AARJMD VOLUME 3 ISSUE 10 (OCTOBER 2016) ISSN : 2319 - 2801

A Peer Reviewed International Journal of Asian Academic Research Associates

AARJMD

ASIAN ACADEMIC RESEARCH JOURNAL OF MULTIDISCIPLINARY

VOLCANICLASTITES AS A KEY FOR GEODYNAMIC CONSTRAINTS IN THE EVOLUTION OF THE CENTRAL-WESTERN MEDITERRANEAN REGION: AN OVERVIEW

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Abstract

In the central-western peri-Mediterranean chains, a consistent latest Chattian-Langhian orogenic calc-alkaline magmatism generated a high amount of volcaniclastites interbedded within penecontemporaneous marine successions. Emplacement of volcaniclastites is due mainly to epiclastic processes, implying paleogeographic constraints that instead do not control the distribution of fall-out pyroclastic deposits. Current knowledge does not allow direct correlations to be established between specific volcanic events and related secondary products; thus, reconstructions are based on field and analytic data. The volcanic activity occurred: (i) in the Adria Plate (during continental collision between the Mesomediterranean Microplate and the Adria-Africa Plate); (ii) along active subduction margins with different volcanic arc systems (“Mesomediterranean Microplate” Margin); (iii) back-arc basins (Apennine-Maghrebian-Betic systems; southwestern Corsica Margin and Sardinia Trough) due to rollback of the subductional slab; (iv) rifting (SE European Margin; e.g. Valencia and Provençal Basins) and (v) basins related to a strike-slip fault zone (Subbetic Basin). In this context it bears noting the scarcity at present of potential source areas consisting of primary products, suggesting that explosive volcanic arcs were quickly effaced during subduction. Instead, in rifting zones in the back arc areas the volcanic activity continues also in successive times and is testified to by several primary volcanic products. Paleogeographic and depositional constraints indicate multiple volcanic sources (arcs) located in different contexts but always near sedimentary basins. The study helps elucidate the evolution of interconnected geodynamic events in an original paleogeographic-paleotectonic framework.

Keywords: Volcaniclastic deposits, Latest Chattian-Langhian, Volcanic sources, Palaeogeography, Geodynamics, Apennine-Maghrebian-Betic Chains

1. State of the matter

Variable amounts of volcanic-rich material interbedded within several uppermost Chattian-Langhian marine formations from penecontemporaneous volcanic activity have been noted (de Capoa et al., 2002; Guerrera et al., 1998; 2015, *and references therein*) in several sectors of the peri-Mediterranean alpine chains (Betic Cordillera, Maghrebides, Apennines; Guerrera et al., 2005; Guerrera and Martín-Martín, 2014; *and references therein*).

Areal distribution and correlability of these volcaniclastites can serve as indicators to reconstruct the space-time relationships between volcanic activity and depositional areas during Tertiary orogenic phases. An understanding of relationships between volcaniclastites and location of the volcanic activity would more clearly define the paleogeographic evolution of the central-western Mediterranean region.

Although volcaniclastites provide important indications for tectonic reconstructions, studies concerning these deposits are not exhaustive, especially at the regional scale. In particular, minero-petrographic studies are scarce and especially those of geochemical nature concerning the volcaniclastic products interbedded in different marine sedimentary successions.

The scarcity of minero-petrographic and geochemical data together with limited sedimentological studies does not often allow a modern characterization of these products. On the other hand, field analyses, stratigraphic analyses and extrabasinal correlations are more developed. However it is possible to provide an objective framework of the data available at the regional scale and also the relationships between volcanic activity (primary products) and location of sedimentary basins containing secondary products (volcaniclastites). This approach makes it possible to identify the main volcanic and sedimentary events taking into account the constraints resulting from the paleogeographic and paleotectonic reconstruction within the proposed geodynamic evolutionary model.

This study seeks: (1) to show the main uppermost Chattian-Langhian volcaniclastic deposits distributed along the Apennine-Maghrebian-Betic Chains and contained in different marine successions (formations) grouped according to the paleogeographic domain to which they belong; (2) to describe the main field and minero-petrographic features of these kinds of volcaniclastites; (3) to delinate the paleogeographic constraints (*e.g.* distance between volcanoes and sedimentary basins) for the distribution of volcaniclastic deposits; (4) to recognize coeval and compatible volcanic products and locate volcanic districts within specific geodynamic contexts; (5) to propose an updated paleogeographic-geodynamic model of the central-western Mediterranean area while also pointing out the major problems arising from the model presented.

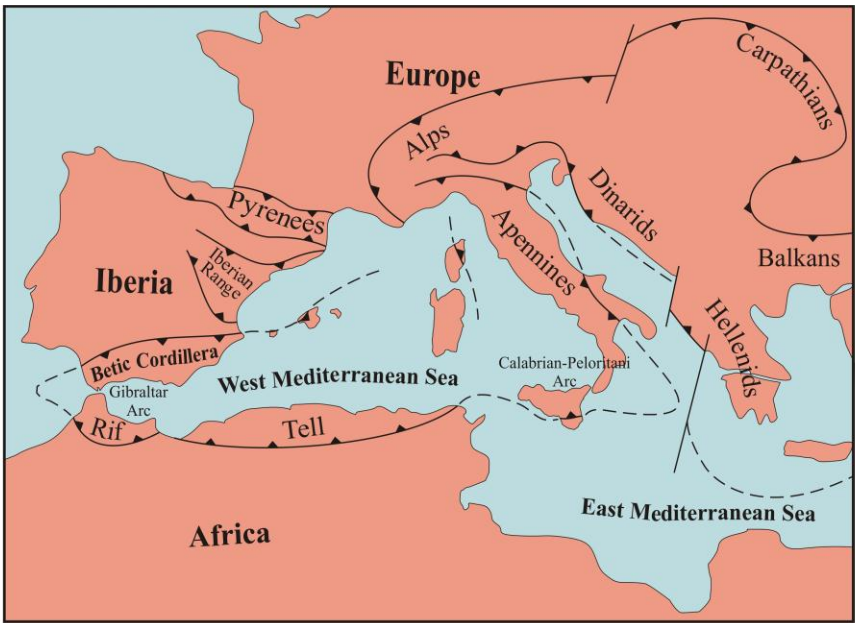

Figure 1. Simplified tectonic sketch map of the peri-Mediterranean chains showing the Betic-Maghrebian-Apennine chain system where volcaniclastites interbedded within different sedimentary units and coeval volcanic remnants are present.

2. Materials and methods

The present research is based on data deriving from different sources represented both by previous studies (Guerrera, 1977; Guerrera and Veneri, 1989; Balogh et al., 1993; de Capoa et al., 2002; Guerrera et al., 1986; 1998; 2004, 2015; *and references therein*), and new analyses taking into account also the recent literature (see below). The first group of data results from systematic field analyses of the recognized volcaniclastites. These data comprise the main volcanogenic lithofacies characters (lithotypes, thickness, grain size, internal structures, emplacement processes, lateral extension and continuity, etc.) and stratigraphic analyses of the successions with volcaniclastites considered in their tectonic context. These data provide indications on the main depositional mechanisms (fall-out and/or resedimentation) and, rougly on the distance between depositional marine basins and the feeding volcanic apparatus.

The second group of data comes from minero-petrographic and geochemical analyses of selected volcaniclastic materials of specific areas (see below). Even if these data are still insufficient to characterize the wide typology of volcaniclastites, they nevertheless furnish sufficient information concerning the type of the volcanism involved. However further detailed investigations concerning the specific composition within the same magmatic series are still necessary.

To characterize the primary products, we referred to the data in the literature available and, most of all, to those adequate to identify the type of volcanism involved and its geodynamic context. The whole data allowed a preliminary check of volcanic (primary) and volcanogenic (secondary) products. Formations including volcaniclastites were referred to their related sedimentary basins and paleogeographic domains. This approach favored the comparison between volcanogenic products recognized in the different chain sectors (see below) indicating the main implications.

The originality of this paper consists of the formulation of a specific geodynamic model of the central-western Mediterranean area based on the reconstruction of distribution and features of the primary and secondary volcanic products. Schematizing, we can refer all previous models to two main ones that consider, since the Mesozoic, the presence of one ocean (one-subduction model) or of two oceans separated by an interposed Microplate (two-subduction models), as summarized in Fig. 5.48 of Chalouan et al. (2008).

In this paper, we refer to the model considering two oceans (two branches of the Tethys) separated by a micro-continent (Doglioni 1992; Guerrera et al., 1993; 2005; Bonardi et al., 2003; 2005; de Capoa et al., 2003; Perrone et al., 2008; 2014; Alcalá et al., 2013; Guerrera and Martín-Martín, 2014; *among others* and *references therein)* and undergoing a different geological history. The evolution of the northern ocean leads to the building of the Alpine Chain (Cretaceous-Eocene) while the evolution of the southern one causes the formation of the Apenninic-Maghrebian-Betic system.

This model was chosen because it may provide a reference for all the data collected and because it has already been applied to different segments of the Betic-Maghrebian-Apennine Chains, offering an explanation of their paleogeographic and paleotectonic evolution at the central-western Mediterranean scale.

3. Geological framework

The central-western Mediterranean region is bordered by three main chains of the Alpine system: the Betics, Maghrebids (Rif, Tell, Sicily, and southern Calabria), and Apennines (Fig. 1). Mesozoic-Tertiary successions involved in these chains were deposited in three major paleogeographic elements (Guerrera et al., 1993; 2005; Guerrera and Martín-Martín, 2014; *and references therein*): the Internal Domain; the "Maghrebian-Lucania-Calvana Flysch Basin" oceanic Domain (MFBD); and the External Domain. The units from the Internal Domain consist of several Hercynian basement crystalline nappes with carbonate Mesozoic-Tertiary covers strongly deformed and frequently affected by Alpine metamorphism (Martín-Algarra, 1987). These units originated from a microcontinent (Mesomediterranean Microplate, MM; *sensu* Guerrera *et al.*, 1993; 2005; 2012; Guerrera and Martín-Martín, 2014) located between the European and African plates, separating (since the Triassic-Jurassic) two oceanic realms: (i) the Nevado-Filabride and Piemontese-Ligurian basins towards NW, undergoing Alpine evolution (Cretaceous-middle Eocene); (ii) the MFBD representing the SE branch of the Tethyan Ocean (Doglioni 1992; Bonardi et al., 2003; 2005; de Capoa et al., 2003; Alcalá et al., 2013; Perrone et al., 2008; 2014; Guerrera and Martín-Martín, 2014; *among others*) undergoing Apenninic-Maghrebian Chain evolution (Miocene). The units resulting from the MFBD deformation are characterized by Cretaceous to Miocene sedimentary clayey and terrigenous successions deposited in deep oceanic basins that opened in the Jurassic-Cretaceous and deformed during the early-middle Miocene, forming several nappes and tectonic mélanges (Durand Delga, 1980; Durand Delga and Fontboté, 1980; Wildi, 1983; de Capoa et al., 2004; Guerrera and Martín-Martín, 2014; *and references therein*). The units resulting from the External Domain are represented by cover nappes of different Mesozoic-Cenozoic successions deposited on continental margins bordering Iberia, Africa, and Adria plates. During the Miocene these margins evolved to foreland basins with prevalent pelagic-hemipelagic or shallow marine sedimentation. The development of the Betic-Maghrebian-Apennine nappes is diachronous being older in the Betic-north African branch than in those progressively younger in Sicily and the Apennines (Guerrera and Martín-Martín, 2014; *and references therein*).

