The Early Miocene “Bisciaro volcanoclastic event” (northern Apennines, Italy): a key study for the geodynamic evolution of the central-western Mediterranean

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Abstract The Early Miocene Bisciaro Fm., a marly limestone succession cropping out widely in the Umbria–Romagna–Marche Apennines, is characterized by a high amount of volcanoclastic content, characterizing this unit as a peculiar event of the Adria Plate margin. Because of this volcanoclastic event, also recognizable in different sectors of the central-western Mediterranean chains, this formation is proposed as a “marker” for the geodynamic evolution of the area. In the Bisciaro Fm., the volcanoclastic supply starts with the “Raffaello” bed (Earliest Aquitanian) that marks the base of the formation and ends in the lower portion of the Schlier Fm. (Late Burdigalian–Langhian *p.p.*). Forty-one studied successions allowed the recognition of three main petrofacies: (1) Pyroclastic Deposits (volcanic materials more than 90 %) including the sub-petrofacies 1A, *Vitroclastic/crystallo-vitroclastic tuffs*; 1B, *Bentonitic deposits*; and 1C, *Ocraceous and blackish layers*; (2) Resedimented Syn-Eruptive Volcanogenic Deposits (volcanic material 30–90 %) including the sub-petrofacies 2A, *High-density volcanogenic turbidites*; 2B, *Low-density volcanogenic turbidites*; 2C, *Crystal-rich volcanogenic deposits*; and 2D, *Glauconitic-rich volcanoclastites*; (3) Mixing of Volcanoclastic Sediments with Marine Deposits (volcanic material 5–30 %, mixed with marine sediments: marls, calcareous marls, and marly limestones). Coeval volcanoclastic deposits

recognizable in different tectonic units of the Apennines, Maghrebian, and Betic Chains show petrofacies and chemical–geochemical features related to a similar calc-alkaline magmatism. The characterization of this event led to the hypothesis of a co-genetic relationship between volcanic activity centres (primary volcanic systems) and depositional basins (depositional processes) in the Early Miocene palaeogeographic and palaeotectonic evolution of the central-western Mediterranean region. The results support the proposal of a geodynamic model of this area that considers previously proposed interpretations.

Keywords Volcanoclastic event · Early Miocene · Umbria–Romagna–Marche Apennines · Stratigraphy · Petrography · Mediterranean-scale correlations · Geodynamic model

Introduction

Sedimentary rocks with significant volcanic clast populations are widespread in the Cenozoic central-western Mediterranean (Apennines–Maghrebian chains and Betic Cordillera). Volcanoclastic deposits are usually consistent with periods of pene-contemporaneous volcanic activity and therefore indicators of coeval magmatic geodynamic process. For this, it is useful to clarify four main aspects at least broadly treated in this paper, among others related to palaeogeographic questions: (1) lithostratigraphic characters and age relationships between successions containing volcanoclastic material (especially correlation of the ages of the sediment containers and those of the volcanic supply); (2) minero-petrographic and geochemical composition of volcanoclastites and their relationships with the original volcanism; (3) depositional process (epiclastic and/or

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pyroclastic) of volcanic material; and (4) bearing between sedimentary source area and volcanic supply.

A good example of these kinds of deposits is found in the Early Miocene Bisciaro Fm. (Umbria–Romagna–Marche Apennines), which can be correlated with similar coeval volcanoclastic sediments recognizable in several units of the central-western peri-Mediterranean chains.

General criteria to discriminate *neo-volcanoclastic* deposits, related to active pene-contemporaneous volcanism, from *palaeo-volcanic* detritus derived from the erosion of ancient volcanic rocks, are discussed by several authors (e.g. Pettijohn et al. 1972; Zuffa 1985, 1987; Guerrero and Veneri 1989; Critelli and Ingersoll 1995; Critelli et al. 2002; Caracciolo et al. 2011, 2012, among others). The deposits investigated here refer to the first type (i.e. volcanoclastic sediments formed during contemporaneous volcanic activity). In the present paper, the term “epi-clastic” (sensu Cas and Wright 1987) is used to indicate an erosion and reworking in sub-aerial and/or submarine environments of lava flows and pyroclastites with successive re-deposition in a marine basin through mass flow processes. By contrast, “pyroclastic” indicates fallout deposition related to pyroclastic explosions or pyroclastic flows with direct sedimentation in a marine basin by decantation and characterized by different proportions of ash, crystals, and lithics. This simple basic distinction involves a different type of interpretation regarding the reconstruction of volcano position with respect to the basin areas.

Generally, in deep to shallow marine environments, the composition of volcano-derived material depends on eruption styles (effusive vs. explosive). Fragmentation of lava flows, in intra-basinal systems or on the fringes of volcanic islands, gives rise predominantly to volcano-lithic sandstones, whereas sub-aerial to shallow marine pyroclastic eruptions may result into syn-eruptive tuffaceous sandstones (ash turbidites) to vitric-crystal-rich volcanic sandstones (Cas 1979; Wright and Mutti 1981; Fisher 1984; Cas and Wright 1987; Critelli and Ingersoll 1995).

In the Late Oligocene–Early Miocene, the western Mediterranean was characterized by a calc-alkaline magmatism forming volcanic arc systems that fed the volcanoclastic sedimentation frequently interbedded in several marine formations of the Betic Cordillera, Maghrebides, and Apennines. The aim of this paper is to present an interdisciplinary study concerning the Bisciaro Fm. corresponding to a “volcanoclastic event” considered in the context of the whole depositional basin of the Umbria–Romagna–Marche Apennines. This formation has been studied regarding the stratigraphic record, the distribution of volcanoclastic materials within the succession, mineralogical and petrographic features, and depositional processes. The data compiled allow correlations with other coeval volcanoclastic sediments of some chains of the central-western Mediterranean

area. The chief part of this research is to propose palaeogeographic relationships between the depositional area of the volcanoclastic sediments of the “Bisciaro event” and the location of the primary volcanoes that fed this type of sedimentation.

The results lead the “Bisciaro volcanoclastic event” to be considered a key for understanding the relationships between volcanoclastic marine sediments and volcanic source areas. At the same time, our findings help to reconstruct the geodynamic regional framework of the developing Apennine–Maghrebic Chains. Palaeogeographic and geodynamic constraints derived from the study will be discussed, and an Early Miocene evolutionary model of central-western peri-Mediterranean will be proposed.

Geological framework

The Umbria–Romagna–Marche Apennines (Fig. 1) represent a thrust-fold belt forming an arc bounded eastwards by the Sibillini thrust and its northward extension. This Apennine sector has been thrust by the External Tuscan and External Liguride Nappes. The chain is typified by faulted E-vergent asymmetric anticlines affecting the Mesozoic–Tertiary sedimentary succession. These anticlines are separated by narrow, often markedly asymmetric, synclines. The Umbria–Romagna–Marche Apennines have been traditionally considered to be a thin-skinned thrust-and-fold chain (Bally et al. 1988, and references therein), but more recently, a deformation involving the Hercynian basement has been pointed out (Lavecchia et al. 1994; Barchi et al. 1998; Coward et al. 1999; Mazzoli et al. 2001, 2005).

The Umbria–Romagna–Marche Apennines are characterized by a sedimentary succession deposited over a Hercynian continental crust (westward margin of the Adriatic Microplate), representing a portion of the northern margin of the African Plate. The Alpine geological history of the Umbria–Romagna–Marche Apennines started about 200 Ma ago, when an old continent characterized by prevailing metamorphic rocks of the previous Hercynian orogenic cycle was affected by marked extensional tectonics. This deformation caused a progressive rifting, leading to the successive development of the passive margin characterizing the southern part of the Tethys (Adriatic Margin) in the Early Jurassic (e.g. Mazzoli and Helman 1994; Turco et al. 2012; and references therein). Towards the west, the oceanic Calvana–Lucania Basin (see later) was separated the Adria continental margin by a continental Microplate (Meso-Mediterranean Microplate; Guerrero et al. 2005; cum bibl.). According to Critelli et al. (2008) and Perri et al. (2013), the western Mediterranean palaeogeography during the Middle–Late Trias–Early Cretaceous foreshadowed the birth of this intermediate microplate (see also Doglioni 1992).

Fig. 1 Geological sketch map of the Umbria–Romagna–Marche Apennines. Location of study areas in which stratigraphic successions (logs) as shown in Fig. 2 were reconstructed, is also indicated

These passive margins developed through a progressive transition from a continental environment to a shallow-water environment (evaporitic carbonate platform) and successively to pelagic environments. Instead, in the Calvana-Lucania Basin, deep marine successions developed above the Jurassic oceanic crust (Plesi et al. 2002) up to the Early Miocene (Perrone et al. 1998; de Capoa et al. 2003; Di Staso et al. 2009; and references therein).

In the Umbria–Romagna–Marche area, the succession was deposited from the Jurassic to Miocene on a Hercynian continental basement. In the lower portion of the succession, mainly carbonates were deposited during tectonic extension linked to the opening and evolution of the Tethys Ocean (Channell et al. 1979). The main Jurassic tectonic phases of the study area are related to normal faulting that controlled the development of the passive margin succession. The Jurassic sedimentation is generally continuous but shows marked lateral variations related to differences

in depositional environments controlled by extensional tectonics (horst and graben system; Donatelli and Tramontana 2012, 2014; cum bibl.). During the Early Cretaceous, the depositional area reached its largest size due to drifting processes, as testified to by the maximum lateral continuity of lithofacies, due to a generalized subsidence. Cretaceous basin carbonate sedimentation has recorded the pulses of accelerated subsidence (Marchegiani et al. 1999) that could also be related to the Late Cretaceous extensional tectonics found in the carbonate platform domains (e.g. Shiner et al. 2004). Carbonate sedimentation continued up to the earliest Miocene with a progressive increase in fine clastic material, resulting in the prevalence of marly lithofacies. Early Miocene sedimentation is marked by volcanoclastic deposits representing a regional event observed in several chains of the central-western Mediterranean (e.g. Guerrera and Veneri 1989; Balogh et al. 1993; Guerrera et al. 1998; de Capoa et al. 2002; Savelli et al. 2007).

