcanic material in the proximities of volcano, probably on its lower outer flank. In this sense, sedimentary processes would be similar to rain-triggered lahars, which would mean no direct volcanic activity involved in their formation; however, the rain-triggered lahars must have been initiated shortly after the eruptions ceased (e.g. having barren, loose tephra on the surface without vegetation cover or soil). These pyroclastic materials could became remobilized and began to flow downhill, being subsequently accumulated in the intra-volcanic flat, in low lying regions similar to those modelled around stratovolcanoes on their ring-plains (e.g., Manville *et al.,* 2009) or on vegetation free ash plains of volcanic complexes such as Ambrym in Vanuatu (e.g., Németh *et al.,* 2009). Remobilization of wet tephra on a tuff ring crater rim is a well-documented process and can produce extensive gully networks that eventually able to feed major sediment channels and to redistribute tephra toward the flank of the tuff ring (e.g., Németh and Cronin, 2007).

Moreover, the occurrence of some stratification and normal grading in the C deposit studied rules out proximal debris flows, and is more in line with a hyperconcentrated flow deposit subsequently accumulated in the intra-tuff ring/scoria cone plains. The location of these hyperconcentrated flow deposits is likely coincident with major artery systems, as convey belts of transporting pyroclasts from monogenetic volcanoes to the normal terrestrial sedimentary basin (e.g., Manville *et al.,* 2009).

The secondary origin can also be caused by volcaniclastic fluvial processes, or a simple washout of pyroclasts. Pyroclast shape and clast rounding are in line with a water-supported transport. Similarly, sorting and sedimentary structure evolution evidence fluvial transport and reworking of volcaniclastic materials, the sedimentary processes being, therefore, similar to those of fluvial environments (see McGowen and Groat, 1971; Eynon and Walker, 1974; or Miall, 1977, 1978 and 1992). Hence, it seems likely that the material was transported as bed load and deposited in form of longitudinal bars in braided fluvial channels.

The Columba Volcano is the best candidate for C lithofacies source, as it is inferred from the fact that this facies is extra-caldera and very close to Columba Volcano (less than 1.5 km) and it is located in the footslope of the volcano. These features, together with the grain size, well sorting, shape and rounding pyroclasts, suggest a origin related with transitional hyperconcentrated flows and dilute fluvial processes. These deposits would be typically remobilised by hyperconcentrated flows that can end up in a sediment-overcharged fluvial network (at least in their proximal area).

Fig. 7.- (next page) (A) Type A volcaniclastic deposit showing a disorganised and massive texture. In the upper part the limit with the Type B3 can be seen. The circle includes a hammer for scale. (B) Type A volcaniclastic deposit showing a massive and disorganized texture of lapilli, blocks and bombs of a mean grain size between 20 and 25 cm and basaltic composition. (C) Type B1 volcaniclastic deposit showing fining-upwards sequences at the bottom, strongly consolidated breccia and coarse lapilli-tuff (dark colours) with a matrix-supported texture, cross-bedding and horizontal stratification. Fine lapilli-tuff and coarse-medium tuff with horizontally lamination (clear colours) are shown in the upper part. Strata with inverse and vertical dips. (D) Detail of type B1 volcaniclastic deposit showing centimetre sequences with scour surfaces between cross-bedding and horizontal lamination. Strata present inverse grading, vertical dips and calcite veins. (E) Type B2 volcaniclastic deposit with beds ranging from coarse-medium lapilli to coarse-medium ashes. Asymmetrical bedforms with trough cross-bedding and asymptotic laminae with the bottom. The flow direction is towards the right. At the top, alternation of coarse-medium lapilli (dark colours) and coarse-medium ashes (clear colours) with horizontal stratification and lamination. The arrows point to several bombs in the deposits. (F) Sag-block deformation structure within the type B2 volcaniclastic deposit. Sequences of coarse-medium lapilli and coarse-medium ashes in centimetre-thick layers with horizontal stratification that were distorted when the bomb fell (ballistic trajectory indicates transportation from right to left on the image).

Fig. 7.- (página siguiente) (A) Depósito volcanoclástico tipo A con textura desorganizada y masiva. En la parte superior se observa el límite con los depósitos volcanoclásticos tipo B3. En el círculo hay un martillo de escala. (B) Depósito volcanoclástico tipo A con una textura desorganizada y masiva de lapilli, bloques y bombas de un tamaño medio entre 20 y 25 cm y composición basáltica. (C) Depósito volcanoclástico tipo B1: secuencias granodecrecientes que en la parte inferior presentan brechas fuertemente consolidadas y lapillis tobáceos gruesos (colores oscuros), con una textura matriz soportada y con estratificación cruzada y estratificación horizontal. En la parte superior, lapillis tobáceos finos y tobas gruesas-medianas con laminación horizontal (colores claros). Estratos con buzamiento inverso y vertical. (D) Detalle del depósito volcanoclástico tipo B1 con secuencias centimétricas con superficies erosivas y estratificación cruzada y laminación horizontal. Estratos con buzamiento inverso y vertical y abundantes venas de calcita. (E) Depósito volcanoclástico tipo B2 con secuencias granodecrecientes de lapilli grueso-medio y cenizas gruesas-medias. Morfologías de fondo asimétricas y con estratificación cruzada en surco y láminas asintóticas con la parte inferior. La dirección de flujo es hacia la derecha. En la parte superior, alternancia de lapillis gruesos-medianos (colores oscuros) y cenizas gruesas-medianas (colores claros) con estratificación y laminación horizontal. Las flechas apuntan a varias bombas en el depósito. (F) Estructura de deformación tipo "sag-block" dentro del depósito volcanoclástico tipo B2. Secuencias de lapillis gruesos-medianos y cenizas gruesas-medianas en capas de espesor centimétrico con estratificación horizontal que fueron distorsionadas cuando cayó la bomba (la trayectoria balística indica transporte desde la derecha hacia la izquierda en la imagen)

4.7. Type D volcaniclastic deposit (D)

This deposit has a local distribution in the sedimentary basins analysed. Near Aldea del Rey in the Calzada-Moral Basin this deposit partly filled the bottom of the Casablanca Maar (Vega de Castellanos) (Fig. 8).