4. Volcaniclastites

Uppermost Oligocene-middle Miocene *p.p.* volcaniclastites of basins involved in the central-western peri-Mediterranean chains show different lithofacies associations. Volcanic material was transported to the adjacent marine basins mainly by debris flows, turbidites, slumping, etc. In the outermost areas, the hemipelagic sedimentation is sometimes interrupted by ash deposition (fall-out) coming from the most explosive volcanism and/or by extremely diluted turbidites.

Abundant volcaniclastic material is interbedded within different formations (Tables 1-4;

Fig. 2) of domains belonging to the above-mentioned chains. Two main distinct populations of volcanic detritus are commonly distinguished with reference to volcanogenic sediments: (i), paleovolcanic material, derived from erosion of old volcanites originated before the sedimentation under consideration); (ii) neovolcanic material, generated by deposition penecontemporaneous to active volcanism. Criteria discriminating supply from old or penecontemporaneous volcanic rocks are discussed by several authors (e.g. Pettijohn et al., 1972; Valloni, 1985; Zuffa, 1985; 1987; Guerrera and Veneri, 1989; Critelli and Ingersoll, 1995; *among others*). In fact, the recognition is not easy when field observations are scarce, minero-petrographic and geochemical data of unaltered volcanogenic products are not available, and the paleogeographic and paleotectonic framework is not clear.

In this study, only the neovolcaniclastic deposits were taken into account, distinguishing epiclastic and pyroclastic deposits and related depositional processes. More in detail, the epiclastites (*sensu* Cas and Wright, 1987) contain volcanogenic material resulting from erosion and reworking of all type of volcanites (effusive and pyroclastic material) shortly after the eruption (in subaerial and submarine environments) and re-deposition in a marine basin mainly through gravity-flows (turbidity currents prevalently). Instead, pyroclastites are due to direct deposition of fragments produced by volcanic explosions into the basins. Moreover, a mixing of pyroclastic and/or epiclastic materials with marine sediments is recognizable.

Volcanic ash from explosive activity is deposited directly onto marine basins and characterized by different proportions of ash, crystals, and lithics, here called pyroclastic ash-fallout or pyroclastic deposits.

Volcaniclastites consist of different rock types (cinerites, tuffites, bentonite beds ash-fall layers, volcanolithic and crystal- to vitric-rich beds, volcaniclastic arenites, etc.) classified as petrofacies and sub-petrofacies (cfr. Guerrera et al., 2015):

(1) Pyroclastic deposits/Pd (>90% volcanic) including three sub-petrofacies: 1A, Vitroclastic/crystallo-vitroclastic tuffs; 1B, Bentonitic deposits; 1C, Ocraceous and blackish layers;

(2) Epiclastic (resedimented) syn-eruptive volcaniclastic deposits/Ed (30-90% volcanic) with four sub-petrofacies: 2A, High-density volcaniclastic turbidites; 2B, Low-density volcaniclastic turbidites; 2C, Crystal-rich volcaniclastic deposits; 2D, Glauconitic-rich volcaniclastites;

(3) Mixing of volcanogenic sediments with marine deposits/Md (5-30% volcanic).

In addition, siliceous deposits are common in all domains within volcanogenic successions, evidencing relationships between volcanic activity and the "bloom" of siliceous organisms. These deposits are siliceous marls, chert beds and/or nodules, very rich in radiolarian (silexites), spongolites, etc. Siliceous components are also diluted into pelagic deposits.

The marine sedimentary formations containing volcanogenic products reported below have been referred to the respective paleogeographic domains and related basins (Tables 1-4; Fig. 2). Domains correspond to the margins of the following plates: (i) Adria-Africa Plate; (ii) "Mesomediterranean Microplate" (*sensu* Guerrera et al., 1993, 2005); (iii) European Plate. Moreover they are identified with oceanic basins mainly represented by the Maghrebian Ocean (*sensu* Guerrera et al., 2005) and its extention in Betic Cordillera (Western Betic Ocean, *sensu* Guerrera et al., 1993) and Apennines (Lucania and Calvana Oceans, *sensu* de Capoa et al., 2003; Bonardi et al., 2003; 2005; Perrone et al., 2008; 2014).

The paleogeographic framework considered allowed a homogeneous presentation of the volcanoclastites and favored the comparison of different chain sectors in a geodynamic way and the final interpretations.

The main sedimentary characters of volcaniclastites are described below and summarized in Tables 1-4; the location of each formation is shown in Fig. 2.

4.1. Adria-Africa Margin

The main basins and units affected by volcaniclastites belonging to this margin are: (i) Venezia Foreland Trough (northern margin), (ii) Tertiary Piedmont Basin Foreland (northern margin), and (iii) Bisciaro Basin (western margin); (iv) Apulian Platform Basin.

The main characters of volcaniclastites deposited within the basins of this margin (Table 1) are: (i) the thickness of the stratigraphic interval containing volcaniclastites (SIV) varies from 8-10 m up to 100-200 m (Tertiary Piedmont Basin Foreland and Bisciaro Basin); (ii) the total thickness of volcaniclastites beds in a single succession (TVB) can reach 18 m (Bisciaro Fm); (iii) the maximum thickness of a single volcaniclastic bed (MVB) reaches its maximum in the Bisciaro Basin with 6.9 m; (iv) the grain size varies from fine to medium sand and values slightly higher (coarse sand) are found in the Tertiary Piedmont Basin Foreland and Bisciaro Basin; (v) the emplacement processes are pyroclastic fall and gravity flows (turbidites); (vi) the volcanic fragments can all be referred to petrofacies characterized by acid (rhyolite, dacite) to intermediate (andesite) chemistry; (vii) the occurrence of the siliceous deposits is very common in all basins of this margin.

The only succession with volcaniclastites of the Apulian Platform Basin is characterized by a SIV of 287 m and a MVB > 0.4 m; the emplacement processes are represented mainly by gravity flows (turbidites). Siliceous deposits also characterize this succession.

The volcaniclastites of basins of this margin have been amply studied, in particular regarding the Bisciaro Basin of the Umbra-Marche-Romagna Apennines for the wide range of volcanogenic products (cfr. Guerrera et al., 2015; *and references therein*). For this reason they may be considered representative also of products characterizing other sectors of this domain.

Domain	**Basin**	**Stratigraphic unit, age**	**Volcanic rocks fragments**	**Main mineralogical features, grain size (mm), thickness (m)**	**Petro facies**	**Emplacement processes**	**Main references**
Africa-Adria Margin (External Units)	Venezia Foreland Trough	1. Monte Baldo lower Langhian (+)	rhyolite	colorless glass shards and crystals (very fresh Pl, Bi, Qz, Px), grain size up to 0.25-mm SIV 10; TVB 2; MVB 1	Pd Md	pyroclastic fall	Poli et al., 2007; Grandesso and Stefani, 1990
		2. Marna di Monfumo, upper Burdigalian (+)	rhyolite	colorless glass shards, grain size up to 0.25mm SIV 8; TVB 2; MVB 1			
		3. Arenarie di San Gregorio upper Burdigalian (+)	rhyolite	colorless glass shards and crystals (very fresh Pl, Bi, Qz, Px), grain size up to 0.25 mm SIV 10; TVB 2; MVB 1			
	Tertiary Piedmont Basin Foreland	4. Tonengo Calcarenites lower Langhian (+)	rhyolite	glass shards, pumice, crystals, grain size up to 0.6 mm, vitric fraction up to 70% non volcanic grains < 10% , TVB 10; MVB several meters.	Pd Ed	pyroclastic fall, gravity flows (turbidity currents, etc.)	Ruffini et al., 1995
		5. Pietra di Cantone Group upper Burdigalian (+)	rhyolite-dacite	glass shards, crystals, grain size up to 0.6 mm, volcanic components 87-94% intra-basinal grains 4-9% terrigenous grains 2-4% SIV 200; TVB 10; MVB 2.8	Pd Ed		Ruffini et al., 1995; D'Atri et al., 1999; 2001
		6. Marne a Pteropodi lower Burdigalian (+)	rhyolite	crystals grain size up to 0.6 mm size vitric fraction up to 70% non-volcanic grains < 10% TVB 10; MVB several mets	Ed Md		Ruffini et al., 1995; Clari et al., 1988
		7. Marne di Antognola lower Miocene (+)	trachite	glass shards and minor crystals (Pl, Bt, Px, Opq, opaque), grain size up to 0.25 mm, MVB 0.3	Pd Md	pyroclastic fall	Clari et al., 1988
		8. Marne di Rigoroso-Marne di Cessola Aquitanian (+)	andesite, dacite	zeolites (35%), smectites (30%) and crystals (Cal, Feld, Px, Amph, Opq, Qz) grain size up to 0.25 mm SIV 25; MVB 1-1.8			D'Atri and Tateo, 1994; Bonci et al., 1994
	Bisciaro Basin	9. Bisciaro Group Aquitanian *p.p.*-	andesite, dacite	glass shards, crystals, lava clasts; grain size up to 0.6 SIV >100; TVB 18; MVB 6.9	Pd Ed Md	pyroclastic fall, gravity flows (turbidity currents)	Guerrera et al., 2015

		Burdigalian *p.p.* (+)				hyaloclastites	
	Apulian Platform Basin	10. Calcareniti, marne e argille di Monte Sidone Aquitanian-Burdigalian (+)	---	bentonites SIV 287; MVB > 0.4	Ed Md	sediment gravity flows (turbidity currents, etc.), sometimes pyroclastic fall	Russo and Senatore, 1989
(+) occurrence of siliceous deposits; SIV, thickness of the Stratigraphic Interval (meters) containing Volcaniclastites; TVB, Total thickness (meters) of Volcaniclastic Beds in a single succession; MVB, Maximum thickness (meters) of a single Volcaniclastic Bed; Pd, Pyroclastic deposits; Ed, Epiclastic (resedimented) syn-eruptive volcaniclastic deposits; Md, Mixing of volcanogenic sediments with marine deposits.							

Table 1. *Main basins and stratigraphic units with volcaniclastites belonging to the Adria-Africa Margin. Field characters, mineralogical features, petrofacies, and main emplacement processes of volcaniclastites are also listed. Symbols are explained in the lower part of the table. Location of the study units is shown in Figure 2.*

4.2. Calvana-Lucania-Maghrebian Ocean

The main units containing volcaniclastites belonging to different sectors of this ocean are: (i) Calvana Basin units (Extension of the Maghrebian units in the northern Apennines), (ii) Lucania Basin units (Extension of the Maghrebian units in the southern Apennines) and, (iii) Maghrebian Flysch Basin units distinguished in Nebrodi Basin (Sicily), Rif Basin (Morocco) and, Betic Basin (Extension of the Maghrebian units in the Betic Cordillera).