The successive Miocene sedimentation is characterized by a high amount of siliciclastic deposits showing evident diachronism proceeding towards the external Adriatic zones. The beginning of the main compressional tectonic phase is indicated by the deposition of the Marnoso-Arenacea Fm. (Miocene *p.p.*). Subsequently, the deformation migrated progressively towards the Adriatic Foreland to culminate in the building of the chain during Messinian–Pliocene times.

The sedimentation rate in the Umbria–Romagna–Marche succession is highly variable. This variability is revealed by the comparison between the Early Jurassic–Early Miocene calcareous–marly group (which characterize the lower part of the succession) and the overlying Miocene siliclastic deposits. In fact, the calcareous–marly succession shows a medium thickness of about 2,500–3,000 m deposited during a period of about 180 Ma (from about 200 Ma to about 20 Ma). This indicates an average low rate of sedimentation with respect to the 3,000-m-thick siliclastic sediments characterizing the entire diachronous clastic wedge deposited only during a period of 9–10 Ma (within the Early Miocene).

The siliclastic deposition reflects a great palaeogeographic and geodynamic change, with the onset of sedimentary processes controlled directly by the evolution of the Apennine Chain and the migration of the related fore-deep system.

The “Bisciaro volcanoclastic event”

The Bisciaro Fm. represents an Early Miocene succession in the Umbria–Romagna–Marche Apennines characterized by a high content of volcanoclastic sediments (Table 1). This volcanoclastic event represents a “marker” that can be easily recognized in other similar successions of the central-western Mediterranean area. The Bisciaro Fm. is composed of limestones, silicified limestones, and marly limestones with frequent volcanoclastic beds. The thickness ranges from 20 m to 100 m in different sectors of the Umbria–Romagna–Marche area, and the age is Aquitanian *p.p.*–Late Burdigalian, ranging from the upper part of the *Globoquadrina dehiscens* biozone to the lower part of the *Globigerinoides bisphericus* biozone (Guerrera et al. 2012a; and references therein) even if the upper boundary of this formation is still undefined. Several radiometric datings can be found in the literature (Balogh et al. 1993; and references therein) in good accordance with the temporal range indicated above.

This formation has previously been studied from different perspectives (Selli 1952, 1967; Mezzetti and Olivieri 1964; Mezzetti 1969; Guerrera 1977, 1979; Borsetti et al. 1984; Coccioni et al. 1988, 1989, 1994; Guerrera and

Veneri 1989; Coccioni and Montanari 1992; Mezzetti et al. 1992; Amorosi et al. 1994; Montanari et al. 1994; Guerrera et al. 1986, 1998; and references therein). The approach used in the present paper consists of a modern classification where volcanoclastic petrofacies correspond to well-identified beds outcropping in the field. Forty-one stratigraphic sections located in different sectors of the study area have been examined (Fig. 2). Sampling was conducted with particular attention to collecting the lithofacies containing volcanoclastic material.

Lithostratigraphy of the Bisciaro Fm.

The stratigraphic record of the Bisciaro Fm. (Table 1; Fig. 2) shows great vertical and lateral lithofacies variability. The changes involve especially the amount and type of volcanoclastic lithofacies and the total thickness of the successions. The main feature concerns the mixing of volcano-derived products related to an intermediate to acidic volcanic composition and coeval marine sedimentation.

In the Umbria–Romagna–Marche area, the Bisciaro Fm. overlies the Scaglia Cinerea Fm. (Bartonian *p.p.*–Aquitanian *p.p.*) and underlies the Schlier Fm., ranging in age from a synchronous Late Burdigalian boundary to a markedly diachronous boundary varying in age from Early Langhian to Early Messinian (Guerrera et al. 2012a). The lower boundary is characterized by the “Raffaello” marker bed that represents the first volcanoclastic bed occurring within the Miocene succession of the Umbria–Marche Basin (Coccioni et al. 1994; Montanari et al. 1994; cum bibl.). It consists of a volcanogenic bentonitic bed (20–40 cm thick) well recognizable at the scale of the whole basin. The upper boundary with the overlying Schlier Fm. is not well defined because the Bisciaro/Schlier transition is very gradual without evident lithofacies changes. For some authors, this boundary corresponds to a very thin marker bed (i.e. the “Piero della Francesca” level), composed of a volcanoclastic clayey deposit attributed to the Burdigalian (about 17 Ma; Deino et al. 1997). However, the basinal extension of this marker bed has not been confirmed, and it cannot represent a lithostratigraphic boundary because: (a) it is not easily detectable; (b) it is discontinuous; (c) no real lithological changes occur below or above this level in the Bisciaro Fm.; and (d) some diluted volcanoclastic materials are also recognizable in the succession overlying this marker bed often considered as belonging to the Schlier Fm. Therefore, it is not possible to correctly define this boundary at the regional scale, and the only valid criterion to distinguish the two formations seems to be the absence of typical volcanoclastic material in the Schlier Fm. that characterize the Bisciaro one (Dubini et al. 1992). The marly Schlier Fm. is characterized mainly by mud turbidites in the internal Umbria–Romagna zone (de Feyter 1991)

Table 1 New field data of the stratigraphic sections (logs) of the Bisciaro Fm.

(N°) Sector: from internal (SW) to external (NE) areas	N° Log	Log location	Coordinates	Outcrop and max. bed thickness (m)	Estimated volcaniclastic supply in each log (%)	Rough estimated epiclastic/pyroclastic ratio	Grain size of volcano-clastites (mm)	Main recognized Sub-petrofacies (cfr. Table 3)
Marsciano (A)	1	SP 57-Pornellese, km 18	42°51'57"N 12°13'48"E	40/0.6	<25	0.3	0.1–0.5	1A, 1C, 3
Città di Castello (B)	2	Monte S. Maria Tiberina	43°27'28"N 12°08'10"E	30/0.7	>75	0.05	0.2–0.8	1A, 1B, 1C, 3 *
Gubbio (C)	3	La Contessa-II Testimone	43°22'59"N 12°33'52"E	23/0.6	50–75	0.2	0.2–0.8	1A, 1B, 1C, 2D, 3 *
Terni-Rieti (D)	4	Località Finocchietto (Terni)	42°27'04"N 12°39'35"E	60/0.15	<25	0.05	0.2–0.5	1A, 1C, 3
Urbania-Pianello-Piobbico (E)	5	Poggio Perugino (Rieti)	42°21'46"N 12°45'45"E	50/0.20	25–50	0.5	0.2–0.6	1A, 1C, 3
	6	Pianello	43°30'09"N 12°35'35"E	60/0.5	25–50	0.2	0.1–0.5	1B, 1C, 3 *
	7	Piobbico	43°35'56"N 12°28'50"E	52/0.4	<25	0.1	0.1–0.4	1B, 1C, 3 *
	8	Orsaiola	43°37'47"N 12°31'59"E	58/0.9	25–50	0.2	0.1–0.6	1B, 1C, 2A, 2B, 3 *
	9	SP Urbania-Piobbico km 5.5	43°38'16"N 12°28'23"E	73/0.5	25–50	0.3	0.1–0.6	1B, 1C, 2A, 2B, 3 *
Arecevia (F)	10	S. Croce d'Arecevia	43°29'28"N 12°55'40"E	42/0.9	50–75	0.1	0.1–0.4	1A, 1B, 1C, 2D, 3 *
Pergola-Tarugo-San Lorenzo in Campo (G)	11	Tarugo-west	43°35'22"N 12°46'56"E	18/0.3	<25	0.1	0.1–0.3	1C, 2A, 3
	12	Tarugo-east	43°35'28"N 12°47'05"E	35/1.3	25–50	0.4	0.1–0.4	1A, 1B, 1C, 2A, 2B, 3 *
	13	Monte Gherardo	43°34'54"N 12°48'13"E	20/0.6	25–50	0.4	0.1–0.35	1A, 1B, 1C, 2A, 2B, 3 *
	14	Monte della Serra	43°35'50"N 12°49'39"E	25/0.9	50–75	0.6	0.1–0.55	1A, 1C, 2A, 2B, 3
Monte Santa Croce	15	Monterolo	43°35'48"N 12°51'23"E	19/1.2	50–75	0.4	0.1–0.45	1A, 1C, 2A, 2B, 3
	16	Monte Santa Croce	43°36'17"N 12°51'21"E	25/0.8	50–75	0.3	0.1–0.4	1A, 1C, 2A, 2B, 3
	17	Monte Rubbio	43°36'34"N 12°53'29"E	18/1.1	50–75	0.5	0.1–0.5	1A, 1C, 2A, 2B, 3
	18	S. Vito sul Cesano	43°36'13"N 12°53'41"E	54/0.8	25–50	0.4	0.1–0.4	1A, 1C, 2A, 2B, 3
Fosso Cupo	19	Fosso Cupo	43°39'47"N 12°48'56"E	100/1.0	50–75	0.4	0.1–0.5	1A, 1B, 1C, 2A, 2B, 2C, 3