The stratigraphic context of this volcaniclastic deposit is important for understand its formation. The Casablanca Maar is a circular depression 1-2 km across, where two sedimentary units were differentiated (basal unit and upper unit; profile 1, Fig. 5). The predate sediments of the basal unit comprise sandy siltstones and clays, sands and some conglomerate beds. The latters represent sedimentation in braided fluvial channels with gravel bars and sandy megaripples. Sandy siltstones and clays represent sedimentation in a flood plain.

The base of maar depression is an erosive surface with several metres of relief carved in sediments of the basal unit. This surface corresponds to an angular unconformity with a small difference of angle of dipping (less than 15° towards the centre of the depression) between the layers of the units.
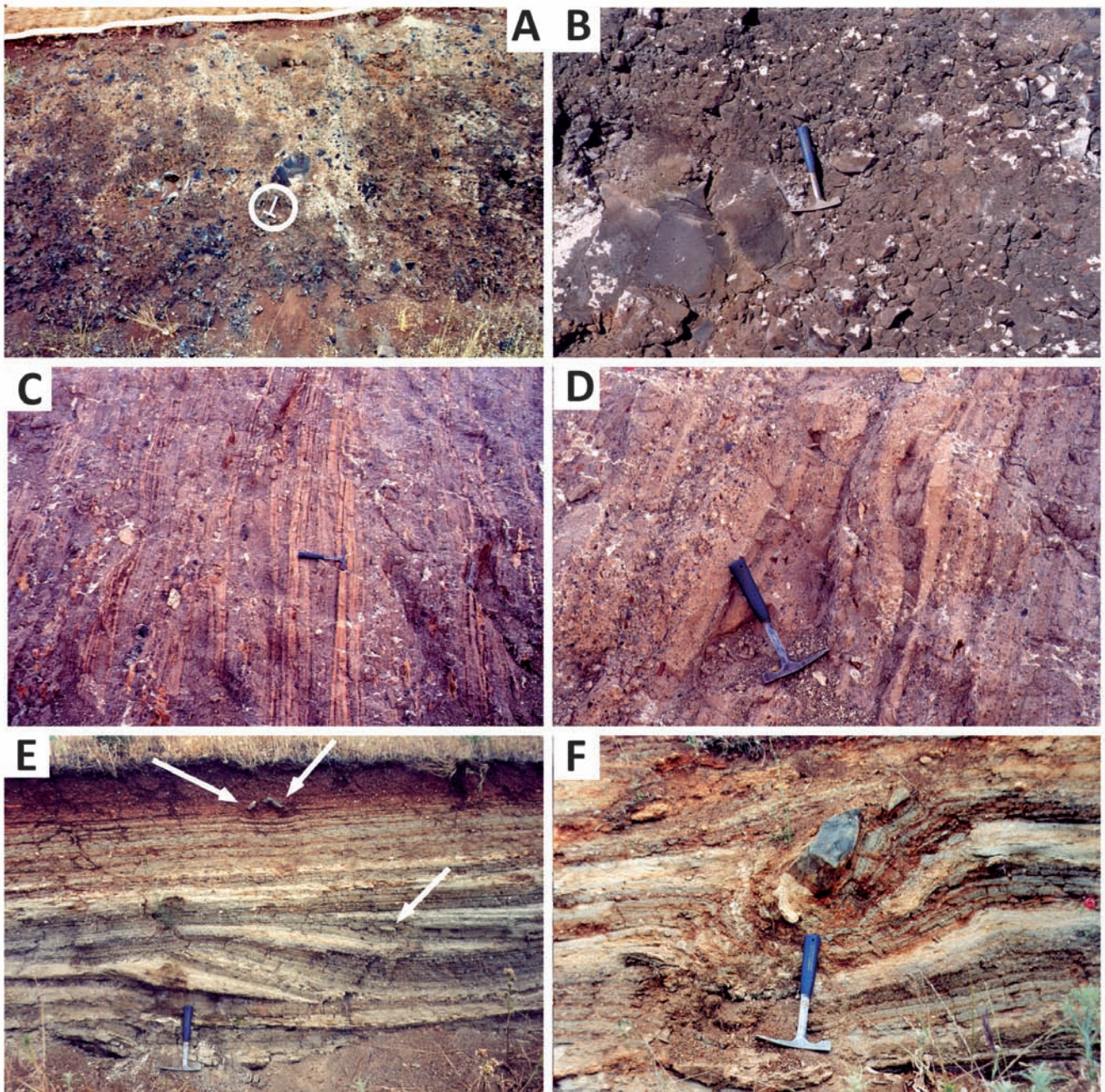