The main characters of the volcaniclastites of these oceanic basins (Table 2) are summarized below and they varies widely: (i) the SIV and the TVB reach the maximum value in Maghrebian Flysch Basin in Sicily (Tusa Flysch, about 600 m and 200 m respectively); the MVB reaches the maximum of 10 m in the Calvana Basin (Contignaco Fm); (ii) also the grain size varies reaching a maximum of 2-2.5 mm; (iii) the prevalent emplacement processes are gravity flows (turbidites) even if some pyroclastic fall cannnot be ruled out; (iv) the volcanic fragments can be referred to petrofacies characterized by acid (rhyolite, rhyodacite, dacite), and more rarely intermediate (andesite, basalt) chemistry; (v) siliceous deposits commoly occur in all basins.

In the field, the volcaniclastites of this extended oceanic basin show on the field different lithofacies (e.g., volcanic fragments, crystals, glass shards, etc.) but the type of volcanic supply remains essentially the same, corresponding to that of other domains. The Tusa Flysch (Sicily) and the correlated Tusa Tuffites-Albanella-Corleto Sandstone formations (southern Apennines) can be considered the most representative of this domain.

Domain	Basin	Stratigraphic unit, age	Volcanic rocks fragments	Main mineralogical features, grain size (mm), thickness (m)	Petro facies	Emplacement processes	Main references
Calvana-Lucania-Maghrebian Ocean	Calvana Basin units (Extension of the Maghrebian units in northern Apennines)	11. Contignaco Aquitanian-lower Burdigalian **(+)**	rhyolite, rhyodacite-dacite	glass shards and minor crystals, grain size < 0.5 mm, vitric fraction up to 90% , SIV15; TVB 15; MVB 10	Pd Ed	pyroclastic fall, sediment gravity flows (turbidity currents, etc.) hyaloclastites	Giammetti et al., 1968; Giannello, Gottardi, 1969; Borsetti et al., 1984
		12.Antognola upper Oligocene-lower Burdigalian **(+)**	---	zeolite-rich ash layers	Pd Md	sediment gravity flows (turbidity currents, etc.), sometimes pyroclastic fall	Tateo, 1993; Delfrati et al., 2003
		13.Vicchio Marls (lower portion) upper Aquitanian-lower Burdigalian **(+)**	rhyolite-dacite	lava clasts, crystals, glass shards, SIV 450; TVB 0.3	Ed Md		Balogh et al., 1992; Delle Rose et al., 1994a; 1994b
		14. Cervarola Aquitanian *p.p.*-Burdigalian *p.p.* **(+)**	andesite, rhyolite	glass shards (secondary analcime and zeolites) SIV 80;TVB 10; MVB 6	Pd Md		Papini and Vannucci, 1993; Delle Rose et al., 1994a
	Lucanian Basin (Extension of the Maghrebian units in southern Apennines)	15.Arenarie di Cannicchio, Aquitanian **(+)**	andesite, dacite, rhyolite	mainly lava clasts SIV 150-200	Ed Md		Critelli and Le Pera, 1990; Cammarosano et al., 2004
		16.Saraceno Aquitanian **(+)**	andesite to dacite	volcanic fragments, crystals (plagioclase)	Ed Md		Critelli, 1991; Di Staso and Giardino, 2002;
		17.Calabro-Lucano Flysch, upper Oligocene **(+)**		lava clasts, glass shards, crystals (Pl, Amph) MVB 1.5	Ed		Critelli and Monaco, 1993
		18. Volcaniclastic greywackes lower-middle Miocene	andesite, basalt	lava clasts (up to 70-90%) SIV 80; MVB 4	Ed		Pieri and Rapisardi, 1973; Santo and Senatore, 1992
		19.Tusa Tuffites-Albanella-Corleto Sandstones Burdigalian **(+)**	andesite to dacite	pumices, glass shards, lava clasts, crystals (up to 80%), SIV 54; TVB 46; MVB 5	Ed Md		Critelli et al., 1990; de Capoa et al., 2003
		20.Numidian upper Burdigalian-lower Langhian **(+)**	rhyolite	glass shards, crystals, pumices, lava clasts	Pd Md	pyroclastic fall	Patacca et al., 1992
		21.Paola Doce upper Oligocene-lower Miocene **(+)**	andesite to rhyolite	glass shards, crystals SIV 500; TVB < 150; MVB > 0.2	Ed Md	sediment gravity flows (turbidity currents, etc.)	Pescatore et al., 2012
		22. Roccadaspide-Cerchiara	basalt	(up to 15%) MVB 5	Pd Ed Md	pyroclastic fall, sediment gravity flows	Perrone, 1987

		upper Burdigalian -Langhian *p.p.*				(turbidity currents, etc.)	
	Maghrebian Flysch Basin units (Nebrodi Basin, Sicily)	23. Tusa Flysch Burdigalian *p.p.* (+)	andesite to dacite	lava clasts (up to 80-85%), grain size up to 2.5 mm SIV 600; TVB 200; MVB 1.5-2	Ed Md	sediment gravity flows (turbidity currents, etc.), sometimes pyroclastic fall	Balogh et al., 1993; de Capoa et al., 2002
		24.Troina Sandstones Burdigalian *p.p.* (+)	andesite	volcanic clast (up to 40%) grain size > 2 mm SIV150; TVB 30-40; MVB 0.5-1	Ed Md		
		25. Poggio Maria Sandstones Burdigalian *p.p.* (+)	andesite to dacite	glass shards, lava clast, crystals (up to 30-35% vol.) grain size >2 mm SIV 200; TVB 30-35; MVB 0.5-1.5	*Ed Md*		
		26. Mixed Successions upper Aquitanian-lower Burdigalian	rhyolite, anite, basalt	mainly lava clasts, grain size > 2 mm SIV 43; MVB 1	*Ed Md*		Hoyez and Andreieff, 1975; Carmisciano et al., 1989;
		27.Numidian Aquitanian *p.p.* -Burdigalian (+)	andesite basalt	mainly crystals SIV 10; TVB 0.5; MVB 0.15	*Pd Md*		Patacca et al., 1992; Faugères et al., 1992; Guerrera et al., 1992
	Maghrebian Flysch Basin units (Rif Basin (Morocco)	28.Beni Ider Flysch, upper Aquitanian-Burdigalian (+)	andesite basalt	lava clasts	*Ed Md*		Zaghloul et al., 2002; 2007
		29. Talaa-Lakra (Mixed Successions) upper Aquitanian-lower Burdigalian	andesite		*Ed Md*		Chiocchini et al., 1978;
	Betic Basin (Extension of the Maghrebian units in Betic Cordillera	30. Algeciras Flysch Aquitanian-Burdigalian (+)	andesite rhyolite	lava clasts, crystals (up to 7%)	*Ed Md*	sediment gravity flows (turbidity currents, etc.)	Puglisi and Carmisciano, 1992

(+) occurrence of siliceous deposits; SIV, thickness of the Stratigraphic Interval (meters) containing Volcaniclastites; TVB, Total thickness (meters) of Volcaniclastic Beds in a single succession; MVB, Maximum thickness (meters) of a single Volcaniclastic Bed; Pd, Pyroclastic deposits; Ed, Epiclastic (resedimented) syn-eruptive volcaniclastic deposits; Md, Mixing of volcanogenic sediments with marine deposits.

Table 2. *Main basins and stratigraphic units with volcaniclastites belonging to the Calvana-Lucania-Maghrebian Ocean. Field characters, mineralogical features, petrofacies and emplacement processes of the volcanoclastites are also listed. Symbols are explained in the lower part of the table. Location of the study units is shown in Figure 2.*

4.3. Mesomediterranean Microplate Margin

The main basins and relative units with volcaniclastites belonging to the margin of this microplate are: (i) Macigno Basin (eastern margin); (ii) Pollica Basin (eastern margin); (iii) Calabria-Peloritani Arc; (iv) Algerian Tell (Algeria); (v) Rif Chain (Morocco); (vi) Betic

Cordillera (Spain).

The main characters of the volcaniclastites deposited in the internal basins at the margin of this microplate are below summarized below: (i) the measurements of SIV, TVB, and MVB parameters are very scarce and only some indications coming from the south Apennine, Algerian Tell, and Rif (Table 3) are available; (ii) the volcanic fragments can be referred to petrofacies characterized by acid (rhyolite, rhyodacite), and more rarely intermediate (andesite, basalt) chemistry; (iii) crystals and lava clasts are abundant (to 52%; see n. 17); (iv) the emplacement processes are prevalently gravity flows (turbidites) and more rarely pyroclastic fall; (v) siliceous deposits is often occur.

Previous studies and the data on volcaniclastites in this domain are uneven and not always updated, although some formations seem to be more representative than others. The minor total amount of volcanogenic products is probably related to sedimentary by-passing related to sediment gravity-flow processes responsible for the transport of these products to the deeper basin areas (i.e. the Calvana-Lucania-Maghrebian Ocean).

Domain	**Basin**	**Stratigraphic unit, age**	**Volcanic rocks fragments**	**Main mineralogical features, thickness (m)**	**Petro facies**	**Emplacement processes**	**Main references**
Mesomedi-terranean Microplate Margin	Macigno Basin (eastern margin)	31.Macigno costiero upper Oligocene	?	high volcanic lithic clasts (up to more than 13%)	Ed Md	sediment gravity flows (turbidity currents, etc.)	Cornamusini, 2002
		32.Macigno Appenninico upper Oligocene-lower Miocene	?	less volcanic lithic clasts (less 13%)	Ed Md		
	Pollica Basin (eastern Margin)	33. Arenarie di Pollica Burdigalian - Langhian (+)	rhyolite-rhyodacite	glass shards, crystals, lava clasts up to 52% in a single bed, great lateral continuity (>20 km); SIV >230; MVB 1	Pd Ed Md	sediment gravity flows (turbidity currents, etc.), sometimes pyroclastic fall	Critelli and Le Pera, 1990; Cammarosano et al., 2004
	Calabria-Peloritani Arc	34. Stilo-Capo d'Orlando Budigalian *p.p.*	andesite, basalt	lava clasts	Ed Md		Critelli, 1991; Faugères et al., 1992; Bonardi et al., 2003; 2005
		35. Paludi upper Oligocene -early Miocene		lava clasts, crystals (Px, Amph)	Ed		
	Algerian Tell (Algeria	36. Oligo-Miocene Kabyle Burdigaian *p.p.* (+)	rhyolite	crystals and glass shards	Pd Ed Md		Bellon, 1976; Rivière et al., 1977; Rivière, 1988
	Rif Chain (Morocco)	37. Sidi Abdeslam-Boujarrah Group	andesite, basalt	mainly crystals SIV 10; TVB 0.5; MVB 0.15	Pd Ed Md		Feinberg et al., 1990; Maaté et al., 1995

		lower-middle Burdigalian					
	Betic Cordillera (Spain)	38. Viñuela Group lower-middle Burdigalian (+)	andesite, rhyolite-rhyodacite	mainly crystals, glass shards SIV 45; TVB 3; MVB 0.5	Ed Pd Md	pyroclastic fall, sediment gravity flows (turbidity currents, etc.),	Rivière, 1988; Boulin et al., 1973; Chauve et al., 1973; Rivière and Courtois, 1975; González-Donoso et al., 1982; Hlila et al., 2008
(+) occurrence of siliceous deposits; SIV, thickness of the Stratigraphic Interval (meters) containing Volcaniclastites; TVB, Total thickness (meters) of Volcaniclastic Beds in a single succession; MVB, Maximum thickness (meters) of a single Volcaniclastic Bed; Pd, Pyroclastic deposits; Ed, Epiclastic (resedimented) syn-eruptive volcaniclastic deposits; Md, Mixing of volcanogenic sediments with marine deposits.							