Table 1 continued

(N°) Sector: from internal (SW) to external (NE) areas	N° Log	Log location	Coordinates	Outcrop and max. bed thickness (m)	Estimated volcanoclastic supply in each log (%)	Rough estimated epiclastic/pyroclastic ratio	Grain size of volcano-clastites (mm)	Main recognized Sub-petrofacies (cfr. Table 3)
Urbino (H)	20	Mt. Soffio (SS 73bis, km 58)	43°42'18"N 12°34'42"E	20/0.6	25–50	0.4	0.1–0.4	1A, 1B, 1C, 2A, 2B, 3 *
	21	S. Marino d'Urbino	43°43'40"N 12°45'13"E	60/0.8	25–50	0.3	0.1–0.4	1A, 1B, 1C, 2B, 3 *
S. Anna del Furlò- Montevecchio–Cartoceto di Pergola (I)	22	Monte Verde	43°39'36"N 12°45'25"E	17/0.3	<25	0.3	0.1–0.35	1A, 1B, 1C, 2A, 3
	23	Candigliano River	43°39'48"N 12°45'30"E	18/0.35	<25	0.1	0.1–0.35	1B, 1C, 2A, 2B, 3 O *
	24	Montalto est	43°38'58"N 12°49'05"E	40/1.6	50–75	0.6	0.1–0.4	1A, 1B, 1C, 2A, 2B, 2C, 3 *
	25	Tarugo River (Isola di Fano)	43°38'59"N 12°50'04"E	8/0.55	25–50	0.4	0.1–0.35	1A, 1B, 1C, 2A, 3 *
	26	Monte delle Allodole	43°37'18"N 12°50'34"E	19/1.7	50–75	0.6	0.1–0.4	1A, 1B, 1C, 2A, 2B, 2C, 3 *
	27	Monte delle Allodole-Est	43°37'17"N 12°50'57"E	13/1.0	50–75	0.7	0.1–0.35	1A, 1B, 1C, 2A, 2B, 2C, 3 *
	28	Montevecchio-sopra	43°37'17"N 12°51'42"E	13/1.6	25–50	0.6	0.1–0.4	1A, 1B, 1C, 2A, 2B, 2C, 3 *
	29	Montevecchio sotto	43°37'20"N 12°51'43"E	28/1.3	25–50	0.4	0.1–0.35	1A, 1B, 1C, 2A, 2B, 2C, 3 *
Fossombrone (J)	30	Monte Cavallino	43°40'59"N 12°48'51"E	40/1.4	50–75	0.6	0.1–0.4	1A, 1B, 1C, 2A, 2B, 2C, 3 *
	31	Calmazzo	43°40'46"N 12°45'13"E	44/0.6	<25	0.3	0.1–0.6	1B, 1C, 2A, 2B, 3 *
Monti della Cesana (K)	32	Il Sasso-Cava	43°44'15"N 12°38'36"E	46/0.8	25–50	0.3	0.1–0.4	1A, 1B, 1C, 2A, 2B, 3
	33	Le Selve	43°43'27"N 12°40'05"E	13/0.4	50–75	0.5	0.1–0.35	1B, 1C, 2A, 2B, 3
	34	Ca' Dondo	43°43'37"N 12°40'32"E	54/0.8	50–75	0.4	0.1–0.4	1B, 1C, 2A, 2B, 3
	35	Molino del Piano	43°41'59"N 12°40'40"E	97/0.7	25–50	0.3	0.1–0.45	1B, 1C, 2A, 2B, 3
	36	Monte Il Sasso	43°43'53"N 12°44'05"E	41/1.2	50–75	0.4	0.1–0.55	1B, 1C, 2A, 2B, 3
	37	Montebello d'Urbino	43°43'40"N 12°45'13"E	75/1.1	25–50	0.6	0.1–0.5	1B, 1C, 2A, 2B, 2C, 3 *
	38	Monte Romanino	43°43'14"N 12°47'23"E	60/1.0	50–75	0.4	0.1–0.45	1B, 1C, 2A, 2B, 3 *

Table 1 continued

(N°) Sector: from internal (SW) to external (NE) areas	N° Log	Log location	Coordinates	Outcrop and max. bed thickness (m)	Estimated volcanoclastic supply in each log (%)	Rough estimated epiclastic/pyroclastic ratio	Grain size of volcano-clastites (mm)	Main recognized Sub-petrofacies (cfr. Table 3)
Montegui-duccio-Montegaudio (L)	39	Monte Aguzzo	43°42'03"N 12°46'57"E	22/0.8	<25	0.1	0.1–0.6	1B, 1C, 2A, 2B, 3 *
	40	Fontecorniale-La Cava	43°46'01"N 12°48'48"E	70/0.6	50–75	0.3	0.1–0.3	1C, 2A, 2B, 3
	41	Montegaudio	43°47'58"N 12°47'21"E	16/0.9	<25	0.1	0.1–0.35	1B, 1C, 2A, 2B, 3 *

Some information coming from previous literature [Guerrera 1977, 1979; Guerrera et al. 1986; Coccioni et al. 1988; Balogh et al. 1993; Amorosi et al. 1994; and unpublished thesis from University of Urbino: Ciabattoni (1996); Onori (1996); D'Atri (1999); Raffaelli (1999)]. Key: * = "Mega-P"; O = barite nodules

and by prevailing hemipelagic deposits (Dubbini et al. 1992) towards the external Adriatic domain (foreland-ramp deposition).

The Bisciaro Fm. shows an extremely varied lithostratigraphy in both thickness and lithofacies association, depending mainly on the different areal distribution of volcanoclastic materials and palaeotopography of the depositional environment. In different sectors of the northern Marche area, three members have been defined (Guerrera 1977), but these members are not recognizable in all others parts of the Umbria–Romagna–Marche Basin (cf. Geological map sheets of Umbria and Marche; CARG Project-Ispira, Roma, www.isprambiente.gov.it). As pointed out by some authors (Guerrera 1977; Guerrera et al. 1986; Balogh et al. 1993; Amorosi et al. 1994; and references therein), the volcanoclastic content can normally be found as interstratified beds or mixed with the non-volcanic marine deposits. Moreover, a significant part of the volcanoclastic material could be partially to completely altered (especially volcanic glass; Guerrera 1977), not allowing a precise or single petrographic attribution.

Petrography of volcanoclastic deposits

The volcanoclastic supply characterizing the Bisciaro Fm. originated gave rise to a large variety of products and lithofacies. The terminology used in the literature to describe the volcanoclastic products is broad and variable, and different terms are often used for the same products (e.g. field determination and/or petrographic determination).

A petrographic study in thin section (modal counting) of the study samples collected in the stratigraphic sections (Fig. 2) is reported in Table 2 and summarized in Tables 3 and 4. Microphotographs of the main petrofacies recognized in thin section and corresponding to the same petrofacies checked in the field are shown in Fig. 3. Three main types of petrofacies (1, 2, and 3) resulting from eruptive mechanisms together with different depositional processes occurring in marine environment have been recognized. In types 1 and 2, eight sub-petrofacies have been distinguished.

Pyroclastic Deposits: Type 1

This type (more than 85–90 % of volcanic materials) comprises four sub-petrofacies with peculiar characters well recognizable also in the field.

Sub-petrofacies 1A-Vitroclastic/crystallo-vitroclastic tuffs: ash deposits (also called cinerites) that, despite the different features in the field, show homogeneous microscopic and compositional characters. In thin section (Fig. 3), tuffs are composed mainly of a skeletal fraction made up of more than 90 % of volcanic materials and a

Fig. 2 Lithostratigraphy of the “Bisciaro volcaniclastic event” in the Umbria–Romagna–Marche Apennines. Numbers below columns correspond to the stratigraphic sections (logs) studied, as shown in Table 1

scarce non-volcanic fraction (Table 3). The groundmass is composed of very fine-grained components. Glass shards show cusate, X–Y-shaped, platy shapes, bubble-wall types are almost always fresh and frequently oriented and welded in the lower part of the layers; pumice fragments are scarce. In some cases, the lower part of the cinerites show a peculiar enrichment of crystals and lithic fragments (up to 15 %) that can be fully viewed both macroscopically (showing a slight gradation) and microscopically, probably due to a gravity selection during deposition. In this case, the deposit can be better defined crystallo-vitrocastic tuff. The occurrence of smectite in the ash layers causes colour changes from grey to green, making these layers similar to the terrigenous argillaceous beds. Moreover, some fine-grained deposits are interbedded with ash layers.

This sub-petrofacies may be very rich in calcite (Guerrera 1977; Guerrera et al. 1986; Balogh et al. 1993). The reference stratigraphic sections for this petrofacies are “Mt Romanino”, “Montesecco”, “Santa Croce di Arcevia”, “Valdolmo”, “Cantia”, and “Marischio” (Guerrera

1977; Coccioni et al. 1988; Balogh et al. 1993; Amorosi et al. 1994). Some distinctive fine-grained ash layers have been observed in “Cantia” and “Marischio” (Amorosi et al. 1994). Chemical analyses of shards from “Santa Croce di Arcevia” and “Monte Romanino” (Tateo 1993; Morandi and Tateo 1992) indicate a dacitic to rhyolitic composition of the glass.

This sub-petrofacies also includes the so-called Mega-Pyroclastite (“Mega-P”; Coccioni et al. 1988) of the Bisciaro Fm., which is made up of several overlapped cineritic beds representing an evident marker bed at the basin scale (Amorosi et al. 1994).

In the field, this sub-petrofacies is represented normally by silty and well-sorted coarse- to medium-sized sandy beds of variable thickness. About 70 % of ash layers display colour changes from dark grey at the base of the beds to whitish/light grey in the upper portion. These colour variations match with the mineralogical composition of the graded beds, richer in mineral fragments at the base with respect to the top where glass shards predominate.

Sub-petrofacies 1B—Bentonitic deposits: bentonites are widespread throughout the Bisciaro Fm. even if they are thicker in the lower portion of the succession. One of these thicker levels, called the “Raffaello level” (Montanari et al. 1988; Coccioni et al. 1989; Balogh et al. 1993), is well recognizable in the field, and it is normally used as a marker bed of the boundary between Scaglia Cinerea and Bisciaro Fms. Petrography of bentonitic beds (Fig. 3) shows a high content (often more than 90 %) of very fine-grained elements, together with rare crystal fragments rather fresh and secondary calcite (Table 3). This sub-petrofacies has been checked at “Gubbio-La Contessa” (Balogh et al. 1993) and other sites (Coccioni et al. 1994). The “Raffaello” marker bed can be considered the earliest explosive product of the calc-alkaline, intermediate volcanism recorded in the Umbria-Marche area (Coccioni et al. 1989). Diffraction and chemical analyses on some samples of bentonites revealed an almost monomineral composition formed by montmorillonite (often with a high crystallinity index), with a lower amount of opale-CT and clinoptilolite (Mezzetti et al. 1992; Tateo 1993).