Fig. 7.- Caption in previous page.
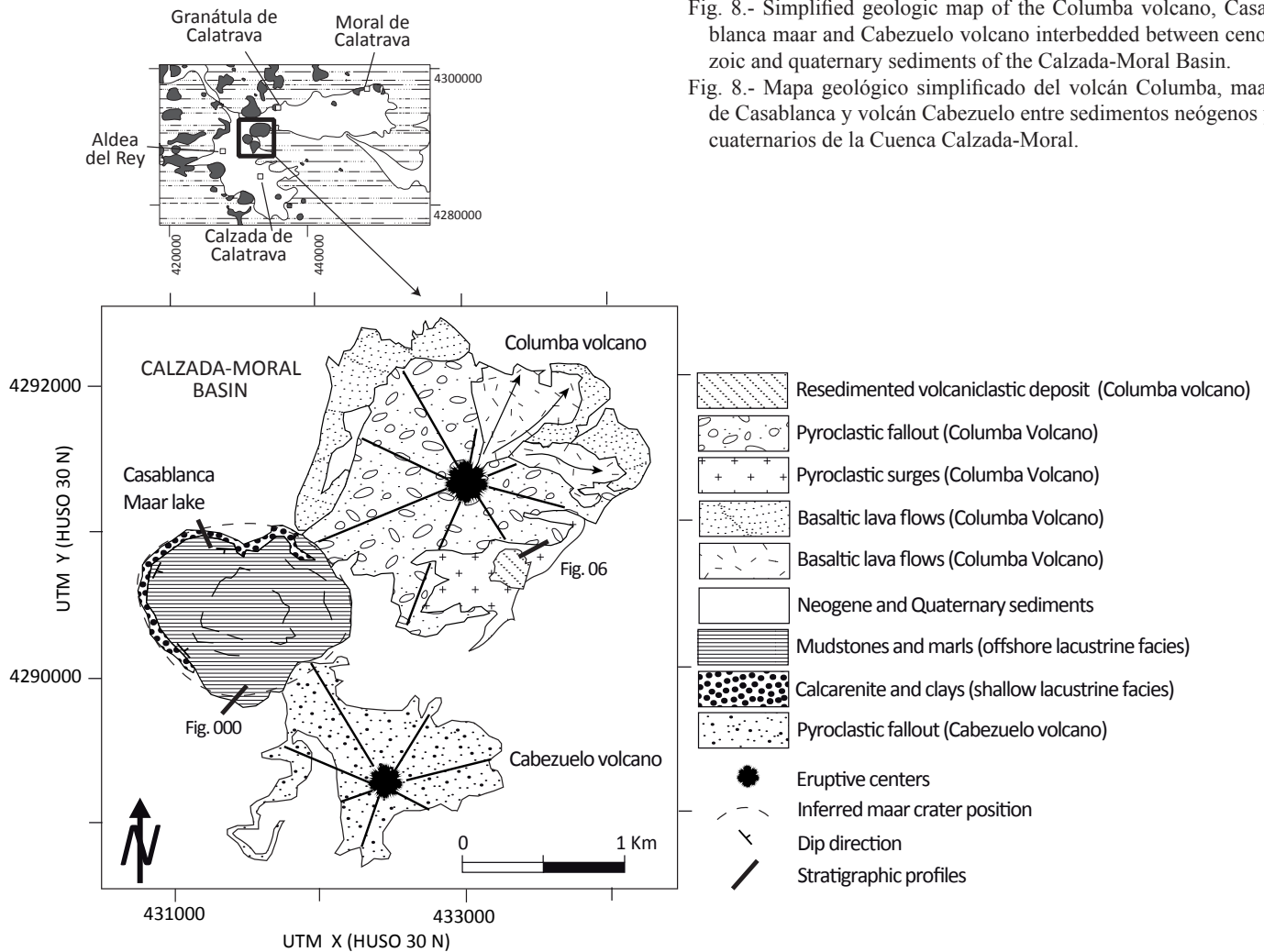Fig. 7.- Pié de figura en la página previa.

Fig. 8.- Simplified geologic map of the Columba volcano, Casablanca maar and Cabezuelo volcano interbedded between cenozoic and quaternary sediments of the Calzada-Moral Basin.

Fig. 8.- Mapa geológico simplificado del volcán Columba, maar de Casablanca y volcán Cabezuelo entre sedimentos neógenos y cuaternarios de la Cuenca Calzada-Moral.

Type D volcaniclastic deposit occurs in the upper unit. Its thickness is around 3 m but a lateral thinning was observed towards the edge of the depression. In the lower part and over the angular unconformity, subrounded bombs and blocks up to 50 cm in diameter are concentrated at the base of this deposit and embedded in the matrix (Fig. 11A). These bombs and blocks can be followed cartographically around a narrow marginal zone of the depression (maar).

Type D lithofacies is formed by well-sorted coarse-to-very coarse-grained lapilli, in a matrix of medium-to coarse-grained ash (Fig. 11 B). It shows a red in colour interval in the lower part, changing to green in the upper part. In this deposit, tractional sedimentary structures are lacking and only inverse grading in the internal organisation was observed.

Finally, the sediments of the upper unit reach a maximum thickness of 15 m (profiles 1 and 7, Fig. 5) and include calcarenites, marls and limestones with scattered and altered pumite fragments (up to 2 cm). These sediments exhibit a dip towards the centre of the depression.

Interpretation

The ancient Casablanca Maar has a small basin formed during a maar-forming eruption. Around and outside of this depression non-volcaniclastic deposits have been found (Fig. 8) and were correlated with non-volcaniclastic terrestrial sediments described in the Calzada-Moral Basin (Profile 1, Fig. 5).

The occurrence of subrounded bombs and blocks up to 50 cm in diameter at the basal surface of Type D deposit, together with its location above the angular unconformity suggest that the basal unit is not part of the maar depression filling deposits. It seems likely that a fluvial network breached the maar, establishing through the shallow and flat maar basin. It should promote the development of a lake that partially or fully filled the maar, providing an extensive lacustrine sedimentary cover over the entire maar basin.