Table 3. *Main basins and stratigraphic units with volcaniclastites belonging to the Mesomediterranean Microplate Margin. Field characters, mineralogical features, petrofacies and emplacement processes of the volcanoclastites are also listed. Symbols are explained in the lower part of the table. Location of the study units is shown in Figure 2.*

4.4. European Margin (external units) and Western Sardinia (Sardinia Trough units)

Some formations of these different sectors such as (i) Subbetic external subdomain (ii) a succession of the Ligurian Basin (marine area), and (iii) a representative unit studied in the western Sardinia (Marmilla Basin of the Sardinia Trough) are affected by volcanoclastites (Table 5). More complete data coming from the volcanoclastites of the Marmilla Basin (Sardinia Through) indicate: (i) SIV, TVB, MVB parameters are of 640, > 10 and 0.6 respectively; (ii) the dominant grain size is medium to coarse (up to 10 mm); (iii) the emplacement processes are gravity flows (turbidites); (iv) the volcanic fragments can be referred to petrofacies characterized by intermediate (andesite, basalt) chemistry; and (v) siliceous deposits frequently occur.

The volcaniclastites of these sectors refer to three basins related to different contexts. Those characterizing the external units of the European Margin and those of the Sardinia Trough may be considered the most representative also for their direct relations with the adjacent source areas.

Domain	Basin	Stratigraphic unit, age	Volcanic rocks fragments	Main mineralogical features, grain size (mm), thickness (m)	Petro facies	Emplacement processes	Main references
European Margin (External Units)	External Betic Basin	39. Almidar, Río Fardes-Mencal (Subbetic) lower Burdigalian **(+)**	rhyolite-rhyodacite	glass shards, crystals MVB 0.25	Ed Md	sediment gravity flows (turbidity currents, etc.)	Soria et al., 1992; 1993; Soria, 1994; 1998
	Ligurian Basin	40. Marine sediments Burdigalian	---	cinerites	?	?	Réhault et al., 1985
Western Sardinia (Back-arc zone)	Sardinia Trough units	41. Villanovaforru Succession (Marmilla Basin) Burdigalian **(+)**	andesite, basalt	great amount volcanogenic detritus, grain size between 0.2 and 10 mm; SIV 640; TVB >10; MVB 0.6	Pd Ed Md	pyroclastic fall, sediment gravity flows (turbidity currents, etc.)	Guerrera et al., 2004

(+) occurrence of siliceous deposits; SIV, thickness of the Stratigraphic Interval (meters) containing Volcaniclastites; TVB, Total thickness (meters) of Volcaniclastic Beds in a single succession; MVB, Maximum thickness (meters) of a single Volcaniclastic Bed; Pd, Pyroclastic deposits; Ed, Epiclastic (resedimented) syn-eruptive volcaniclastic deposits; Md, Mixing of volcanogenic sediments with marine deposits.

Table 4. *Main basins and stratigraphic units with volcaniclastites belonging to extensional basins on southern European Margin (external units) and in the western Sardinia back-arc zone (Sardinia Trough units). Field data characters, mineralogical features, petrofacies, and emplacement processes of the volcanoclastites are also listed. Symbols are explained in the lower part of the table. Location of the study units is shown in Figure2.*

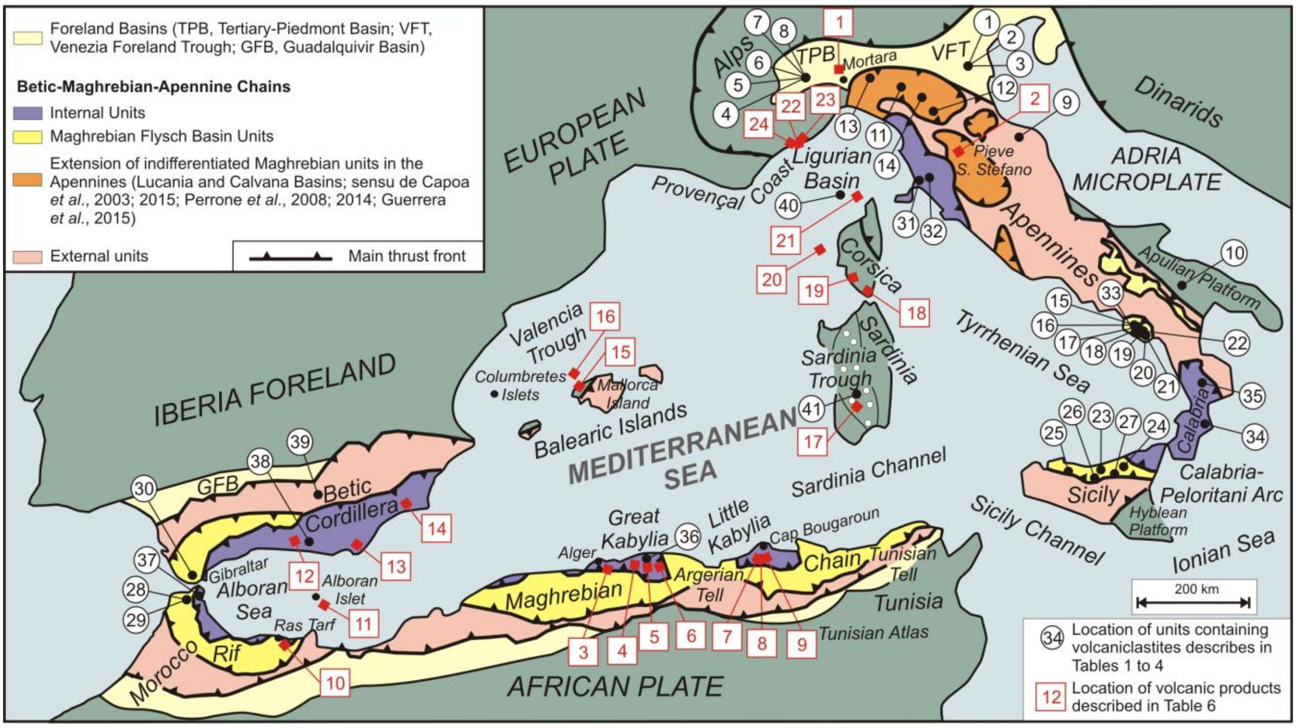

Figure 2. *Distribution of the uppermost Oligocene-middle Miocene p.p. volcaniclastites and primary volcanic products along the Betic, Maghrebian, and Apennine Chains (central-western Mediterranean area).*

In summary (Table 5), the volcanoclastites analyzed throughout the different domains of the Apennine-Maghrebian-Betic Chains show broad variability with respect to the following main aspects: lithofacies and their vertical and lateral distribution, amount of volcanigenic material, color, thickness, sedimentary structures, mineralogical association, and paleogeographic location of the basins.

On the other hand, they reflect a very similar regional geologic significance that results in the following features: age, minero-petrographic composition, geochemistry of the volcanic petrofacies, typology of the volcanic source areas (prevalently explosive), emplacement processes (pyroclastic or epiclastic), grain size, presence of mega events. This uniformity of features implies specific interpretative constraints (see below). However, the uneven areal distribution of the quantity and quality of data (e.g. lacking data in North Africa: Algerian Tell, offshore of the Maghrebian Chain and Tunisian Tell in particular; Table 5) requires some caution in the generalization at least for some sectors of the chains considered.

DOMAIN	BASIN	Type of volcanic supply	Range of some field parameters (m)			Range of grain size (mm)	Emplacement processes	Occurrence of siliceous deposits
			SIV	TVB	MVB			
AFRICA-ADRIA MARGIN, (EXTERNAL UNITS)	Venezia Foreland Trough	rhyolite	8-10	2	1	up to 0.25	PF	VF
	Tertiary Piedmont Basin Foreland	dacite, rhyolite andesite, trachite	25-200	10	0.3-2.8	0.25-0.6	PF, GF	VF
	Bisciaro Basin	dacite andesite	>100	18	6.9	up to 0.6	PF, GF	VF
	Apulian Platform Basin	?	287	---	> 0.4	---	GF	F
CALVANA-LUCANIA-MAGHREBIAN OCEAN	Calvana Basin (Extension of the Maghrebian units in northern Apennines)	rhyolite, rhyodacite dacite andesite	15-450	10-15	0.3-10	0.5	PF, GF	VF
	Lucanian Basin (Extension of the Maghrebian units in southern Apennines)	andesite rhyolite dacite basalt	54-500	46-<150	0.2-5	---	GF, PF	VF
	Maghrebian Flysch Basin	andesite dacite	43-600 --------	30-200	0.5-2 --------	>2–up to 2.5	GF --------	VF

	(Nebrodi, Sicily)	basalt	10	------- - 0.5	0.15	--------------	PF	
	Maghrebian Flysch Basin (Rif, Morocco)	andesite basalt	124-800	---	some meters	fine to coarse-grained sand	GF, PF	F
	Betic Basin (Extension of the Maghrebian units in Betic Cordillera)	andesite rhyolite	850	---	3	---	GF	F
MESOMEDI-TERRANEAN MICROPLATE MARGIN	Macigno Basin (eastern Margin)	?	800	---	---	---	GF	---
	Pollica Basin (eastern Margin)	rhyodacite	>230	---	1	---	GF, PF	F
	Late-flysch basin (Calabria-Peloritani Arc)	andesite dacite	at least 2,100	---	---	---	GF, PF	NF
	Late-flysch basin (Algerian Tell, Algeria)	rhyolite	---	---	---	0.02-0.25	GF, PF	F
	Late-flysch basin (Rif Chain, Morocco)	andesite basalt	10	0.5	0.15	---	GF, PF	---
	Late-flysch basin (Betic Cordillera, Spain)	andesite rhyolite-rhyodacite	45	3	0.5	---	PF, GF	VF
EUROPEAN MARGIN (EXTERNAL UNITS)	Subbetic Basin (External Betic Cordillera)	rhyolite-rhyodacite	---	---	0.25	fine to medium grained sand	GF	F
?	Ligurian Basin	?	---	---	---	---	---	---
WESTERN SARDINIA	Sardinia Trough	andesite basalt	640	> 10	0.6	0.2-10	PF, GF	VF