In the field, bentonitic deposits show a colour from green to black and bright ochre/reddish-yellowish on weathered surfaces.

Sub-petrofacies 1C—Ocraceous and blackish layers: this sub-petrofacies is constituted by a variable amount of very fine-grained locally oxidized minerals not being solved under the microscope with variable proportions of other components (Table 3). Very rare “exotic” minerals (e.g. muscovite, vesuvianite, and spinel) have been also detected in several stratigraphic sections (Guerrera 1977; Guerrera et al. 1986). The presence of these latter minerals may be explained, considering that the primary volcanic activity affected a crystalline basement area. This basement probably enriched the magma paragenesis. In many samples, interstitial brown glass and glass shards with the original shapes are still identifiable: this feature suggests the presence of an original vitroclastic or vitreous texture of these deposits rich in volcanic glass both as fragments and interstitial material that afterwards have been deeply altered and/or oxidized, and therefore, this deposit lacks texture. Thus, in our interpretation, these levels were originally vitroclastic and crystallo-vitroclastic tuffs now deeply altered.

This sub-petrofacies in the field appears as thin (normally a few centimetres thick, rarely decimetre) reddish-ocraceous, yellowish, greenish, and blackish layers with abundant iron hydroxides, probably due to the alteration of the original volcanic products. Some beds have a marked basal surface, variation in grain size (usually composed by sandy-silty grains) and highly competent without evident internal sedimentary structures (massive bedding).

Resedimented Syn-Eruptive Volcanogenic Deposits: Type 2

This type (from 30 to 90 % of volcanic materials) includes four sub-petrofacies with peculiar features well recognizable also in the field.

Sub-petrofacies 2A—High-density volcanogenic turbidites: this sub-petrofacies (Fig. 3) is constituted by variable amounts of volcanic component and non-volcanic fragments (Table 3). The relative percentages of these components vary within the beds: in fact, the volcanic component decreases upwards, while the non-volcanic component increases. The related sedimentary processes are clearly sediment gravity flows (turbidity currents).

This sub-petrofacies appears in the field as dark grey volcanoclastic beds, 40–60 cm thick, characterized by basal erosive surfaces and graded bedding. The basal interval is characterized by medium-sized sand grains, followed by an interval with thin laminae and by an upper fine-grained massive interval. Sometimes water-escape structures are recognizable.

Sub-petrofacies 2B—Low-density volcanogenic turbidites: in thin sections (Fig. 3), this sub-petrofacies is characterized by predominant volcanic material with respect to the non-volcanic fraction (Table 3). This common sub-petrofacies has been found in many stratigraphic sections as “Fossombrone-Monte Cavallino”, “Fontecorniale-La Cava” (Guerrera et al. 1986), and in the Monti della Cesana sector. These deposits are related to sediment gravity flow processes and appear in the field as graded and laminated beds (coarse to fine sands) with a basal erosional surface, followed by an upper massive interval (fine sand to silt) often bioturbated upwards.

Sub-petrofacies 2C—Crystal-rich volcanogenic deposits: this sub-petrofacies is constituted by crystals and fragments of crystals (up to 2 mm of diameter, very often oriented parallel to the stratification, both fresh or oxidized) that predominate over the other volcanic and non-volcanic fragments. This sub-petrofacies can be found as a single bed or in the lower part of the high-density volcanogenic turbidites. As these deposits are very rich in biotite crystals, they could represent almost the most abundant crystal fragments and have been indicated in the literature as “biotite inputs” (Mezzetti et al. 1992).

This sub-petrofacies is characterized in the field normally by about 40 cm thick clearly graded beds showing an orange yellow colour in the basal part and ocraceous grey in the upper part. These beds consist of coarse sands followed by fine sands at the base and characterized by massive deposits at the top.

Sub-petrofacies 2D—Glauconitic-rich volcanoclastites: this sub-petrofacies (Table 3) is characterized by altered vitroclastic particles, crystal fragments, and lithoclasts (prevalently found at “Contessa–Gubbio”

Table 2 Modal point-counting analysis (in %) of the Early Miocene “Bisciaro volcanoclastic event” studied in many successions of the Umbria–Romagna–Marche Apennines

Sample	N° Log	VI	Petrofacies	VM	GS	PS	Fs	FM	Qtz	VLF	NVM	NVLF	MTX	Ca	OM	Bio
PO4	1	Yellow	1A VT	95.0	88.0	6.0	0.5	–	0.5	–	5.0	–	1.0	3.5	0.5	–
CC3	2	Red	1A VT	94.5	87.0	5.5	1.0	–	1.0	–	5.5	–	1.0	4.0	0.5	–
CO3	3	Purple	1A VT	96.0	87.0	6.0	1.5	–	1.0	0.5	4.0	–	0.5	3.5	–	–
FI2	4	Yellow	1A VT	85.5	72.5	10.5	15.0	–	–	0.5	15.0	–	2.5	12.5	–	–
PP6	5	Pink	1A VT	95.0	85.0	6.5	2.0	0.5	1.0	–	5.0	–	1.5	2.5	1.0	–
SC7	10	Purple	1A VT	95.0	87.0	4.0	1.5	1.5	1.0	–	5.0	–	1.0	3.0	1.0	–
ME7	24	Purple	1A VT	97.0	89.0	4.5	1.5	0.5	1.5	–	3.0	–	0.5	2.0	0.5	–
DO6	34	Purple	1A VT	87.5	69.0	10.5	5.5	2.0	0.5	–	12.5	–	–	5.5	6.5	–
MS1	36	Purple	1A VT	95.0	87.0	5.0	1.5	0.5	–	1.0	5.0	–	1.0	2.0	2.0	–
MS2	36	Purple	1A VT	97.0	90.0	4.5	2.5	–	–	–	3.0	–	1.5	1.0	0.5	–
MR4	38	Purple	1A VT	93.0	85.5	3.5	1.0	1.0	0.5	1.5	7.0	–	2.5	3.5	1.0	–
MB2	37	Pink	1D C-VB	85.0	72.5	10.5	1.5	–	–	0.5	15.0	–	2.5	12.5	–	–
MR1	38	Purple	1D C-VB	85.0	68.0	9.5	4.5	1.5	1.5	–	15.0	–	–	6.5	8.5	–
TE33	12	Pink	2A H-DVT	57.0	37.0	7.5	3.0	3.0	6.5	–	43.0	0.5	24.5	13.0	5.0	–
FC4	19	Purple	2A H-DVT	80.0	70.0	5.5	3.0	0.5	1.0	–	20.0	1.5	4.0	6.0	2.0	6.5
FC9	19	Purple	2A H-DVT	78.0	67.0	6.0	2.0	2.0	1.0	–	22.0	2.5	1.5	7.0	1.0	10.0
MU5	21	Pink	2A H-DVT	53.5	37.5	6.0	4.5	2.0	1.0	2.5	46.5	–	12.5	12.5	6.0	15.5
ME4	24	Purple	2A H-DVT	74.0	57.0	3.5	5.0	2.5	5.5	0.5	26.0	1.5	7.0	7.5	1.5	8.5
SS7	32	Pink	2A H-DVT	68.5	52.5	6.5	4.0	3.5	2.0	–	31.5	0.5	12.5	8.5	2.5	7.5
DO1	34	Purple	2A H-DVT	85.0	74.0	7.5	2.0	–	–	1.5	15.0	–	2.5	5.0	7.5	–
DO2	34	Purple	2A H-DVT	70.0	55.0	3.0	8.5	2.0	0.5	1.0	30.0	5.5	2.5	5.0	–	17.0
DO3	34	Purple	2A H-DVT	55.0	34.5	8.5	7.5	2.0	1.5	1.0	45.0	8.5	1.0	3.5	8.0	24.0
MS3	36	Purple	2A H-DVT	75.0	57.0	5.5	10.5	1.5	0.5	–	25.0	2.5	3.5	7.5	1.5	10.0
MR2	38	Purple	2A H-DVT	87.0	54.5	14.5	8.5	5.0	2.0	2.5	13.0	–	–	3.5	9.5	–
CA2	40	Purple	2A H-DVT	60.5	56.0	–	4.0	–	0.5	–	39.5	–	38.0	–	1.5	–
SC3	10	Purple	2B L-DVT	21.0	18.0	–	2.5	–	–	0.5	79.0	–	35.5	31.5	6.5	5.5
GH56	13	Pink	2B L-DVT	43.0	25.5	1.7	7.1	–	8.7	–	57.0	–	–	38.0	9.3	9.7
CR49	16	Purple	2B L-DVT	12.5	9.0	–	0.5	–	3.0	–	87.5	–	–	50.5	5.0	32.0
MU14	21	Pink	2B L-DVT	47.0	30.5	7.5	6.0	1.5	0.5	1.0	53.0	5.0	18.5	14.0	5.5	10.0
AL5	26	Purple	2B L-DVT	41.0	29.0	2.5	4.0	–	5.5	–	59.0	0.5	–	38.5	8.0	12.0
VS13	29	Pink	2B L-DVT	21.5	14.0	1.5	3.0	0.5	2.5	–	78.5	–	–	50.0	2.5	26.0
MC7	30	Purple	2B L-DVT	20.0	19.0	–	1.0	–	–	–	80.0	–	–	71.0	9.0	–
MC8	30	Purple	2B L-DVT	20.0	17.5	–	2.5	–	–	–	80.0	–	27.0	18.0	10.5	24.5
MC9	30	Purple	2B L-DVT	40.0	34.5	–	4.5	–	–	1.0	60.0	–	26.0	21.0	5.0	8.0
SS11	32	Pink	2B L-DVT	29.5	24.4	1.5	2.0	1.0	0.5	–	70.5	3.5	1.0	43.0	4.5	18.5
MR3	38	Purple	2A L-DVT	45.0	22.0	13.5	8.5	0.5	0.5	–	55.0	9.0	5.5	4.5	4.0	32.0
CA1	40	Purple	2B L-DVT	42.0	32.0	0.5	6.5	0.5	0.5	2.0	57.0	–	24.0	32.0	1.0	1.0
CA3	40	Purple	2B L-DVT	32.0	29.0	–	1.5	0.5	–	1.0	68.0	0.5	27.0	16.5	0.5	23.5
CA4	40	Purple	2B L-DVT	38.5	35.5	–	2.0	–	–	1.0	61.5	–	25.5	31.0	0.5	4.5
CA5	40	Purple	2B L-DVT	24.5	21.5	–	2.0	–	–	1.0	75.5	–	64.5	0.5	2.0	8.5
CA6	40	Purple	2B L-DVT	28.0	9.0	–	10.0	4.0	5.0	–	72.0	4.0	1.0	62.0	–	5.0
MB1b	37	Pink	2C CR	90.0	14.5	4.5	17.0	45.5	5.0	3.5	10.0	0.5	2.0	3.0	4.5	–
MB1t	37	Pink	2C CR	75.0	12.5	5.0	12.5	34.5	4.5	6.0	25.0	2.0	4.5	4.0	3.0	11.5
DO4	34	Purple	3	20.0	8.5	9.0	1.5	0.5	0.5	–	80.0	15.5	5.5	4.5	9.0	45.5