Similarly, the absence of impact craters by ballistic bombs allows interpret the occurrence of volcanic bombs and blocks appearing at the base of this volcaniclastic deposit as rolling large bombs from the inner crater wall of
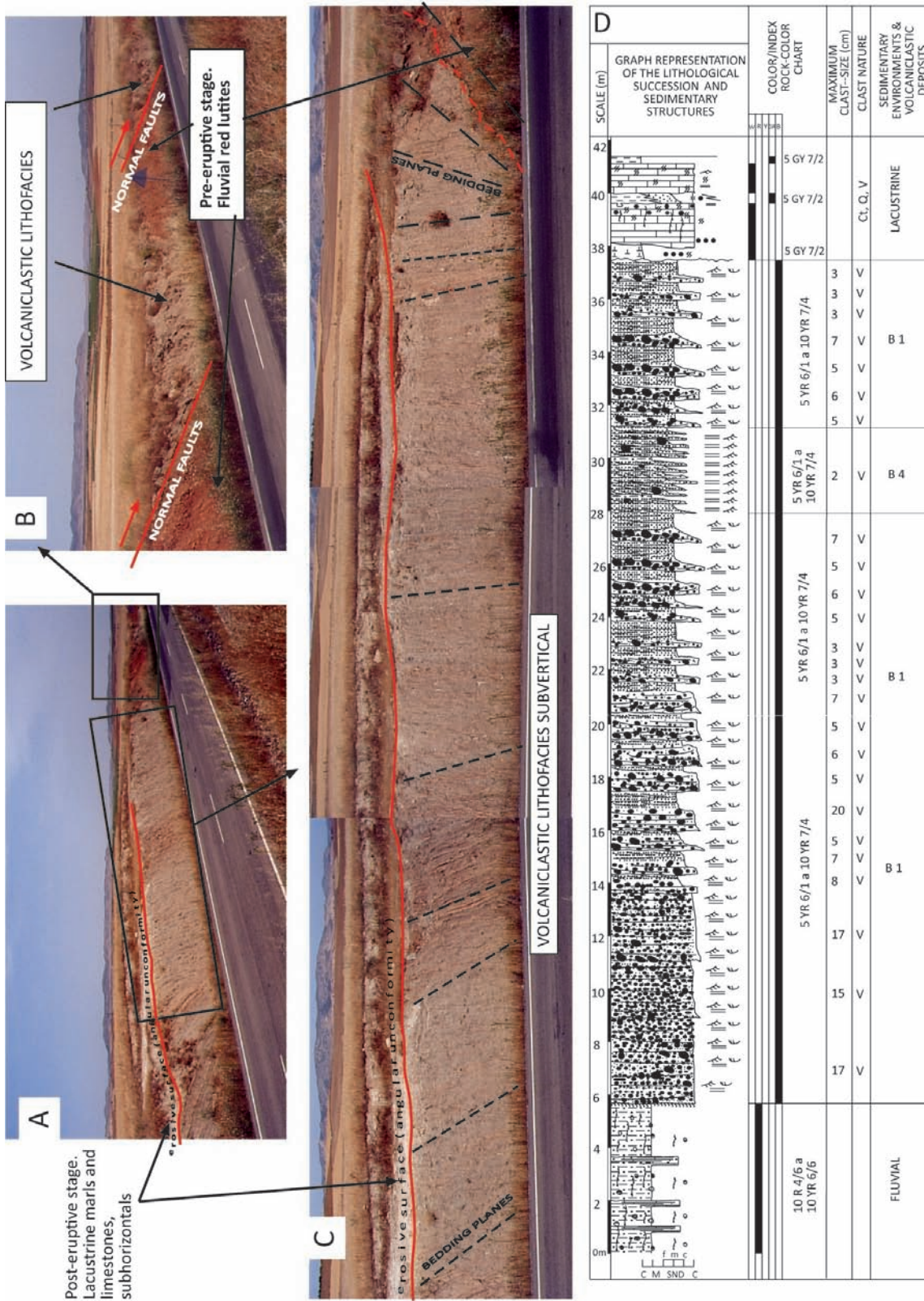
Fig. 9.- (A) Outcrop in the neighbourhood of Calzada de Calatrava. (B) Detail of the previous image showing different normal faults that repeat the contact between red lutites (flood plain) and volcaniclastic deposits. (C) Detail of the initial image showing white marls and limestones in subhorizontal beds (lacustrine deposits) (left) with a thickness lower than 4 m. In the central part of the image is showing a volcaniclastic assemblage (top left) with clear colours over red lutites of fluvial flood plain (right). Volcaniclastic beds have inverse and vertical dips. (D) Stratigraphic profile close to Calzada de Calatrava. The section consists of fluvial flood plain deposits as well as different types of volcaniclastic deposits.