SIV, thickness of the Stratigraphic Interval (meters) containing Volcaniclastites; TVB, Total thickness (meters) of Volcaniclastic Beds in a single succession; MVB, Maximum thickness (meters) of a single Volcaniclastic Bed; PF, pyroclastic fall; GF, gravity flows; F**,** frequent; VF, very frequent; NF, not frequent

Table 5. *Synthesis of the useful parameters to evaluate the distribution and amount of volcaniclastites within each basin considered along the different domains of the Apennine-Maghrebian-Betic Chains. Symbols are explained in the lower part of the table.*

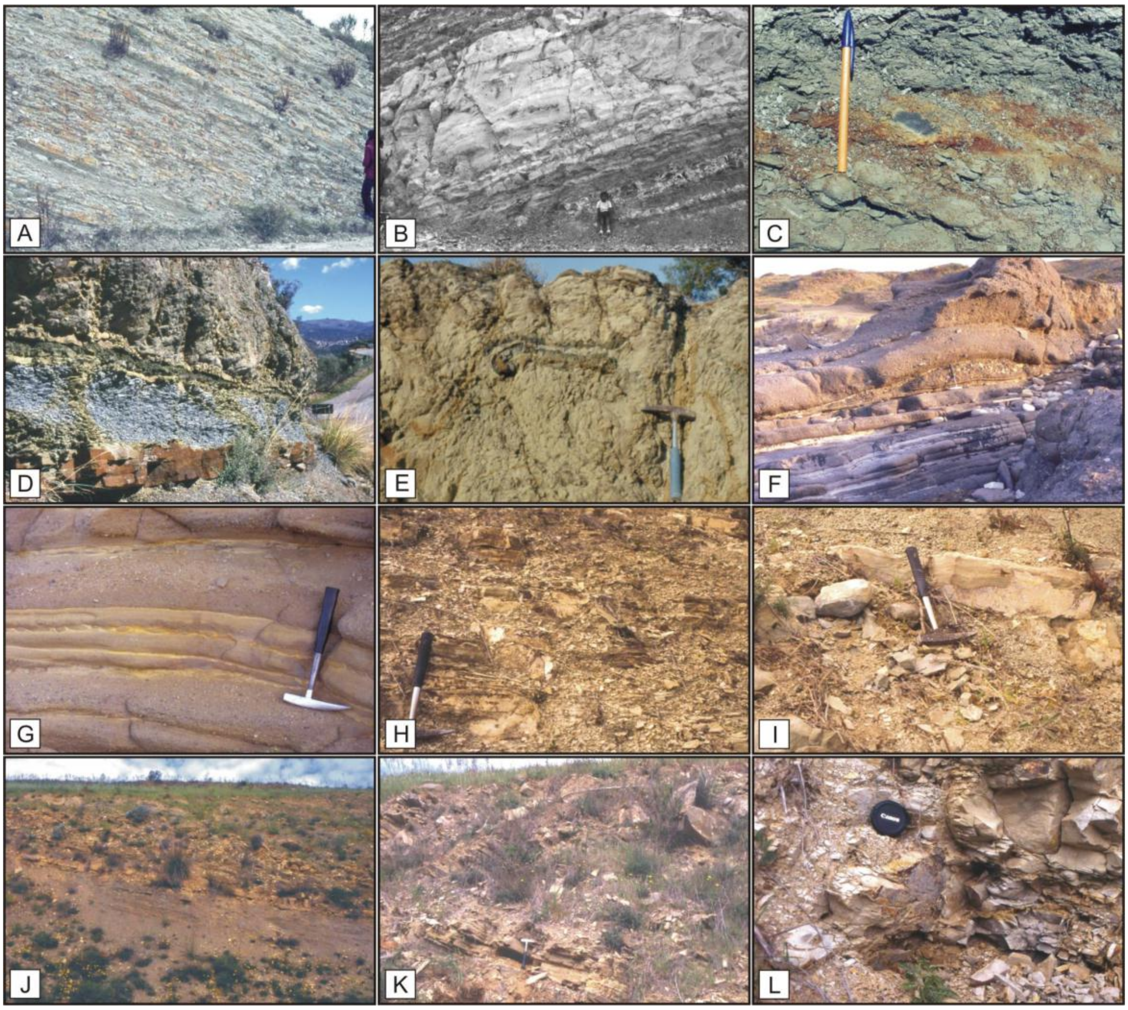

Figure 3. *Examples of volcaniclastites cropping out within different formations in some sectors of the Apennine-Maghrebian-Betic Chains. A, Bisciaro Fm with different types of volcanoclastites (eastern Marche Apennine): (i) Pyroclastic deposits (Vitroclastic/ crystallo-vitroclastic tuffs and Bentonitic beds); (ii) Epiclastic deposits; (iii) Mixing of volcanogenic sediments with marine deposits prevalently; B, Pyroclastic deposits ("Mega Pyroclastite"), in the Bisciaro Fm near Santa Croce d'Arcevia (Marche Apennine); C, Typical "Ocraceous layer" (Pyroclastic deposits) within the Bisciaro Fm (Tarugo area, Marche Apennine); D, Typical turbidite bed (Epiclastic syn-eruptive volcaniclastic deposits) in the Tusa Flysch (Halaesa stratigraphic section, Sicily); E, A particular of another turbidite (syn-eruptive volcaniclastic deposits) in the Tusa Flysch (Halaesa stratigraphic section, Sicily); F, whitish altered volcaniclastites (Crystal-rich volcaniclastic deposits) in the Sidi Addeslam Fm (Rif, Morocco); G, a particular of the previous picture F; H, volcaniclastites (Pyroclastic and Epiclastic syn-eruptive deposits) in the Viñuela Fm (Viñuela stratigraphic section, Betic Cordillera); I, Pyroclastic deposits (Bentonites) in the Viñuela Fm (Viñuela stratigraphic section, Betic Cordillera); J, general picture of the volcaniclastic deposits (pyroclastic and epiclastic syn-eruptive beds) in the Villanovaforru succession (Sardinia Through, Sardinia); L, a particular of different volcaniclastites in the Villanovaforru succession (Sardinia Trough, Sardinia); M, Mixing of volcanogenic sediments with marine deposits in the Villanovaforru succession (Sardinia Trough, Sardinia; from Guerrera et al., 2004, reinterpreted).*

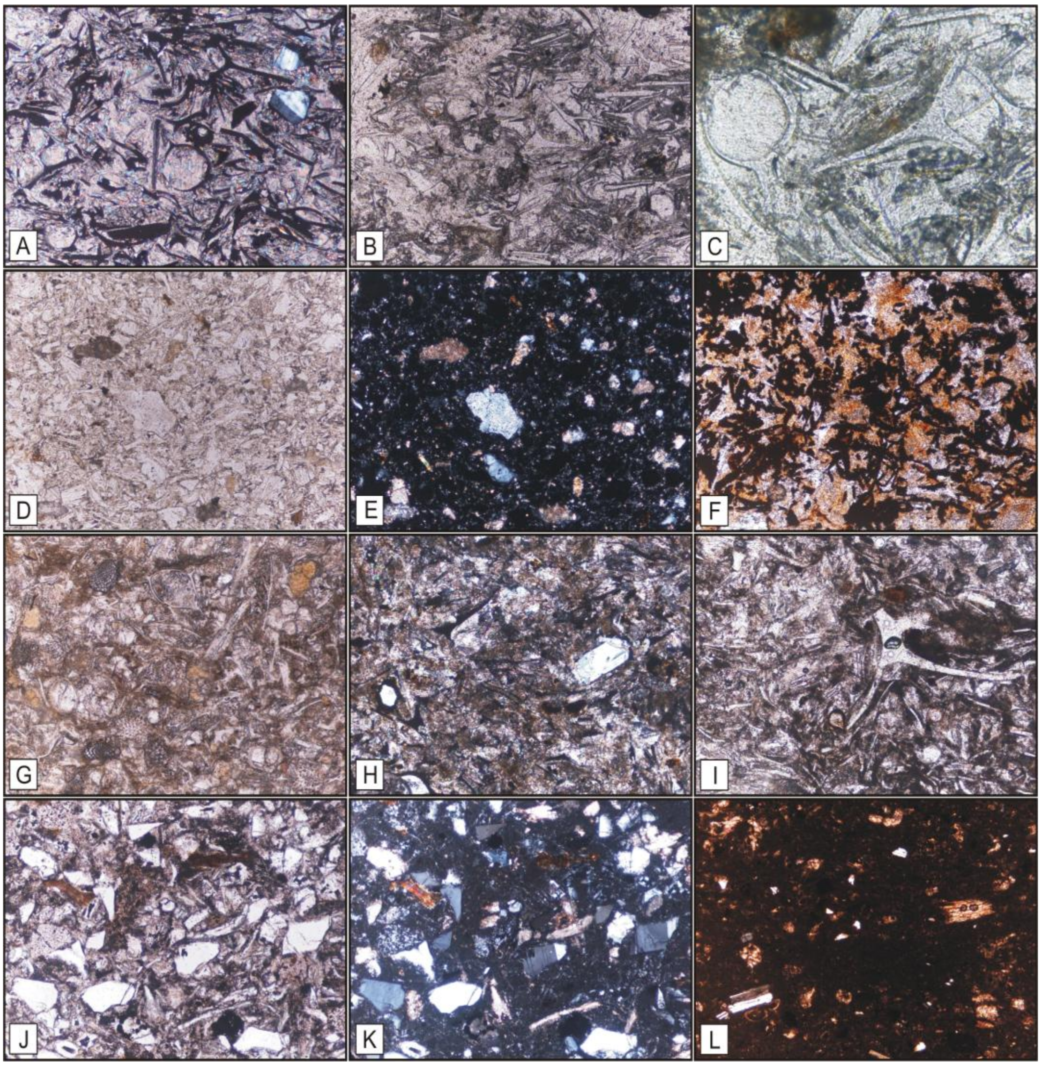

Figure 4. *Optical microphotographs of some representative different rock types of the volcaniclastites according to petrofacies and sub-petrofacies classification adopted in this paper. The samples come from the volcanogenic deposits of the Bisciaro Fm (Umbria-Marche-Romagna Apennines) for being the most representative to show the high variability of the petrofacies. A, Vitroclastic tuff (Petrofacies 1A; cross-polarized light); B and C, prevalent colorless glass shards with variable morphologies (platy, cuspate, bubble) and subordinate crystal fragments (plagioclase), plane-polarizes light, base of the photos 1.25 mm; in C also details of some morphologies of glass shards (bubble, platy, Y-shaped) are shown; D and E, vitroclastic/crystallo-vitroclastic tuff (Petrofacies 1A): abundant fine-grained glass shards with less abundant and coarse-grained crystals and lithic fragments (D, cross-polarized light; E, plane-polarizes light, base of the photos 1.25 mm); F, ocraceous layer (Petrofacies 1C): abundant amount of fine-grained, oxidized and ocraceous minerals and fragments of deeply altered glass shards (plane-polarized light, base of the photo 1.25 mm); G, high-density volcaniclastic turbidite (Petrofacies 2A): abundant glass shards and bioclasts and minor amount of lithic and crystal fragments (plane-polarized light, base of the photos 1.25 mm); H and I, low-density volcaniclastic turbidite (Petrofacies 2B): very abundant glass shards and crystals with respect to non-volcanic fraction (plane-polarized light, base of the photo 1.25 mm); J and K, crystal-rich volcaniclastic deposit (Petrofacies 2C): abundant crystals and fragments of crystals (quartz, plagioclase, mica, etc.), glass shards and lithic fragments (J, plane-polarized light; K, cross-polarized light, base of the photos 1.25 mm); L, marls with volcaniclastic material (Mixing of* volcanogenic *sediments with marine deposits, Petrofacies 3): glass shards and crystals (plagioclase, quartz, dark minerals), lithic fragments and bioclasts in a very fine matrix (cross-polarized light, base of the photo 2.5 mm).*