Abbreviations and symbols. N° Log: Log Number (referring to Fig. 2); VI: Volcanoclastic Interval (referring to Fig. 2); VM: volcanic material; GS: glass shards; PS: pumice shards; Fs: feldspars; FM: feric minerals (pyroxene, amphibole, and biotite); Qtz: quartz; VLF: volcanic lithic fragments; NVM: non-volcanic material; NVLF: non-volcanic lithic fragments; MTX: matrix (interstitial fine-grained materials, clay minerals, glass, bioclasts); Ca: carbonates (carbonatic cement-like fissure filling or clast-replaced); OM: other minerals (oxides, silica minerals, and muscovite); Bio: bioclasts, values in percentages. 1A VT = Vitroclastic/crystallo-vitroclastic tuffs; 2A H-DVT = High-density volcanogenic turbidites; 2B L-DVT = Low-density volcanogenic turbidites; 2C CR = Crystal rich; 2D G-RV = Glauconitic-rich volcanoclastites; 3 = Volcanogenic sedimentary deposits

Table 3 Detailed mineralogical composition of the recognized petrofacies

Petrofacies	Sub-petrofacies	Mineralogical composition (<i>in order of decreasing abundance</i>)
Type 1 (Pyroclastic Deposits)	1A	Glass and pumice shards, plagioclase, pyroxene, amphibole, biotite, calcareous and/or siliceous microfossils, rock fragments (mainly porphyric lavas), and matrix of very fine-grained shards, clay minerals, rare micrite
	1B	Vitric particles and lithoclastic grains (altered in smectite), plagioclase, quartz, dark minerals, foraminifers, secondary calcite
	1C	Glass and pumice shards, plagioclase, quartz, clinopyroxene, lithic fragments (aphyric lavas, siltstones, chert), bioclasts, secondary calcite
Type 2 (Resedimented Syn-Eruptive Volcanogenic Deposits)	2A	Glass and pumice shards, plagioclase, clinopyroxene, biotite, lithic (lavas, chert, sedimentary rocks) and bioclastic fragments, secondary calcite
	2B	Glass (unaltered and mainly colourless) and pumice shards, plagioclase, clinopyroxene, biotite, quartz, lava and non-volcanic lithic fragments (siltites, chert, and polycrystalline quartz), bioclasts, spatic calcite and matrix made up of glass, micrite, clay, very fine-grained bioclasts with siliceous shells (mainly diatoms), clays (illite/montmorillonite and montmorillonite)
	2C	Crystals mainly of biotite, plagioclase, clinopyroxene, amphibole, quartz, muscovite, glass and pumice shards, bioclasts (globigerina, globorotalia, sponge spicules, echinoderms, bryozoa, and radiolaria), lithic fragments (siltites, lavas, and chert)
	2D	Glass shards, plagioclase, glauconies, dark minerals (hornblende, biotite altered to chlorite), quartz, rare opaque minerals (mainly magnetite), volcanic lithoclasts (hyalopilitic-pilotaxitic texture and often partly replaced by iron hydroxide), phosphates, fragments of sedimentary rocks and bioclasts
Type 3 (Mixing of Volcaniclastic Sediments with Marine Deposits)	3	Glass and pumice shards (altered in smectite), crystals of plagioclase, quartz, clinopyroxene, dark minerals (hornblende, often replaced by iron hydroxide, and augite), lithic fragments (effusive rocks), brown/blackish rich in foraminifers matrix

The % of different components are shown in Table 2

and “Santa Croce d’Arcevia”; see also Balogh et al. 1993). Glauconies are represented by a transition variety between glauconite and celadonite minerals, forming mixed layers with montmorillonite (20–40 % of montmorillonite). Glauconies also replace foraminifera shells. The volcaniclastic component of these beds is the same as that of the “Raffaello marker bed” (closer to a dacitic composition, based on the greater occurrence of biotite, hornblende).

This sub-petrofacies is recognizable mainly in the field for the high diffusion of greenish colours related to glauconies.

Mixing of Volcaniclastic Sediments with Marine Deposits: Type 3

This type includes some lithotypes characterized by a mixing with a varying content of volcaniclastic supply (from 5 to 30 % of volcanic materials), which is not easily quantifiable macroscopically in the field.

Petrofacies 3—marls, calcareous marls, and marly limestones with volcaniclastic material: this petrofacies includes all the sedimentary deposits related to the marine deposition, which contain a variable amount of

volcanic supply (Table 3), generally between 5 and 30 %. Under the value of 5 %, this volcaniclastic content was not considered. This petrofacies is recognizable in all stratigraphic sections. The volcanic material is similar to that of the previously described petrofacies (Table 3). Associated with the calcareous-marly lithofacies, especially in the lower part of the Bisciaro Fm., blackish silicifications (often in lens) are widespread and constituted by different phases of silica (cristobalite, opal-CT, and opal-A), calcite (30–75 %), and small amounts of minerals (quartz, smectite, feldspars, and very fine-grained mafics).

In the field, this petrofacies normally characterizes the Bisciaro succession and is well distinguished by typical volcaniclastic sediments. This petrofacies represents the result of the dilution of the volcaniclastic supply within the marine sedimentation that must be considered as regards the quantitative evaluation of the total volcaniclastic supply. Deposits are normally greyish and show a thin lamination. Sometimes clayey and clayey-sandy volcaniclastic layers, typically ocreaceous, brownish, greenish, and blackish and frequently rich in organic matter (bituminous thin levels), are also interbedded.

Table 4 Location and main features of the coeval Late Oligocene–Early–Middle Miocene volcanoclastic deposits related to the “Bisciaro volcanoclastic event” in the Apennines, Maghrebids, and Betics, after Bonardi et al. (2003); Borsetti et al. (1984); Boulín et al. (1973); Carnisciano et al. (1989); Clari et al. (1988, 1994); Critelli and Le Pera (1990); Critelli and Monaco (1993); D’Atri and Tateo (1994); De Capoa et al. (2002 cum bibl.); Delle Rose et al. (1994a, b); Di Staso and Giardino (2002); Faugères et al. (1992); Fontana (1980); Guerrera (1981/1982); Guerrera et al. (1998, 2004, 2005 cum bibl.); Mattioli et al. (2000); Mezzetti and Olivieri (1964); Mezzetti et al. (1992); Papini and Vannucci (1993); Perri et al. (2012); Perrone (1987); Rivière and Courtois (1975); Rivière et al. (1981); Ruffini (1995); Santo and Senatore (1992); Soria et al. (1992); Zaghoul et al. (2002)

Sector	Formation	Age	Volcanic rocks	Volcanoclastic bed Type, %/vol, TV, TB, MT (metres)	Sedimentary processes and related deposits
Betic Cordillera	Víñuela Group (Internal domain)	Early Burdigalian	Andesite, rhyolite-rhyodacite fragments	Mainly crystals and glass shards; TV: 45; TB: 3; MT: 0.5	Fallout—pyroclastites; sediment gravity flow (turbidity currents)—epiclastites, volcanoclastic arenites
	Algeciras Flysch (Internal MFB)	Aquitanian Burdigalian <i>p.p.</i>	Andesite, rhyolite fragments	Felsitic lava clasts and crystals (up to 7 vol%)	Sediment gravity flow (turbidity currents)—epiclastites, volcanic arenites
	Almidar, Río Fardes-Mencal (Subbetic; External domain)	Early Burdigalian	Rhyodacite–rhyolite fragments	Glass shards, crystals; MT: 0.25	
	Sidi Abdeslam–Boujarrach (Internal domain)	Early Burdigalian	Andesite, basalt	Mainly crystals, TV: 10; TB: 0.5; MT: 0.15	
	Beni Ider Flysch (Internal MFB)	Late Aquitanian Early Burdigalian	Andesitic–basaltic lavas fragments	Lava clasts	
Rifian Chain	Talaa Lakra (Mixed Successions; MFB)	Late Aquitanian–Early Burdigalian			
Algerian Tell	Oligo-Miocène Kabyle (Internal domain)	Burdigalian <i>p.p.</i> (19.1 ± 1.0 Ma)	Rhyolitic fragments	Crystals, glass shards	
Sicily	Tusa Flysch (Internal MFB)	Burdigalian <i>p.p.</i>	Andesite to dacite fragments	Mainly lava clasts (80–85 vol%), grain size up to 2.5 mm; TV: 600; TB: 200; MT: 1.5–2	
	Troina Sandstones (Internal MFB)	Burdigalian <i>p.p.</i>	Andesite fragments	Up to 40 % volcanic clasts, grain size > 2 mm; TV: 150, TB: 30–40; MT: 0.5–1	
	Poggio Maria Sandstones (Internal MFB)	Burdigalian <i>p.p.</i>	Volcanic glass andesite to dacite fragments	Lava clasts, crystals (30–35 vol%), grain size > 2 mm; TV: 200; TB: 30–35; MT: 0.5–1.5	
	Mixed Successions (MFB)	Late Aquitanian–Early Burdigalian	Rhyolite, andesite, basalt fragments	Mainly lava clasts, grain size > 2 mm, TV: 43; MT: 1	
	Numidian Flysch (External MFB)	Aquitanian <i>p.p.</i> –Early Burdigalian	Andesitic–basaltic fragments	Glass shards, crystals, pumices and lava clasts, TV: 20	
Calabria-Peloritani Arc	Stilo-Capo d’Orlando	Late–Middle Burdigalian		Lava clasts	
	Paludi	Late Oligocene–Early Miocene	Andesitic–basaltic fragments; crystals	Lava clasts, crystals (pheno-andesitic and pheno-quartz andesitic tuffites)	