Fig. 9.- (A) Afloramiento en las cercanías de Calzada de Calatrava. (B) Detalle de la imagen anterior ilustrando varias fallas normales que repiten en la vertical el contacto entre lutitas rojas (llanura de inundación) y los depósitos volcanoclásticos. (C) Detalle de la imagen inicial ilustrando margas y calizas blancas subhorizontales (depósitos lacustres) (izquierda) en capas con un espesor inferior a 4 metros. En la parte central de la imagen aparece el paquete volcanoclástico con colores claros sobre las lutitas rojas de llanura de inundación fluvial (derecha). Las capas volcanoclásticas tienen un buzamiento inverso y verticalizado. (D) Columna estratigráfica cerca de Calzada de Calatrava. La sección consta de depósitos de llanura de inundación fluvial así como una sucesión con varios tipos de depósitos volcanoclásticos.
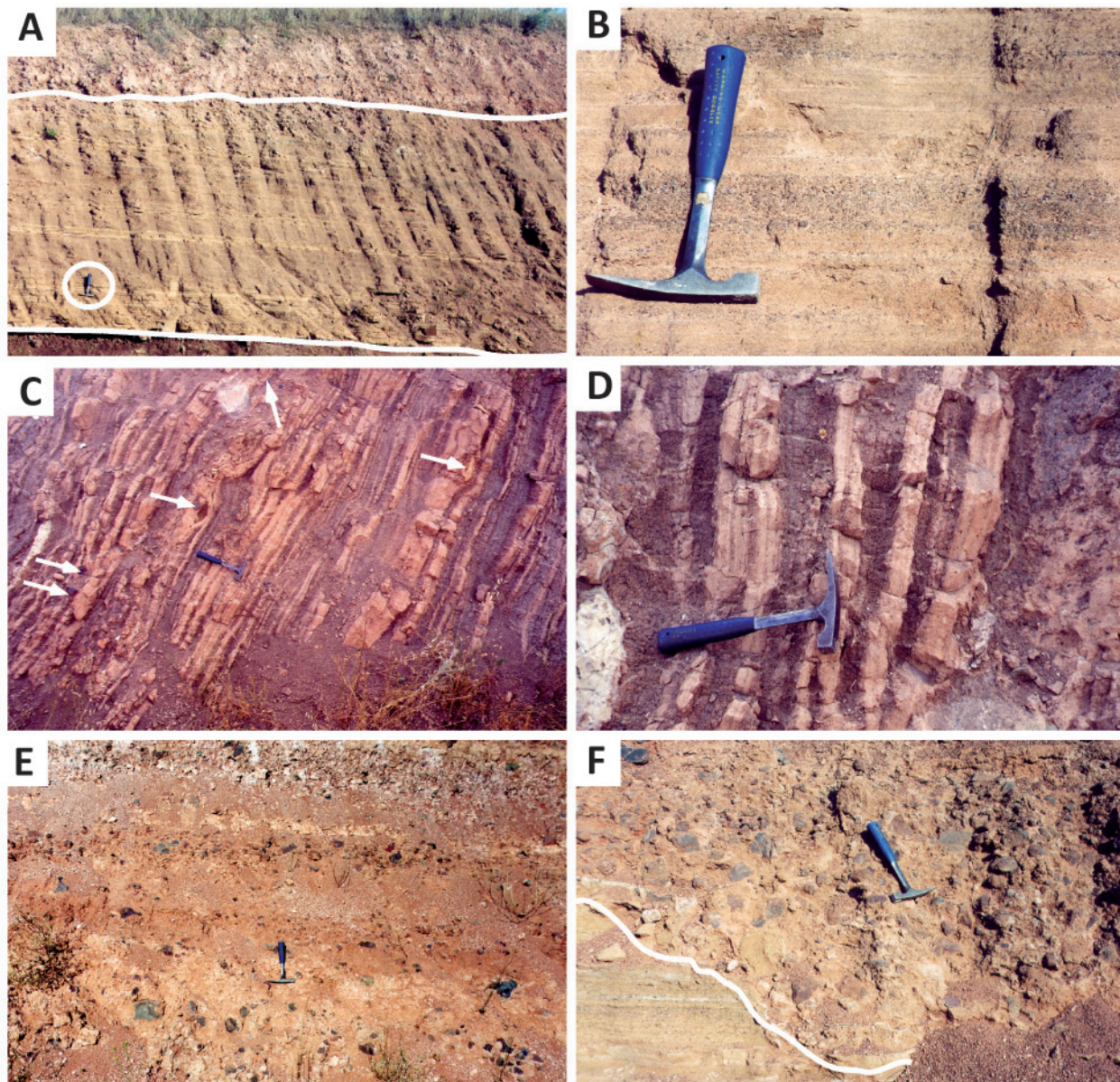
Fig. 10.- (A) Type B3 volcaniclastic deposit. In this image fining-upwards sequences of fine-medium lapilli tuffs change upwards to fine-medium tuffs, in beds of less than 15 cm of thickness, with horizontal lamination and normal grading. (B) Type B3 volcaniclastic deposit. Detail of the previous image showing centimetre sequences of fine-medium lapilli-tuffs and fine-medium tuffs in beds with horizontal lamination, well sorting and with normal grading. (C) Type B4 volcaniclastic deposit. Fining-upwards sequences of well welded fine-medium lapilli tuffs (clear colours) in beds alternating with coarse-medium ash in dark colours. Strata with inverse and vertical dips. Arrows point to scatter bombs. (D) Type B4 volcaniclastic deposit. Detail of the previous image showing fine-medium lapilli tuffs and coarse-medium ash in clear and irregular transit with horizontal lamination and normal grading. (E) Type C volcaniclastic deposit. Conglomerate and breccias with clast-supported texture and showing massive or parallel bedding. (F) Erosive and channelled basal contact of the type C volcaniclastic deposit. Note that blocks and bombs are subrounded and with clast-supported textures. The deposit is massive or with horizontal stratification and with normal grading.