5. Volcanites

A large igneous calc-alkaline activity (Table 6; Fig. 2) linked to complex geodynamic processes affected the central-western Mediterranean area during the latest Chattian-Langhian (about 26-15 Ma). This type of magmatism is represented by typical products of convergent plate-margin tectonics characterized by a medium- to high-K andesite-dacite-rhyolite suite (Gill, 1981). The generation of cal-alkaline magmas is considered to be geologically coeval with active subduction, but this magmatism in some case may occur without contemporaneous subduction in different geotectonic contexts (Mattioli et al., 2012; *and references therein*).

The climax of this volcanism occurred in the early Miocene, consequently to the Aquitanian tectonic events mainly related to subduction of Calvana-Lucania-Maghrebian Ocean, with eruptive styles ranging from weak to moderate effusions of lava flows to violent explosive pyroclastic eruptions. This volcanic activity affected also back-arc areas and extensional and strike-slip deformation along the southern European Margin (Fig. 2; Table 6).

The magmatic activity linked to this complex tectonic setting causes the emplacement of geochemically different volcanic and plutonic associations that are mainly of calc-alkaline affinity including MORB-type and back-arc oceanic basalts, from calc-alkaline to ultrapotassic lavas, plutonic and volcanic rocks of crustal-anatectic origin, and alkali-basalt series. Possible co-genetic relationships between volcanic activity and coeval volcaniclastites can be checked in the known volcanic products and their main features, summarized in Table 6.

Domain	Volcanic systems	Type of volcanism	Rock-type	Age (Ma)	Main References
ADRIA MARGIN	1. Mortara 1 drilling (Po plain)	calc-alkaline	andesite, dacite (lava flows)	~34-16 16.1-20.9	Cassano et al., 1986; Bonci et al., 1994; Ruffini, 1995; Mattioli et al., 2002
	2. Pieve S. Stefano 1 drilling (Tuscany)	orogenic calc-alkaline	andesite (lava flows)	Oligocene? -Early Miocene	Anelli et al., 1994
NORTHERN AFRICA MARGIN	3. Algiers to Bougaroun Cape	orogenic (calc-alkaline)	----	22-15	Bellon and Letouzey, 1977
	4. Dellys, Cap Dijnet, Thénia, El Kerma areas (Great Kabylia)	orogenic (calc-alkaline, k- calc-alkaline)	basalt, andesite, dacite, rhyolite, granodiorite	19.1-14	Belanteur et al., 1995
	5. West Cherchel (Great Kabylia)	orogenic (calc-alkaline)	rhyolite, rhyodacite (lava flows)	16-15	Bellon, 1976; 1981; Marignac and Zimmermann, 1983; Penven and Zimmermann, 1986; Monié, et al., 1992
	6. Amizour area (Great Kabylia)	orogenic (calc-alkaline -anatectic; high potassic calc-alkaline)	andesite, dacite, diorite, monzonite	24.4, 18.5-15.2	

	7. Toufut (Little Kabylia)	orogenic (calc-alkaline crustal-anatectic; high potassic calc-alkaline)	granitoid	22-16	
	8. Edough Massif (Little Kabylia)	orogenic (calc-alkaline)	rhyolite	16-15	
	9. Annaba (Little Kabylia)	orogenic (calc-alkaline crustal-anatectic; high potassic calc-alkaline)	diorite	15.8	
	10. Ras Tarf area (Morocco)	calc-alkaline (anatectic)	basaltic andesite, andesite (pyroclastic breccias)	lower ?-middle Miocene *p.p.*	Duggen et al., 2004
ALBORAN SEA	11. Alboran Islet and surrounding area	orogenic (calc-alkaline-anatectic) tholeiite	andesite (pyroclastite,lava flows, blocks)	18-15	Bellon, 1981; Comas et al., 1992; Hernandez et al., 1987; Chalouan et al., 2001; *and references therein*
SSE IBERIAN MARGIN	12. Betic Cordillera (Malaga area: east of Marbella, Mijas, Velez-Malaga)	orogenic (calc-alkaline-anatectic) tholeiitic	andesite, basaltic- andesite (dikes), andesitic basalt, dacite, rhyolite, granite	23 -18	Bellon, 1981; Torres-Roldan et al., 1986; Hernandez et al., 1987; Duggen et al., 2004
	13. Betic Cordillera (Almeria-Cabo de Gata area: Velez-Blanco, Serrata, Carboneras, etc.)	orogenic (calc-alkaline-anatectic)	basaltic to andesite, dacite, rhyolite (pyroclastite), hornblende-bearing tuffs ? leuco-granite, (dike, blocks, pebbles)	24-14	Bellon, 1981; Bellon et al.,1983; Hernandez et al., 1987; Scotney et al., 2000
	14. Betic Cordillera (Murcia, Mar Menor)	calc-alkaline	dacite (lava)	18.5	Duggen et al., 2004
MALLORCA ISLAND	15. Puig de L'Ofre	orogenic (calc-alkaline)	rhyodacite (ash-flow; pyroclastite)	18.6-19 (Budigalian)	Mitjavila et al., 1990
VALENCIA THROUGH	16. DSDP 123 (near Mallorca Island)	orogenic (calc-alkaline-crustal anatectic)	dacite, rhyodacite hyaloclastite, rhyolite	19.4-24.4 20.8-21.9	Ryan et al., 1972; Rivière et al., 1981; Rivière, 1988
CORSICA-SARDINIA BLOCK	17. Sardinia Through (different sites)	high-K calc-alkaline, calc-alkaline, tholeiitic	rhyolite to dacite, dacite to rhyolite ignimbrite, andesite, basaltic-andesite, high-Mg basalt	~38-14 (peak at ~22-18)	Coulon, 1977; Savelli et al., 1979; Assorgia et al., 1997; Morra et al., 1997; Downes et al., 2001; Lustrino et al., 2009; Conte et al., 2010
	18. South Corsica (Francolu, Balistra, Tre Paludi; etc.)	orogenic (calc-alkaline)	dacite, rhyolite tuff (ignimbrite)	17.8 -18.9-19.3	Bellon 1976; Ottaviani-Spella et al., 1996; 2001
	19. Southwest Corsica margin	orogenic (calc-alkaline)	basalt to amphibole-biotite, andesite	16-17.2	Rossi et al., 1998
	20. West Corsica (sites offshore)	calc-alkaline	andesite, glassy laves, basalt, pyroclastic breccias	18.1-16.4 (17.2) 16.1-15.8	
	21. Corsica-Ligurian basin (Cap Corse area)	low- to high-K calc-alkaline	basalt, basaltic andesiteandesite, trachyte	post 31-until18	Lustrino et al., 2011; Réhault et al., 2012
LIGURIAN SEA	22. Provence (Nice area)	orogenic calc-alkaline	andesite, trachyandesite	28-22 (peak at 24-17)	Réhault et al.,1985
SE EUROPEAN	23. Provençal coast (Cap-d'Ail- Monaco)	calc-alkaline	andesite, dacite, microdiorites,	Burdigalian (18.7)	Ivaldi et al., 2003

MARGIN			rhyolite (blocks)		
	24. Provençal coast (Nice, Cap-d'Ail, area)	orogenic (calc-alkaline-anatectic)	andesite	28-20	Bellon, 1981

Table 6. *Active volcanic systems, type of volcanism, main rock-type and radiometric age, during the latest Oligocene-middle Miocene p.p. in the central-western Mediterranean region. Location of the study units is shown in Figure 2.*

These acid-intermediate calk-alkaline volcanic products are recorded in different areas of the Apennine-Maghrebian-Betic Chain and in the Mediterranean Sea (Valencia Trough; Algero-Provençal Basin, Corsica-Sardinia Block). These products may represent potential source areas for volcaniclastites, as inferred by compatible age and geochemistry.

Paleogeographic domains where this volcanic activity is documented lie at variable distances from the sedimentary units containing volcanoclastites, implying difficulties in recognizing real source areas. Moreover, the lack of specific–geochemical analysis of volcanogenic products prevents direct correlations of specific volcaniclastic beds and primary volcanic bodies. Only when geochemical compatibility has been established and sedimentary parameters are known can the paleogeographic framework be reconstructed and constraints for geotectonic evolution be defined.

6. Discussion

Abundant volcaniclastites are interbedded in different marine formations along the central-western peri-Mediterranean chains (Fig. 2) although the original amount of volcanic materials is reduced due mainly to: (i) high dispersion especially during fallout, and (ii) alteration processes and marked erosion during sedimentary epiclastic processes (erosion, transport, and sedimentation); (iii) alteration and chemical transformation processes during the diagenetic phase (e.g. deep calcification of the Bisciaro Fm of Umbria-Marche-Romagna Apennines).

Volcaniclastites vary markedly in thicknesses and lateral distribution, as indicated by SIV, TVB, and MVB parameters (Tables. 1-5). The maximum thickness of a single volcaniclastite can reach 10 m and the volcanic content in a single bed may be 80-85% (e.g. Tusa Flysch in Sicily). Thick Apennine volcaniclastites (e.g. the "Mega-P" in the Bisciaro Fm; 6.9 m thick; Guerrera et al., 2015, *and references therein*) and some volcaniclastic turbiditic beds in the Tusa Flysch (up to 1.5-2.0 m thick) derived from major volcanic events but their mutual relationships are difficult to verify. Only field observations, sedimentary structures, geochemical affinity, age, etc. provide reliable interpretations and correlations. In particular, resedimentation processes and grain-size values imply specific constraints for paleogeographic reconstructions, reflecting the closeness (or distance) between the volcanic apparatus and sedimentary basins, while pyroclastic beds are not controlled by paleogeography. Sediment gravity flows are the prevailing emplacement processes, as indicated by the feautures observed and also from the comparison with previous descriptions of volcaniclastites (Fischer, 1984; Schneider, 2000; Mulder, 2011).