Table 4 continued

Sector	Formation	Age	Volcanic rocks	Volcaniclastic bed Type, %/vol, TV, TB, MT (metres)	Sedimentary processes and related deposits
Southern Apennines	Calabro-Lucano Flysch (Liguride Complex)	Late Oligocene	Andesite, basalt, rhyodacite fragments	Lava clasts, crystals, glass shards (pheno-andesite, pheno-quartz. andesite, tuffites), MT: 1.5	
	Saraceno (Liguride Complex)	Early Miocene	Andesite to dacite fragments; crystals	Lava clasts, crystals (pheno-andesite, pheno-quartz andesite tuffites)	
	Tusa Tuffites (Sicilide Complex; (Internal MFB)	Burdigalian	Andesite to dacite fragments	Clasts, crystals (80 vol%) pelites with crystals, pumices, glass shards; TV: 54; TB: 46; MT: 5	
	Numidian Flysch (External MFB)	Late Burdigalian -Early Langhian	Rhyolite	Glass shards, crystals, pumices, lava clasts	Fallout-pyroclastites
	Pollica/upper member (Cilento Group)	Burdigalian-Langhian	Rhyolitic-rhyodacitic fragments	Lava and tuff clasts, MT: 3	Sediment gravity flow (turbidity currents)-epiclastites, volcaniclastic arenites
Northern Apennines	Roccadaspite (Daunia Complex; External Apennines)	Late Burdigalian -Langhian <i>p.p.</i>	Andesitic and/or basaltic fragments	3–15 vol% of lava clasts, crystals, glass shards clasts; MT: 5	Fallout-pyroclastites; sediment gravity flow (turbidity currents)-epiclastites, volcaniclastic arenites
	Macchialupo-Serra Funaro Basin? (Daunia Complex; (External Apennines)	Burdigalian <i>p.p.</i>		Lava clasts (70–90 vol%) TV: 80; MT: 4	Sediment gravity flow (turbidity currents)-epiclastites, volcaniclastic arenites
	Tripoli di Contignaco (Epiligurides)	Aquitanian-Burdigalian <i>p.p.</i>	Rhyodacitic-dacitic fragments	Glass shards (<90 vol%), crystals (grain size <0.5 mm); TV: 15; TB: 15; MT: 10	Fallout-pyroclastites; and/or sediment gravity flow (turbidity currents)-epiclastites, hyaloclastic, volcaniclastic arenites
Northern Apennines (Adria Margin)	Bisciaro Group	Aquitanian <i>p.p.</i> -Burdigalian <i>p.p.</i> (22.4 Ma)	Andesite, rhyolite	Glass shards, crystals, holo-Crystalline to felsitic-vitric lava clasts TV: >100; TB: 18; MT: 6.9	
	Cervarola (Cervarola Unit-Tuscan Nappe)	Aquitanian <i>p.p.</i> -Burdigalian <i>p.p.</i> ?	Different Lavas (rhyolitic prevalent)	Great amount of glass shards (altered in analcime and zeolite) crystal-vitric tuffs, TV: 80; TB: 10; MT: 6	Sediment gravity flow (turbidity currents)-epiclastites, volcaniclastic arenites
Northern Apennines	Vicchio Marls (Cervarola Unit-Tuscan Nappe)	Late Aquitanian-Burdigalian <i>p.p.</i>	Rhyolitic-dacitic fragments	Lava clasts, crystals and glass shards TV: 450; MT: 0.3	
	Bagni S. Agostino, Manciano (Tuscan Nappe)	Burdigalian	Basaltic-andesitic fragments	TV: 200	
	Antognola, M.te Zuccaro, Rigoroso, Pteropodi Marls, P. da Cantoni Gr., T. Calcareni	Late Oligocene-Burdigalian	Trachytic composition (transitional alkaline)	90 vol% of glass shards, crystals glass (ash layers), TV: 50; MT: 10	Fallout-pyroclastites; sediment gravity flow (turbidity currents)-epiclastites, volcaniclastic arenites

Table 4 continued

Sector	Formation	Age	Volcanic rocks	Volcaniclastic bed Type, %/vol, TV, TB, MT (metres)	Sedimentary processes and related deposits
Sardinia Trough	Villanovaforru Succession–Marmilla Basin	Burdigalian	High-Mg basalt (transitional tholeiitic)	Great amount of volcanic detritus, TV: 640; TB > 10; MT: 0.6	
Unit 3 (DSDP, Leg 13)	Internal domain	Late Aquitanian–Early Burdigalian (21 ± 2 Ma)	?	–	Fallout–pyroclastites

TV, stratigraphic interval (m) containing volcanogenic deposits; TB, total thickness (m) of volcaniclastic beds in a single succession; MT, maximum thickness (m) of volcanogenic beds

Discussion

Correlation of the “Bisciaro volcaniclastic event”

The importance of the “Bisciaro volcaniclastic event” of the Umbria–Romagna–Marche Apennines is demonstrated by the possibility of correlating this event among different sectors of Apennine, Maghrebian, and Betic Chains, where similar and contemporaneous volcaniclastic deposits occur. The coeval volcaniclastic deposits show similar petrofacies (Table 4) even if they can be interbedded within different lithologic successions.

With the aim of reconstructing the vertical and lateral distribution of these volcaniclastic deposits and making a correlation, different Early Miocene formations have been considered in the southern Alpine central-western peri-Mediterranean area. Table 4 lists the main features of volcaniclastic deposits and sedimentary processes.

The extent of the recognized “volcaniclastic event” at a regional scale indicates that in the Early Miocene, major geodynamic processes affected the central-western Mediterranean area. Moreover, the abundance of volcaniclastic deposits, their features, and distribution indicates a great diffusion of active volcanic centres during this temporal range. This implies the necessity of recognizing their location to reconstruct a palaeogeographic and palaeotectonic picture of the portion of the Mediterranean region considered.

Meaning of the “Bisciaro volcaniclastic event”

On the basis of the above-reported features, some main considerations arise concerning the meaning of the “Bisciaro volcaniclastic event”.

- In contrast to previous interpretations, the Bisciaro Fm. represents the result of the deposition related mainly to volcanic activity occurring contemporaneously to the marine sedimentation during the Early Miocene. In fact, the hemipelagic marine deposits seem to be subordinated with respect to the volcaniclastic content, especially considering the widespread alteration processes (mainly calcification) subtracting high amounts of the original volcanic supply.
- The “Bisciaro volcaniclastic event” constitutes a significant episode among many other ones strictly linked to the wide Early Miocene primary volcanic activity that is not easy to locate but occurred in the central-western Mediterranean region in areas involved in the orogenic chains during Miocene times.
- The recognized depositional processes controlling the volcaniclastic material are represented by: (a) fallout and/or pyroclastic flows originating pyroclastic depos-

its (Types 1 and 3; Table 4) and (b) sediment gravity flows (turbidity currents) generating the volcanoclastic sediments (Types 2 and 3; Table 4). In addition, the volcanoclastic sedimentation is often represented by fine-grained ash layers, generally altered to clay minerals originating from pyroclastic and/or epiclastic deposits (Type 1: 1B and 1C and Type 3; Table 3), after their primary emplacement.

4. Even if it is not easy to define the % ratio of different kinds of volcanoclastic sediments, a rough estimation has been made in each stratigraphic succession studied (Table 1). On the basis of this evaluation, a moderate prevalence of pyroclastites with respect to epiclastites is recognizable. These results do not confirm what was assumed by Amorosi et al. (1994), who considered the volcanoclastic deposition to be exclusively the result of re-sedimentation processes. Meanwhile, other authors (Selli 1952; Borsetti et al. 1984; Mezzetti and Olivieri 1964; Mezzetti 1969; Mezzetti et al. 1992; among others) considered the pyroclastic supply to be the only type of sedimentary contribution.
5. Normally, the grain size of volcanoclastic products ranges between silt and medium- to coarse-sized sands (Table 1), implying some constraints in the reconstruction of the distance between volcanoes and sedimentary basins. Unfortunately, on the basis of our data, it is not possible to recognize the eruption styles, volcanic forms, or environment. However, the maximum grain size of the pyroclastic sediments indicates depositional areas located near the volcanic centres. By contrast, the grain size is not significant for the volcanogenic turbidites deposits because these are controlled by specific characters of related depositional processes.
6. Considering the correlations of the “Bisciaro volcanoclastic event” across the Apennines, Maghrebids, and Betics, it is necessary to identify the remnants of coeval volcanoes along these chains that are characterized by chemical affinity and located in a compatible palaeogeographic framework with respect to the distance from the depositional areas.