Fig. 10.- (A) Depósito volcanoclástico tipo B3. En esta imagen secuencias granodecrecientes de lapillis tobáceos de grano medio a fino cambian hacia la parte superior a tobas finas y medias, en capas de menos de 15 cm de espesor, con laminación horizontal y gradación normal. (B) Depósito volcanoclástico tipo B3. Detalle de la imagen anterior donde se ilustran secuencias centimétricas de lapillis tobáceos de grano medio a fino y tobas de grano fino a medio en capas con laminación horizontal, bien clasificadas y con gradación normal. (C) Depósito volcanoclástico tipo B4. Secuencias granodecrecientes de lapillis tobáceos de grano medio a fino bien soldados y colores claros que alternan con cenizas de grano grueso a medio en colores oscuros. Estratos con buzamientos inversos y verticales. Las flechas apuntan a bombas dispersas. (D) Depósito volcanoclástico tipo B4. Detalle de la fotografía anterior. Lapillis tobáceos de grano medio a fino y cenizas de grano grueso a medio en tránsito neto e irregular, mostrando laminación horizontal y gradación normal. (E) Depósito volcanoclástico tipo C. Conglomerados y brechas de textura clastoportada y estratificación masiva o paralela. (F) Contacto basal erosivo y canalizado del depósito volcanoclástico tipo C. Bloques y bombas subredondeadas y texturas clasto-soportadas. El depósito es masivo, con estratificación horizontal y gradación normal.

the freshly developed maar crater rim.

The sedimentary features of the Type D deposit, namely well sorting, grain-size, matrix of deposits, inverse grading and absence of tractional sedimentary structures are in line with a deposit of an intra-maar scoria/spatter cones erupted in the maar crater that was developed right after maar formed. Likewise, the above sedimentary features indicate that the deposit is present in beds at the distal part of the scoria/spatter cones. This case is not an isolated example, since a small scoria mound in the base of a maar depression covered by maar lake deposits have been also reported in Hungary (e.g., Németh *et al.,* 2008).

The post-eruptive episode of filling corresponds to a carbonated lacustrine succession deposited in a maar lake (Casablanca Maar). The lake water may have modified the texture of these materials with hydromorphic processes, dominated by hydrolysis caused by the migration and reduction of Fe ions. These ions became fixed in the sediments in the form of ferrous ions (Fe^{2+}), conferring a greenish colour on them.

5. Discussion: factors controlling sedimentation

Lithofacies analysis together with the use of paleogeographic, sedimentological, tectonic and geomorphological constraints may allow to establish those factors controlling sedimentation in intra-continental sedimentary basins with volcanic material supplies. In this particular scenario, magma-feeding paths in the CCVF, and hence the emplacement of the volcanoes, was directly controlled by regional structural lineaments, with main directions of N45-60E, N80-85E and N135-160E, where vents were mainly placed. A similar scenario has also been reported in West Eifel Volcanic Field (Germany) and in the Central Pannonian Basin (Hungary) (Büchel, 1993; Németh and Martin, 1999, respectively). Likewise, the reactivation of the above structural lineaments in the Calzada-Moral Basin triggered seismic activity, evidenced by gravel intrusions together with liquefaction, pillow and mushroom structures in volcaniclastic deposits (Rodríguez Pascua and Barrera, 2002), clearly conditioning these deposits.

Another crucial factor controlling sedimentation was the eruption style, which depends on the composition of the CCVF volcanoes (alkaline to ultrapotassic; e.g., Ancochea and Ibarrola, 1982). The main eruptive styles in the CCVF are explosive to effusive Strombolian and explosive phreatomagmatic (Ancochea, 1982, 2004; Cebriá, 1992). Explosive phreatomagmatic eruptions had an important role in the overall evolution of individual volcanoes of the CCVF, resulting in explosion craters with preserved tuff-rings in the sedimentary basins. In addition, these eruptions provided volcanic detritus to
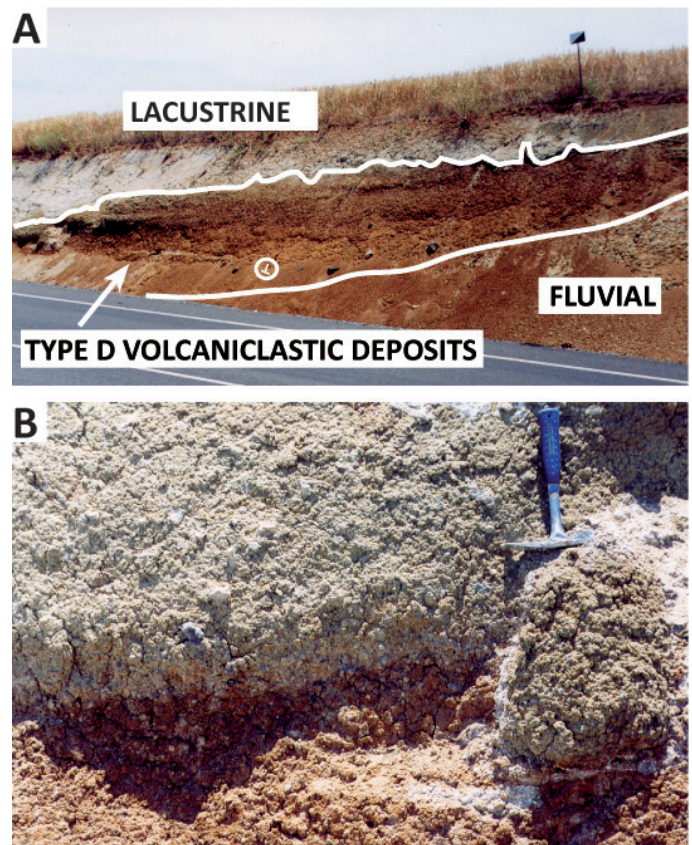

Fig. 11.- (A) Type D volcaniclastic deposit. Coarse-to-very coarse lapilli in a medium-to-coarse ash matrix at the sharp-erosive boundary. Note that the texture is matrix-supported and the occurrence of subrounded bombs and blocks up to 50 cm in diameter. The volcaniclastic deposits are interbedded between fluvial and lacustrine sediments (in the base and above, respectively). (B) Detail of the matrix-supported texture and the inverse grading. The transition from red to green at the top is a consequence of hydromorphic processes and is associated with an increase in grain size.