Field analyses revealed frequent siliceous deposits (Lorenz, 1984) such as, silexites, radiolarites, jaspers, spongolites, diatomites, and tripolaceous beds within the marine successions containing volcaniclastites (Tables 1-4). Their origin is linked mostly to volcanic activity (Martín-Algarra, 1987; Chalouan et al., 2001; Guerrera et al., 2015) during the opening of the Mediterranean. The distribution of these deposits, almost always present in the same successions containing volcaniclastic materials, testify a strong relationship with silica supply due to volcanic activity.

The latest Oligocene-middle Miocene acid to intermediate calc-alkaline orogenic magmatism of the central-western Mediterranean area (Table 6) often with high-magnitude eruptions is compatible with the nature of the volcaniclastic material. This volcanic activity is related mainly to subduction of oceanic basins and related backarc systems, continental collision and subordinately to extensional deformation developing in the western Mediterranean during the evolution of the Apennine-Maghrebian-Betic system (de Capoa et al., 2002; 2004; Chalouan et al., 2001; Lustrino et al., 2009; Guerrera et al., 2015; *among others*).

The hypothesized volcanic areas responsible for the volcanogenic supply have been tentatively individualized in the following five geotectonic provinces affected mainly by acid-intermediate volcanism: (i) Adria Plate, where volcanism must have been activated during the continental collision between the Mesomediterranean Microplate and the Adria-Africa Plate (Perrone et al., 2008; Guerrera et al., 2015; *and references therein*) with a mechanism similar to that proposed by Simakin (2014); (ii) eastern and southern Mesomediterranean Microplate (MM) margins, representing active continental margins related to the subduction of the Betic, Maghrebian, Lucania, and Calvana oceans that caused the development of the accretionary wedge of central-western Mediterranean chains (de Capoa et al., 2002; 2015; Guerrera et al., 2005; *and references therein*); (iii) Back Arc zones resulting from the extensional deformation affecting the internal zone of the Apennine-

Maghrebian orogenic systems recognized mostly on the western side of the Sardinia-Corsica Block (Guerrera et al., 2004); (iv) rifting of the SE European (Iberia) Margin (e.g. Valencia and Provençal Basins; e.g. Maillard and Mauffret, 1993), which was affected by an extensional deformation related to drifting and rotation of the Sardinia-Corsica Block; and (v) the south-western Iberia Margin undergoing strike-slip tectonics related to a right-hand transform fault zone with volcanic emissions as well as a strong silica concentration (Soria et al., 1992).

In fact, the scant presence of compatible primary volcanic products (Table 6) seems insufficient to explain the abundance of volcaniclastites; however, it should be considered that the volcanic apparatus is poorly preserved due mainly to: (i) erosion of the incoherent explosive centers; (ii) burial and cancellation caused by thrusting processes; and (iii) "cannibalization" related to the activity of strike-slip transform-fault systems or subduction processes affecting convergent plate margins (Sylvester, 1988). Therefore, primary volcanic products recognized up to now must represent relicts of larger volcanic activity. For these reasons it is not easy to locate the position of primary volcanic centers with respect the sedimentary basins also because the orogenic deformation canceled the original paleogeography.

The general geodynamic evolutionary models of the central-western Mediterranean area well synthesized by Chalouan et al. (2008; Fig. 5.48) propose the presence between Europe and Africa of a single ocean affected by only one subduction or the presence of an intermediate microplate with two subductions. Following the "two-subduction model" (cfr. Guerrera and Martín-Martín, 2014; *and references therein*; see also Fig. 5), we assume the presence of a "Mesomediterranean Microplate" located since the late Jurassic-early Cretaceous between Europe and Africa, separating two different Tethyan oceanic branches (Fig. 5A): (i) the Nevado-Filabride-Piemontese-Ligurian Basin that closed during the Cretaceous-Paleogene (Alpine history *s.s.*) and (ii) the Maghrebian-Lucania-Calvana Basin, closed during the Miocene (Apennine-Maghrebian history; Guerrera et al., 1993; 2005; Bonardi et al., 2003 o 2005; de Capoa et al., 2003; Perrone et al., 2008; de Capoa et al., 2015; Guerrera and Martín-Martín, 2014; *among others*). During the Oligo-Miocene Africa/Europe convergence, the breakup of the MM generated minor crustal blocks (Alboran, Kabilydes, Calabro-Peloritano and Toscana basement), constituting the internal zones of the Betic-Maghrebian-Apennine Chains. The different rate and direction of block migration and the contemporaneous Africa-Adria Plate subduction produced diachronous volcanic systems located mostly in internal positions with respect to the different sedimentary basins during the early Miocene (Figs. 5B, 5C, 5D).

The discussion on this subject and the reconstruction of a model encompassing the high amount of data that increase in time, are still open. In this context an appropriate clarification of terminology is necessary and it seems useful to specify that some authors (e.g. Lustrino et al., 2009; Chalouan, Michard, 2004; *among others*) consider the paleogeographic AlKaPeCa block (model introduced by Bouillin, 1986) to be equivalent to the Mesomediterranean Microplate (*sensu* Guerrera et al., 1993; 2005; Guerrera and Martín-Martín, 2014; *and references therein*). In the original conception, the AlKaPeC*a* forms part of the European Margin separated from the Africa Margin by a single Jurassic oceanic basin; while the MM represents an intermediate continental Hercynian crustal block separating two oceanic basins since the late Jurassic-early Cretaceous. In addition, the MM was involved into two opposite subductions (Alpine: Cretaceous-middle Eocene; and Apennine-Maghrebian: Late Oligocene-Miocene). Moreover, according to other authors (e.g. Chalouan and Michard, 2004; Michard et al., 2002; Chalouan et al., 2008) AlKaPeCa does not seem to correspond to the differently defined AlKaPeCa of Bouillin (1986) but in fact corresponds to the MM (*sensu* Guerrera et al., 1993; 2005).

Many authors consider Sardinia the main volcanic source area for Apennine volcaniclastites (e.g. Perri et al., 2012; Critelli et al., 2013; *among others*). However, considering the paleogeographic distance of several hundred kilometers of Sardinia-Corsica Block from Apennine basins (Gueguen et al., 1998) and the presence during early Miocene of morphologic dams (i.e. the Alpine Chain, the MM, and the building Apennine Chain), this source area could not be compatible with the recognized volcaniclastic turbidites**.** This complex paleogeography in the time span considered is widely confirmed by different authors (e.g. Dewey et al., 1989; Doglioni, 1992; Maillard and Mauffret, 1993; Guerrera et al., 1993; 2005; 2007; 2012; de Capoa et al., 2002; Guerrera and Martín-Martín, 2014; Amendola et al., 2016; *and references therein and among outhers*). Therefore, a relationship with primary Sardinia volcanism seems possible only for pyroclastic deposits, especially for large explosions also causing great volumes of Sardinia igninbrites (Assorgia et al., 1997). In fact, the role of the Miocene volcanism of the Sardinia-Corsica Block as regards the supply in the basins of the Maghrebian-Apennine chains is probably restricted to thin pyroclastic beds.

On the other hand, the Sardinia Trough, where minor sedimentary basins with volcaniclastites are located near 50-100 km from remnants of volcanic primary sources (e.g. Marmilla Basin, Guerrera et al., 2004) may represent a realistic model applicable elsewhere. A comparable case is the Bisciaro Fm (Adria Margin), where the distance between the volcanic source and the sedimentary basin was estimated at <100 km (Guerrera et al., 2015). A similar approach for considering the closeness between source areas and sedimentary basins has been adopted in some sectors of the Apennines (Clari et al., 1988; Ruffini et al., 1995; D'Atri et al., 1999; 2001; de Capoa et al., 2002; Guerrera et al., 2015).

With respect to the possible volcanic source (i.e. Mortara 1 and Pieve S. Stefano 1 drillings, Table 6) compatible with the volcaniclastites found in the Adria Margin (Foreland basins; i.e. Bisciaro, Venezia and Tertiary Piedmont basins), the geodynamic context appears complex. In fact, primary volcanic products would result from the involvement of the Adria Microplate in the continental collision where the volcanism occurred in the late evolutionary stage after an accretion event according to the model recently proposed by Symakin (2014).

The paleogeographic and paleotectonic model proposed here is schematically illustrated in Fig. 5, where some main evolutionary stages of the geodynamic evolution of the central-western Mediterranean are summarized.

Fig. 5A schematically shows the paleogeography during the late Jurassic-early Cretaceous with evidence of the Mesomediterranean Microplate surrounded by two branches of the western Tethys (Nevado-Filabride/Ligure-Piemontese Basin and Maghrebian-Lucania-Calvana Basin respectively) and located between the Europe and Africa Plates. In Fig. 5B the main late Oligocene geodynamic features, post-dating the Alpine and neo-Alpine history, are pointed out. The starting of the syn-orogenic volcanic activity and related volcaniclastites, occurring in very few areas (Tables 2, 3, 6; Fig. 2), are also shown. In particular, the volcanic activity is limited to the southern and eastern margins of the MM (subduction volcanic arcs in Kabylides and probably Tuscanides, respectively) and in the Valencia Trough and Ligurian Basin (rifting). In Fig. 5C, referring to the early Miocene, the maximum distribution (Fig. 2) of volcaniclastites (Tables 1, 2, 3, 4) and the climax of the volcanic events (Table 6) are reported; the associated geodynamic evolutionary phase of the development of the central-western Mediterranean chain systems is shown. The volcanic source areas are prevalently located along the external margin of the MM (subduction volcanic arcs), in the Adria Margin (continental collision), Provençal Basin and Corsica-Sardinia Block (back-arc) and Valencia Trough-Ligurian Basin (rifting). In Fig 5D the last step of the restructuction is presented, indicating a marked reduction in volcanic products and volcaniclastites (Tables 1, 2, 3, 6). The volcanic source areas of this period are represented mainly in the Corsica-Sardinia Block and Alboran Basin (back-arc zones**).** Geotectonic contexts and geodynamic processes are summarized in Table 7.