Volcanoclastic supply and depositional processes

Field data, stratigraphy, and petrofacies features indicate that the main processes of emplacement of volcanoclastic materials in the Bisciaro depositional area (Table 5) are represented by: (a) fallout (pyroclastic processes) and (b) sediment gravity flows (turbidity currents and epiclastic processes). The pyroclastic processes are controlled mainly by two main factors: (1) the amount of pyroclastic products during volcanic eruptions and (2) the distance of volcanic centres with respect to the sedimentary basin. The epiclastic processes imply the remobilization of volcanic material

due to more or less diluted turbidity currents probably controlled by syn-sedimentary tectonics and topographic features. The palaeotopography of the depositional area was probably irregular with the presence of deep and shallow zones as pointed out by Guerrera (1977). These irregularities together with the variability of sedimentary processes normally cause a short lateral continuity of the volcanoclastic beds even if some pyroclastic deposits show a basal correlation of up to 5 km (e.g. Fossombrone sector) and much more for the “Raffaello” and the “Mega-P” marker beds (Table 1; Fig. 2). The volcanoclastic supply is laterally highly variable, and a rough evaluation has been made in all the stratigraphic sections (Fig. 2).

Furthermore, the frequency of pyroclastites, the substantial correspondence between radiometric and biostratigraphic ages, the similar chemistry between pyroclastic and epiclastic products, and the freshness of volcanic glass and various other crystals and minerals demonstrate that volcanic activity and marine sedimentation were contemporaneous.

All mineralogical–petrographic and geochemical data of volcanoclastic deposits, when the literature is taken into account, imply an intermediate to acid volcanism for the source areas. This type of volcanism prompts considerations on the palaeogeographic location and distribution of volcanic systems. Generally, pyroclastic deposits provide little information on the distance between volcanoes and basins because the volcanic particles are transported by wind for long distances, and only the thickness and grain size of beds can provide more useful indications. Moreover, epiclastic deposits (turbidites) imply more palaeogeographic constraints because the expansion of mass flow processes along great distances needs a suitable palaeotopography characterized by a depositional environment without intra-basinal barriers (e.g. a building chain).

Geodynamic context

The abundance and the broad distribution of the volcanoclastic material resulting from this event imply a contemporaneous development of calc-alkaline magmatism from volcanic arc systems in different Mediterranean sectors. This primary volcanic activity occurred between 24 and 17 Ma (Late Oligocene–Early Miocene, Table 5). It is difficult to have more information about the type of volcanoes and eruptive style because volcanoes rarely crop out and at present the related products form part of orogens. Nevertheless, petrographic data from the Bisciaro volcanoclastic deposits indicate a calc-alkaline volcanism characteristic of continental subduction zones (Andean-like). This kind of volcanism is usually related to Plinian-like eruptions and stratovolcano forms (Mahlburg-Kay and Ramos 2006). Each depositional area, of those at present in different

Fig. 3 Optical microphotographs of some representative samples from volcanoclastic deposits of Bisciaro Fm. **a, b** Vitroclastic Tuff (Petrofacies 1A) from SP 57-Pornellese section: prevalent colourless glass shards with variable morphologies (platy, cusped, and bubble) and subordinate crystal fragments (plagioclase). This sample displays a high calcite content. **a** Plane-polarized light, **b** cross-polarized light, base of the photographs 1.25 mm. **c** Vitroclastic Tuff (Petrofacies 1A) from Montalto Est section: longitudinal section of a pumice shard that displays elongated parallel vesicles characteristic of vesiculation during magmatic eruptions. Plane-polarized light, base of the photograph 1.25 mm. **d, e** Crystallo-Vitroclastic Tuff (Petrofacies 1A) from Poggio Perugino section: abundant glass shards with crystal fragments and lithoclasts. **d** Plane-polarized light, **e** cross-polarized light, base of the photographs 1.25 mm. **f** Blackish layer (Petrofacies 1C) from Monte Cavallino section: glass shards are still well recognizable in the fine-grained oxidized matrix. Plane-polarized light, base of the photographs 2.5 mm. **g–i** High-density volcanogenic turbidite (Petrofacies 2A) from Ca' Dondo (**g**) and Tarugo Est (**h, i**) sections: abundant glass shards and bioclasts and minor amounts of lithic and crystal fragments (**g**) and prevalence of crystals and lithic fragments (**h, i**). **g, h** Plane-polarized light, **i** Cross-polarized light, base of the photographs 1.25 mm. **j, k** Low-density volcanogenic turbidite (Petrofacies 2B) from Fonte Corniale-La Cava section: abundant fine-grained matrix rich in glass shards, crystals, and lithic fragments. **j** Plane-polarized light, **k** cross-polarized light, base of the photographs 1.25 mm. **l** Crystal-rich volcanogenic deposit (Petrofacies 2C) from Montebello d'Urbino section: abundant crystals and crystal fragments, glass shards, and lithic fragments. Plane-polarized light, base of the photographs 1.25 mm. **m** Marl with volcanoclastic material (Petrofacies 3) from Orsaiola section: abundant glass shards and scarce crystals (plagioclase, quartz, and dark minerals), lithic fragments, and bioclasts in a very fine matrix. Plane-polarized light, base of the photograph 2.5 mm. **n, o** Marl with volcanoclastic material (Petrofacies 3) from Finocchietto locality (Terni) section: very abundant glass shards and scarce crystals of fresh plagioclase and quartz. **n** Plane-polarized light, **o** crossed-polarized light, base of the photographs 2.5 mm

chains, was linked to a related volcanic system. In fact, it would hardly be possible for only one volcanic arc to feed all Early Miocene peri-Mediterranean basins. Moreover, it is necessary to consider the different palaeogeographic and geodynamic contexts in which volcanic systems arise.

1. *Iberian margin*. The andesite, rhyolite-rhyodacite volcanism of the Internal Betic Zone could be related to internal subduction and thrusts in the Mesomediterranean Microplate but also to the opening of back-arc basins (Martín-Algarra 1987). The Valencia Trough is related to an “aborted rift” formed before the Early Miocene opening of the western Mediterranean Sea, leading to the Iberian Range (Maillard and Mauffret 1993) and to the present location of the Balearic Islands, which began to separate from the Iberian Peninsula in the Early Miocene (Arias et al. 2004) giving rise to a related volcanism. On the other hand, the External Betic Zone rhyodacite-rhyolite volcanism is related to the development of a main transform fault (Intra-Subbetic fault; Soria et al. 1992). Late volcanism (Middle Miocene) related to the Mediterranean

Sea opening is recognizable in the “Cabo de Gata” area (Zeck et al. 2000).

- African margin (Rifian Chain)*. The andesitic and basaltic volcanism (Guerrera 1981/82; Zaghloul et al. 2002) appears to be related to the northward subduction of the African Plate beneath the southern margin of the Mesomediterranean Microplate.
- African margin (Algerian Tell)*. The rhyolitic explosive phase (Monié et al. 1992) is probably connected to a northward subduction of the African Plate (Rehault 1981) beneath the southern margin of the Mesomediterranean Microplate.
- Maghrebian Flysch Basin*. In Sicily and Calabria-Peloritani Arc, mainly andesitic to dacitic and also rhyolitic volcanism has been detected (Balogh et al. 1993; de Capoa et al. 2002; Bonardi et al. 2003; Guerrera et al. 2005; Perri et al. 2012). This volcanism is probably connected with the northward subduction of the African Plate beneath the southern margin of the Mesomediterranean Microplate but also to the opening of back-arc basins.
- Adria margin (Apennines)*. The volcanism recognized could be related to the westward subduction of Adria Plate even if this volcanism is considered to have high diffusion, since at present it has been found only in a few places. Two deep wells, called Mortara 1 on the Po Plain (Cassano et al. 1986) and Pieve S. Stefano 1 in the Central Apennines (Anelli et al. 1992), were drilled into Oligocene–Miocene volcanites. In Mortara 1, the available data show the presence of Early–Middle Miocene andesitic lavas of 16.1–20.9 Ma (Bonci et al. 1994) and Oligocene–Miocene andesitic to dacitic lavas (Ruffini 1995; Mattioli et al. 2002). The volcanic effusive rocks drilled at Pieve S. Stefano 1 consist of andesitic lavas of uncertain age (Oligocene–Miocene; Anelli et al. 1992). The easternmost volcanoes that have been hypothetically located above the Adria continental margin (Fig. 4) are related to the continental collision between Adria and the Mesomediterranean Microplate after the consumption of the oceanic crust of the Calvana-Lucania Basin. This collision involves the inversion of the subduction from west to east dipping direction with the continental crust of the Mesomediterranean Microplate subducting below the Adria Microplate in the last stage of subduction zone transference during the accretion of the Apennine Chain. A modelling of this type of deformation has been recently presented by Simakin (2014).
- European margin (Sardinia Trough)*. The high-Mg basalt (transitional tholeiitic) volcanism (Mattioli et al. 2000) and the volcano-sedimentary successions (Assorgia et al. 1997; Guerrera et al. 2004) are presumably connected with the volcanic activity from the

Table 5 Volcaniclastic petrofacies and recognized depositional processes of the “Bisciaro volcaniclastic event”

Petrofacies	Sub-petrofacies	Depositional processes of volcaniclastic material
Type 1 Pyroclastic Deposits	1A: Vitroclastic/crystallo-vitroclastic tuffs (Ash layers, Cinerites)	Fallout and/or pyroclastic flows
	1B: Bentonitic deposits	Weathering of fallout volcanic ash
	1C: Ocraceous and blackish layers	Alteration of volcanic products
Type 2 Resedimented Syn-Eruptive Volcanogenic Deposits	2A: High-density volcanogenic turbidites	Sediment gravity flow processes (turbidity currents)
	2B: Low-density volcanogenic turbidites	Sediment gravity flow processes (turbidity currents)
	2C: Crystal-rich volcanogenic deposits	Sediment gravity flow processes (turbidity currents)
	2D: Glauconitic-rich volcaniclastites	Sediment gravity flow processes (turbidity currents)
Type 3 Mixing of Volcaniclastic Sediments with Marine Deposits	3: Marls, calcareous marls, and marly limestones with volcaniclastic material	Fallout mixing with marly calcareous marine sedimentation

opening of the Sardinia Trough during the drift rotation of the Sardinia–Corsica Block.