Fig. 11.- (A) Depósito volcanoclásticos tipo D. Lapillis de tamaño grueso a muy grueso en una matriz de ceniza de grano medio a grueso con un límite erosivo brusco. Nótese como la textura es matriz-soportada y la presencia de algunos bloques y bombas subredondeadas de hasta 50 cm de diámetro. El depósito volcanoclástico está emplazado entre sedimentos fluviales en la base y lacustres por encima. (B) Depósito volcanoclásticos tipo D. Detalle de la textura matriz-soportada y la gradación inversa. La transición del rojo al verde en la parte superior es debida a procesos de hidromorfía y está asociada a un aumento de tamaño de grano.

be incorporated in fluvial and normal lacustrine sedimentary processes. Explosive eruptions may also cause catastrophic processes in the sedimentary basins. In our case, the volcanism in both sedimentary basins resulted in changes in the fluvial drainage system, formation of depressions and the deposition of pyroclastic materials.

The changes in fluvial drainage system are evidenced by changes in the geometry and pattern of channels, modifications of paleocurrent directions and the creation of accommodation space and base-level adjustments. The depressions in the CCVF are abundant and scattered, re-

sulting in lacustrine environments with a shallow carbonate-dominated sedimentation (e.g., profiles 1 and 7, Fig. 5). These depressions in the CCVF seem to be strongly controlled by the pre-volcanic environment, specifically, the so-called "hard-substrate" and "soft-substrate" (Ancochea, 1983; Poblete, 1995; Martín-Serrano *et al.,* 2009). In the former, magma interacted with water in joint aquifers and the explosive volcanic processes extracted deep source country rock fragments, which along with juvenile fragments constitute a significant "exotic" debris source to local sedimentary basins (lava-flow, pyroclastic deposits, volcanic building). In the soft-substrate, the explosive

volcanic processes affected poorly-consolidated sediments and maars and tuff rings redistributed fine-grained country rock fragments (sand and mud grains with various minerals), contributing to the total sedimentary budget of shallow maar pitted fluvio-lacustrine basins (e.g., Casablanca Maar-Lake, Fig. 8). The occurrence of salty playa lakes and rare evaporitic deposits in these basins suggests an arid/semi-arid climate in the area, similar to that described in the Hopi Buttes eruptive environments in Arizona (White, 1990).

Finally, the sedimentation of the aforementioned syn-eruption volcaniclastic lithofacies occurred in short pe-
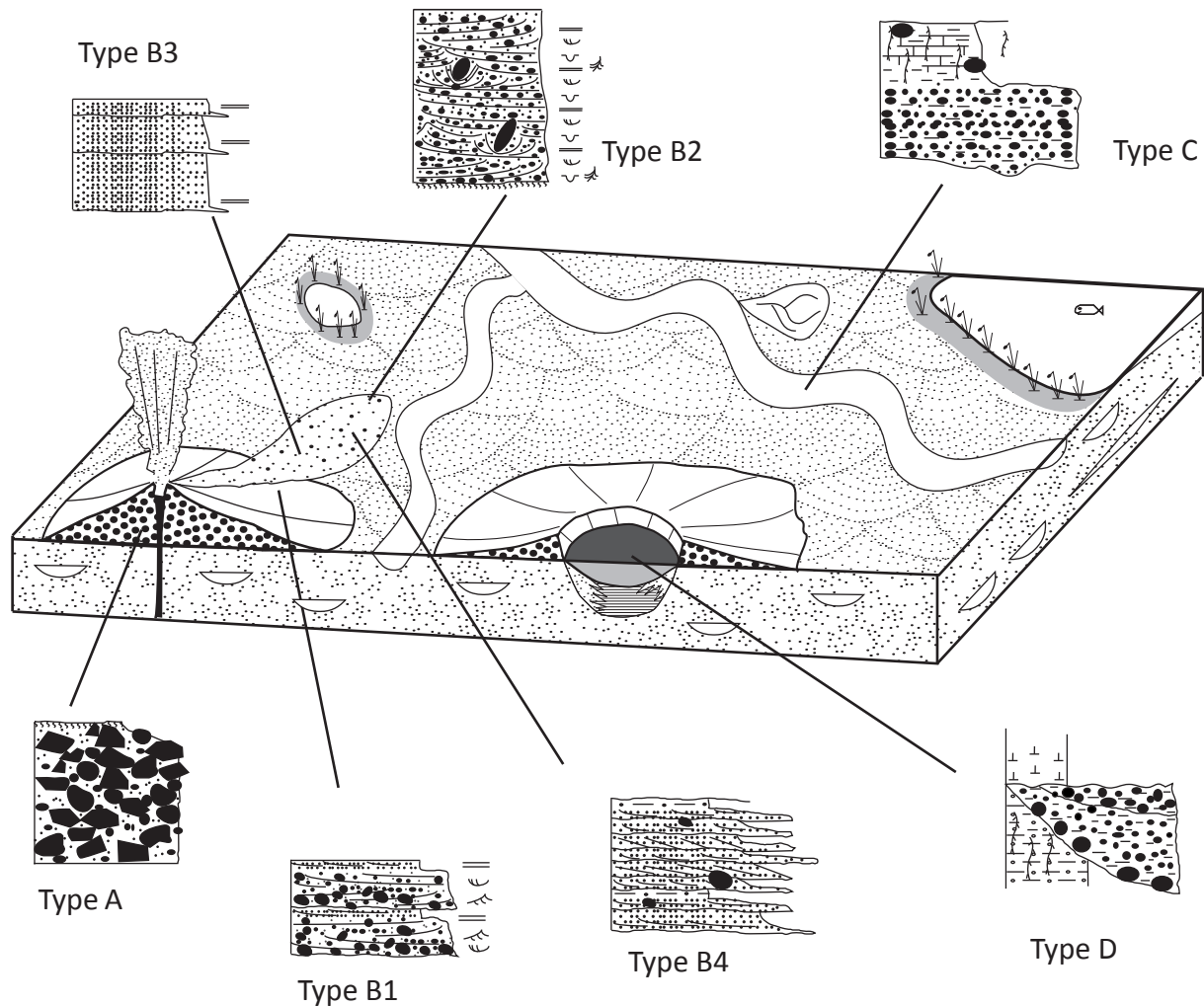