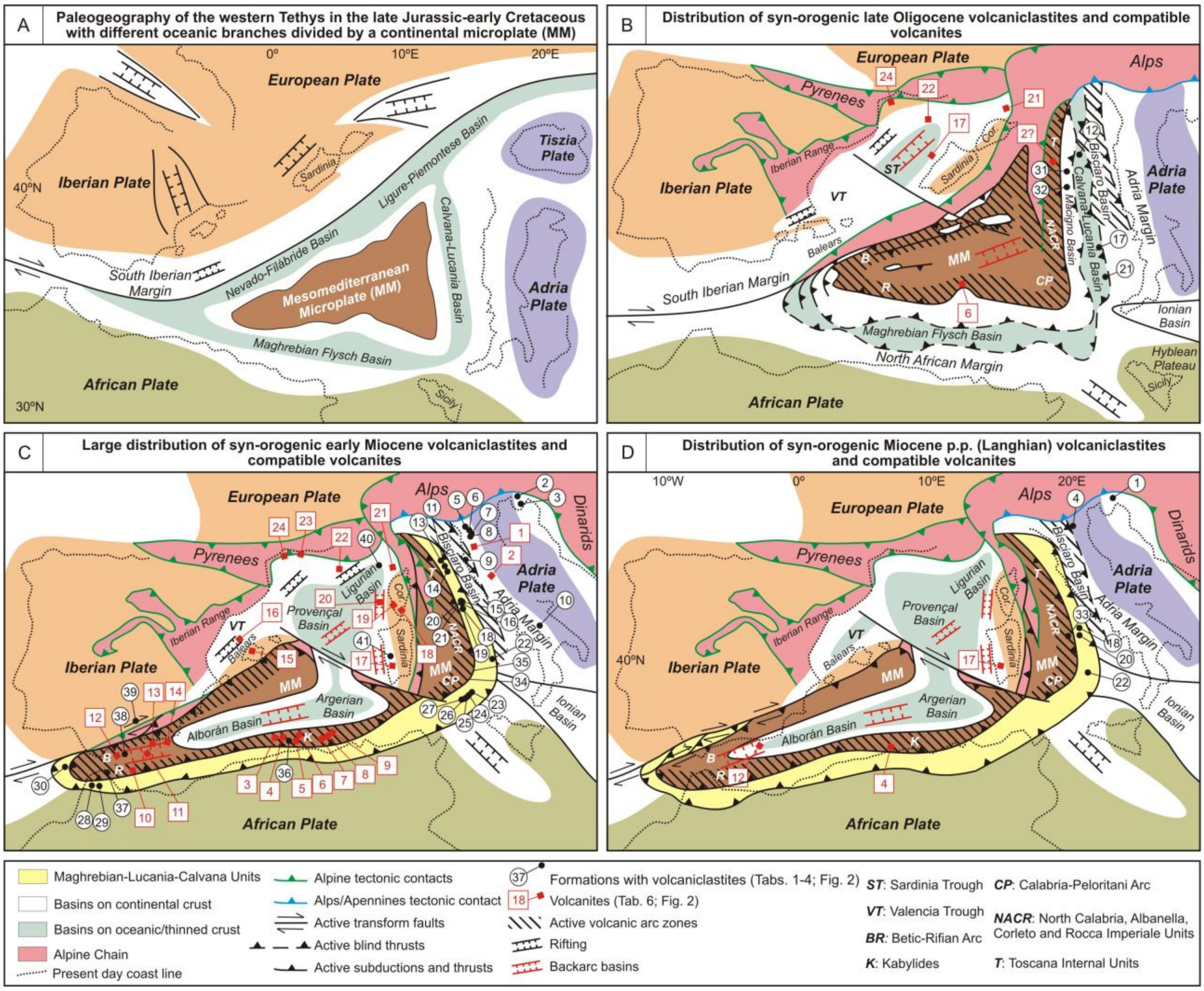

Figure 5*. Paleogeographic and paleotectonic evolutive model of the central-western Mediterranean region sketched in four steps: A, late Jurassic-early Cretaceous; B, late Oligocene; C, early Miocene; D, middle Miocene p.p. (Langhian). Relationships between sedimentary basins and volcaniclastites, and distribution of active volcanic systems during the late Oligocene, early Miocene and middle Miocene p.p. (Langhian) are shown.*

7. Final remarks

The present study has provided the following main findings, also summarized in Fig. 5 and Table 7.

1. The presence of abundant volcaniclastites interbedded in marine formations along the central-western peri-Mediterranean chains (Fig. 2), brought about by penecontemporaneous latest Oligocene-middle Miocene *p.p.* volcanic activity, climaxed during the early Miocene. These results have been definitively verified.

2. A compatible acid to intermediate volcanic activity in the central-western Mediterranean area is present and characterized by high-magnitude eruptions. This activity is prevalently generated from a calk-alkaline orogenic magmatism (subduction and collision) and syn-orogenic extensional deformation and strike-slip tectonics.

3. In particular, five different geotectonic contexts with calcalkaline volcanism supplying volcaniclastites in adjacent basin areas were identified: (i) Adria Plate involved in continental collision between the Mesomediterranean Microplate and the Adria-Africa Plate, after the consumption of the Calvana-Lucania-Maghrebian oceanic crust; (ii) eastern and southern Mesomediterranean Microplate (MM) subduction margin; (iii) Back-Arc zones of the Apennine-Maghrebian-Betic orogenic systems (South-western Corsica Margin and Sardinia Trough); (iv) rifting of the SE European (Iberia) Margin (e.g. Valencia Trough and Provençal-Ligurian Basin; cfr. Vera, 2004); (v) the southwestern Iberia Margin (Basin related to a right-hand strike-slip fault zone; Subbetic Basin). In all these geotectonic provinces very widespread primary volcanic products were generated.

4. Direct relationships between the location of volcanic apparatus and sedimentary basins have been canceled by orogenic deformation, and therefore reconstructions are strongly influenced by the interpretative geodynamic model adopted at the scale of the central-western Mediterranean. However, many data suggest that reconstructions considering the distance between each sedimentary basin and its volcanic source contained within some tens or some hundreds of km are preferable.

5. Among the different geotectonic provinces considered, the Sardinia Trough may represent an interpretative model concerning relationships between volcanic sources and secondary products. In fact, in this area, the closeness between the depositional areas of volcaniclastites and primary volcanic products is recognizable. A similar situation is documented also in the Biscaro Basin (Umbria-Marche-Romagna Apennines) and it is attested to by the presence of volcanites (well Pieve Santo Stefano 1) near the depositional areas. On this basis, a short

distance between source areas and sedimentary basins (in the order of 100 km) is likely for the Betic-Maghrebian-Apennine Chains.

6. The recognized primary products represent only the remnants of a wider volcanic activity. The low amount of compatible volcanic products seems insufficient to explain the abundance of volcaniclastites. However, erosion, alteration, transformation, burial by thrusting, and "cannibalization" related to fault-system activity can explain this apparent discrepancy. Only primary products related to back-arc zones (e.g. Sardinia-Corsica Block) are abundant.

7. Volcanic apparatuses were located mostly in the eastern and southern Mesomediterranean Microplate active subduction margin (Fig. 5) and the volcanic activity climaxed during the early Miocene. This volcanic activity was generated by the consumption of the Calvana-Lucania-Maghrebian Ocean under the Mesomediterranean Microplate. However, it is noteworthy that in the Internal Units of the chains (Hercynian crystalline basement nappes with Mesozoic carbonate cover) primary products are known in some places (e.g. Betic-Rifian Arc, Kabylides, etc.; Table 6). However, the scarcity of volcanic products is probably due to: (i) a rapid and complete removal of the inconsistent volcanic apparatus; (ii) burial of these products within thrust sheets not yet exhumed or transformed by metamorphic processes as for example the lava flows attested to by deep drillings in Po Plain (well Mortara 1) and northern Apennines (well Pieve S. Stefano 1 in Tuscany).

DOMAIN WITH VOLCANI-CLASTITES	**BASIN**	**INFERRED LOCATION OF VOLCANIC SOURCE**	**GEOTECTONIC CONTEXT**	**GEODYNAMIC PROCESS**
Africa-Adria Margin	Venezia Foreland Trough	Adria Microplate (Mortara 1 drilling, Po Plain; Pieve S. Stefano 1 drilling)	Adria Plate involved in continental collision	Inversion of subduction in the late evolutionary stage after accretion
	Tertiary Piedmont Basin Foreland			
	Bisciaro Basin			
	Apulian Platform Basin			
Calvana-Lucania -Maghrebian Ocean	Calvana Basin (Extension of the Maghrebian units in northern Apennines)	Eastern MM Margin	Eastern and southern MM active subduction margin	Westward subduction of the Calvana-Lucania Ocean
	Lucania Basin (Extension of the Maghrebian units in southern Apennines)			

	Maghrebian Flysch Basin (Nebrodi Chain, Sicily)	Southeastern MM Margin		Northward subduction of the Maghrebian Ocean
	Maghrebian Flysch Basin (Rif Chain, Morocco)	South MM Margin		
	Betic Basin (Extension of the Maghrebian units in Betic Cordillera	Southwestern MM Margin		Eastward subduction of the Maghrebian Ocean
Mesomediterranean Microplate Margin	Macigno Basin (Eastern margin)	Eastern MM Margin		Westward subduction of the Calvana-Lucania Ocean
	Pollica Basin (Eastern Margin)			
	Calabria-Peloritani Arc	Southeastern MM Margin		Northward subduction of the Maghrebian Ocean
	Algerian Tell (Algeria)	Southern MM Margin		
	Rif Chain (Morocco)			
	Betic Cordillera (Spain)			Eastward subduction of the Maghrebian Ocean
European (Iberia) Margin	Subbetic Basin (External Betic Cordillera)	Southwestern Iberian Margin (Subbetic)	Basin related to strike-slip fault zone	Transform faulting
	Valencia Trough and Provençal Basin	Local volcanism	Rifting	Rifting affecting the European (Iberia) Margin
Ligurian Sea	Ligurian Basin			
Sardinia-Corsica Block	South western Corsica	Local volcanism (Southwestern Corsica margin; on land and offshore)	Back Arc Basin	Opening of the Sardinia Through during the drifting and rotation of the Sardinia-Corsica Block
	Marmilla Basin	Local volcanism (Sardinia Trough)		

Table 7. *General framework showing the relationships between domains with volcaniclastites and interpretative location of volcanic source areas. Reconstruction of the geotectonic context and geodynamic processes is also presented.*

Our interpretation implies that the central-western Mediterranean during the late Oligocene-middle Miocene was characterized by a complex geodynamic context resulting from the movement of structural crustal segments arising from the fragmentation of a main microplate (Mesomediterranean Microplate) located in the Jurassic paleogeography between the European and African Plates. These fragments (e.g. Betic-Rifian and Calabria-Peloritani Arcs) were later included in the Betic-Maghrebian-Apennine Chains to form their internal zones.

In conclusion, the space/time evolution of the central-western Mediterranean volcaniclastites provides keys to recognize interconnected geodynamic events such as volcanic activity, sedimentary and tectonic processes and to interpret them in a coherent paleogeographic-paleotectonic framework. However, the proposed interpretations must be considered as a preliminary contribution to the complex topic addressed in this paper and need further investigation.

Acknowledgments

All this research was supported by Urbino University grants to F. Guerrera and M. Tramontana; CGL2012-32169 and CGL2016-75679-P research project (Spanish Ministry of Education and Science), by Research Groups and projects of the Generalitat Valenciana from Alicante University (CTMA-IGA). The English language was revised by David Nesbitt.

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