Sardinia has often been proposed as the source area for the Apennine volcaniclastites, as recently reported by Perri et al. (2012). However, the location of Sardinia during the Late Oligocene–Early Miocene would not agree with results of our study and in particular with the presence of epiclastic processes because Sardinia was palaeogeographically located too far from the Umbria–Romagna–Marche sedimentary basins (Fig. 4). In particular, the distance between Sardinia and basins in the reconstructed palaeogeographic framework (Fig. 4) is estimated to be several hundred kilometres. Moreover, the epiclastic processes (turbidites) from Sardinia would have been prevented by the complex palaeogeography of the western Mediterranean region in the time span considered (Dewey et al. 1989; Doglioni 1992; Guerrera et al. 1993, 2005, 2012b; Maillard and Mauffret 1993; de Capoa et al. 2002; among others). A possible relationship with Sardinia volcanism can be invoked only for thin and very fine-grained volcaniclastic pelites (fallout processes) deposited between 22–20 and 17–13 Ma, when a large volume of ignimbrites and fallout deposits developed in Sardinia (Assorgia et al. 1997).

The Sardinia Trough exemplifies an important fossil record of a small distance between primary volcanic centres and depositional areas. Our studies on the tectono-sedimentary evolution of this trough (Mattioli et al. 2000; Guerrera et al. 2004) point to volcano-sedimentary successions deposited in marine basins near 50–100 km from the primary remnants of volcanic sources. This may be a reference evolutionary model also for the Bisciaro depositional areas that therefore could not be fed by the Sardinia area, as

indicated by previous authors. Therefore, most of the Late Oligocene–Early Miocene volcaniclastic material dispersed throughout the Apennines, Maghrebides, and Betides were erupted by volcanic source vents located closer than Sardinia. In fact, available data seem to indicate the existence of calc-alkaline volcanic arc systems adjacent to the depositional area of the Bisciaro Fm. and located in an internal position with respect to the basins themselves.

Palaeotectonic and palaeogeographic reconstructions of the central-western Mediterranean region during the Late Oligocene–Aquitian and Burdigalian–Langhian times evidence the presence of a microplate (Mesomediterranean Microplate) located between the European and African Plates (Doglioni 1992; Guerrera et al. 1993, 2005, 2012b; among others) and bordered northwards by a transform fault separating from the European margins (Guerrera et al. 2012b; Alcalá et al. 2013) and southward by another oceanic area called the Maghrebian Flysch Basin–Lucania Basin (de Capoa et al. 2003; Perrone et al. 2008; and references therein).

On the basis of both transport and sedimentation processes recognized for the volcaniclastic sediments of the “Bisciaro volcaniclastic event”, and the short distance and the palaeogeography between volcanic areas and the sedimentary basins (Guerrera et al. 1993, 2005, 2012b, Guerrera and Martin-Martin 2014; Alcalá et al. 2013), the main volcanism affecting the Bisciaro depositional area should probably be located along the external active margins of this Microplate and/or, in a late evolutionary stage, along the suture zone between the Adria Plate and the Mesomediterranean Microplate (Fig. 4) in a way different from that indicated previously by Critelli et al. (2013) who located volcanic arcs only in Sardinia.

Fig. 4 Palaeogeographic and geodynamic model of the central-western Mediterranean area showing the relationships between volcanic systems and sedimentary basins. Volcanoes located on Adria Margin

activated during the continental collision stage after the closure of the Calvana–Lucania Basin

Intense volcanism should be located also on the southern external margin of the Mesomediterranean Microplate, which deformed starting from the Aquitanian–Burdigalian when the adjacent sedimentary basins located in more external position (Tusa Flysch Fm. in the southern Apennines and Sicily correlate with the Flysch along North Africa and the Betic Cordillera), were affected by a marked volcanoclastic supply (Table 5; Fig. 4).

Late Oligocene–Early Miocene primary volcanoes might have undergone quick erosional processes and/or subsidence, and remnants of volcanic bounding could also have been buried and concealed in depth by underthrusting during the post-Early Miocene tectonic evolution (e.g. central Apennines, Pieve S. Stefano 1 and Mortara 1 wells). In addition, the volcanic activity could have

occurred along major strike-slip faults affecting the plate margin convergence (Sylvester 1988). The Late Oligocene–Early Miocene kinematic evolution of the central-western Mediterranean (Dewey et al. 1989) could have accounted for short-lived volcanoes linked to a dominant transform-related tectonics. Thus, part of the eruptive centres located along these faults constituted transient volcanic systems above a tectonic mobile substratum.

Conclusions

The above-reported considerations allow some main constraints to reconstruct the relationships between volcanoclastic supply and depositional sites of the “Bisciaro

volcaniclastic event” and at the same time imply many considerations for the reconstruction of the geodynamic evolution of the central-western Mediterranean region during the Early Miocene.

The main conclusions are as follows:

1. The Early Miocene “Bisciaro volcaniclastic event” is recorded within a succession recognized in the Umbria–Romagna–Marche Apennines in which the start of the volcaniclastic supply is marked by the Aquitanian “Raffaello” marker bed. The volcaniclastic event ends in the Late Burdigalian–Early Langhian within the lower part of the Schlier Fm.
2. In the “Bisciaro volcaniclastic event”, three types of petrofacies have been recognized (Tables 1, 2, 3, 5):
 - *Type 1 Pyroclastic Deposits*, including three sub-petrofacies: 1A, Vitroclastic/crystallo-vitroclastic tuffs; 1B, Bentonitic deposits; and 1C, Ocraceous and blackish layers.
 - *Type 2 Resedimented Syn-Eruptive Volcanogenic Deposits*, including four sub-petrofacies: 2A, High-density volcanogenic turbidites; 2B, Low-density volcanogenic turbidites; 2C, Crystal-rich volcanogenic deposits; and 2D, Glauconitic-rich volcaniclastites.
 - *Type 3 Mixing of Volcaniclastic Sediments with Marine Deposits* constituted by marls, calcareous marls, and marly limestones containing volcaniclastic material.
3. Two main depositional processes of the volcaniclastic material have been recognized: (a) fallout and/or pyroclastic flows and (b) sediment gravity flow (turbidity currents). However, a slight predominance of the fallout deposition has been indicated.
4. The Bisciaro succession results from a mixing of volcaniclastic materials coming from strong volcanic activity with contemporaneous hemipelagic marine deposits during the Early Miocene. The volcaniclastic material is linked strictly to the coeval primary volcanic activity, the volcaniclastic products being well correlated with many others across the central-western Mediterranean area. Thus, this volcaniclastic event can be considered as a regional marker useful for palaeogeographic reconstructions.
5. The high amount of volcaniclastic materials points to the occurrence of different contemporaneous volcanic systems near the sedimentary basins with disparate specific geodynamic contexts, as attested to by acid (dacitic, rio-dacitic, rhyolitic, etc.) to acid-intermediate (basaltic, andesitic, etc.) volcanic products of a calc-alkaline volcanism, presumably connected to a subduction zone. The subduction firstly occurred between the

oceanic crust of the Calvana Basin beneath the Mesomediterranean Microplate (Andean-like subduction). With the closure of this basin and the complete consumption of the oceanic crust, a continental collision developed with a subduction towards the east of the continental crust of the Mesomediterranean Microplate beneath the Adria Margin.

6. The scarcity of remnants of products related to primary volcanic activity is probably due to the following factors: (a) these products could have been buried and concealed in depth by thrusting processes during the post-Early Miocene tectonic evolution (e.g. Apennines and Po Plain); (b) the “cannibalization” of primary volcanoes during subduction activity; (c) a quick erosion of the inconsistent explosive volcanic centres; and (c) the tectonic mobility due to strike-slip faults along which the volcanic activity occurred. In fact, the kinematic evolution of the central-western Mediterranean (Dewey et al. 1989) could have accounted for short-lived volcanoes prevalently linked to transform zone tectonics.
7. The Late Oligocene–Early–Middle Miocene palaeogeographic-palaeotectonic model of the central-western Mediterranean area (Fig. 4) can explain the data compiled in relation to the presence of a microplate (Mesomediterranean Microplate) located between the European and African Plates. Taking into account the transport and sedimentation processes recognized for the volcaniclastic material, the primary volcanic systems must be located along the external (southern) active margins of the Mesomediterranean Microplate and probably also on the internal margin of the Adria Plate. The volcanism was probably related to the westward subduction of the Calvana Basin and the successive continental collision between the Mesomediterranean Microplate and Africa-Adria Plate. At the same time, a strong volcanism developed along the rifting of the Valencia Basin caused by the extension-related drifting-rotation of the Corsica–Sardinia Block also determining the intense volcanic activity of the Sardinia Trough.
8. The data gathered imply that the distance between volcanoes and depositional area of the “Bisciaro volcaniclastic event” must be less than 100 km, and in some cases, the volcanic centres could be located directly on the basin margin.
9. The Early Miocene reconstruction of the palaeogeographic and geodynamic relationships between volcaniclastic deposits and volcanoes of different sectors in the central-western peri-Mediterranean region is complex (Guerrera et al. 1998; cum bibl.). However, some identified Late Oligocene–Early Miocene primary volcanic products (e.g. Pieve S. Stefano 1 drilling; Anelli et al.

1992; Mortara 1 drilling; Cassano et al. 1986; Bonci et al. 1994; Sardinia; Mattioli et al. 2000; Guerrero et al. 2004; Valencia Through; Maillard and Mauffret 1993; Algeria; Monié et al. 1992; and discussion in Guerrero et al. 1998) may explain the presence of volcanoclastic products in different considered palaeogeographic context that are related to the various geodynamic settings of the peri-Mediterranean chains considered.

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