Fig. 12.- Sedimentological conceptual model and location of the different types of volcaniclastic deposits. The latter are inferred to be related to volcanic centres of small volume and monogenetic volcanoes such as scoria cones, tuff rings and maars. Type A volcaniclastic deposits are interpreted as subaerial pyroclastic fall deposits. Subtypes B1, B2, B3 and B4 volcaniclastic deposits are interpreted as the products of low-density (dilute) pyroclastic surges with different volcanic sources. Type C volcaniclastic lithofacies is a secondary volcanic sediment. Finally, Type D volcaniclastic deposits are interpreted as scoria/spatter cone deposits into the maar basins.

Fig. 12.- Modelo conceptual sedimentológico y ubicación de los diferentes tipos de depósitos volcanoclásticos. Estos últimos están relacionados con centros volcánicos de pequeño volumen y volcanes monogenéticos tales como, conos de escoria, anillos de tobas y maares. Los depósito volcaniclásticos de Tipo A se interpretan como depósitos de caída piroclástica subaérea. Los depósitos volcaniclásticos de los subtipos B1, B2, B3 y B4 se interpretan como los productos de oleadas piroclásticas de baja densidad (diluidas) con diferentes fuentes volcánicas. La litofacies volcaniclástica Tipo C corresponde a un sedimento volcánico secundario. Finalmente, los depósitos volcaniclásticos de Tipo D se interpretan como depósitos de conos de escoria/spatter dentro de maares.

riods and with small thicknesses, separated by longer inter-eruption periods, where non-volcanic processes were dominant. The influence of volcaniclastic materials in sedimentation is evidenced in terms of source of materials and rapid and episodic aggradation, the latter inferred by the existence of small volcaniclastic layers interbedded between non-volcanic sediments.

6. Conclusions

The occurrence of volcano edifices into continental basins, exemplified by the Argamasilla and Calzada-Moral basins in the CCVF, has constituted an opportunity to address the influence of volcanism in intra-continental depositional environments, especially by the existence of periods of volcanic activity and quiescence providing an alternation of terrigenous and carbonated sediments with a varied sequence of primary and secondary volcaniclastic deposits. The stratigraphic analysis, the paleocurrent measures and other sedimentological features resulted to be very suitable tools to identify and correlate volcaniclastic deposits in both basins and to determine the deposition environment, the source of volcaniclastic materials and the processes involved. Volcanic breccia with poor sorting, uncharacteristic grading and a massive nature were interpreted as air fall deposits close to vents that developed scoria cones and rings around them (Type A). However, it seems likely that other air fall deposits (upper part of Type B4) are further from the vent, as inferred by the presence of coarse-medium ashes and mantle bedding laminations. The sedimentological analysis revealed the formation of abundant low velocity, dilute and turbulent phreatomagmatic base surges in both basins. The grain size and sedimentary structures indicated deposits from a proximal source in some cases (Type B1). In contrast, the finest grain size, together with the presence of bombs with ballistics projection and structures reflecting a lower flow stage are in line with a more distal source (Types B2, B3 and lower part of Type B4). Moreover, transitional hyperconcentrated flows and dilute fluvial processes seem to have played an important role in explaining the reworking of previous volcaniclastic deposits (Type C), as it is deduced by the normal grading and the occurrence of stratification that would exclude the participation of other mechanisms as proximal debris flow. Likewise, the development of maars in these sedimentary basins provided deposits with well sorting, inverse grading and absence of tractional sedimentary structures, being interpreted as intra-maar scoria/spatter cone deposits (Type D).

The volcaniclastic lithofacies studied in both basins allowed us to infer the type of volcanic eruption associated with the deposits, even if the volcanic edifice is poorly conserved, resulting in explosive phreatomagmatic and explosive and effusive Strombolian eruptions.

Sedimentation in both basins was strongly determined by the orientation of basement faults, paleogeographic and sedimentological intra-basinal controls, style of eruption and volcaniclastic deposit type. The first conditioned the emplacement of volcanic edifices. The second led to drainage-pattern disruption, the modification of sedimentological intra-basinal features, internal changes in fluvial system and the creation of shallow lakes (e.g., Casablanca Maar and Calzada de Calatrava). Finally, the eruption style together with its related deposits strongly controlled the input rate of these volcaniclastic deposits in the sedimentary basin.

Acknowledgements

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