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Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **88 (1995)**

Heft 2

PDF erstellt am: **22.05.2024**

Persistenter Link: https://doi.org/10.5169/seals-167678

Eclogae geol. Helv. 88/2: 347-363 (1995)

0012-9402/95/020347-17 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

Ash layers in the Monferrato (NW Italy): Records of two types of magmatic source in Oligocene-Miocene time

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Key words: Ash layers, Oligocene-Miocene, rhyolitic magmatism, trachytic magmatism, Monferrato, North-Western Italy

ABSTRACT

The mode of occurrence, biostratigraphy (planktonic foraminifers and calcareous nannofossils), petrography, mineral chemistry and zircon typology of ten volcanic ash layers recently discovered in Monferrato (NW Italy) are described. Two compositionally different types of tephra layers, mainly composed of vitric tuffs, were recognized: a) trachytic vitric tuffs, almost completely altered to Ba-zeolites, suggesting a mildly alkaline magmatic source, and b) rhyolitic vitric tuffs derived from a calc-alkaline magmatic source. The biostratigraphical data referred the trachytic and rhyolitic ash layers to Oligocene and Miocene respectively. The disappearence of volcanic sources may be an outcome of the Tertiary tectonics of the Alps/Apennine junction in Monferrato.

RIASSUNTO

In questo lavoro sono descritte le caratteristiche sedimentologiche, la biostratigrafia (foraminiferi planctonici e nannofossili calcarei), la petrografia, la minerochimica e la tipologia degli zirconi di 10 livelli vulcanoclastici recentemente rinvenuti nelle successioni oligo-mioceniche del Monferrato (Italia NW). Sono stati riconosciuti due tipi di livelli vulcanoclastici: a) tufi vetrosi quasi completamente alterati in zeoliti di Ba, di presunta composizione trachitica originaria; b) tufi vetrosi a composizione riolitica, derivati da una sorgente magmatica calcalcalina. I dati biostratigrafici permettono di attribuire il vulcanismo trachitico e riolitico rispettivamente all'Oligocene ed al Miocene. La scomparsa degli apparati vulcanici originari può essere messa in relazione con la tettonica terziaria dei sistemi strutturali presenti alla giunzione Alpi/Appennino in Monferrato.

Introduction

Volcanic related sediments referred to an Oligocene-Miocene magmatism are widespread in the sedimentary successions of the Langhe basin (e. g. Galbiati 1976; Gelati 1977; d'Atri 1990; d'Atri & Tateo 1994) and of the Northern and Central Apennines (e. g. Guerrera et al. 1986; Mezzetti et al. 1991; Tateo 1992), currently described as ash layers, Ba-zeostones, bentonites and plagioclase and amphibole-bearing fine-grained

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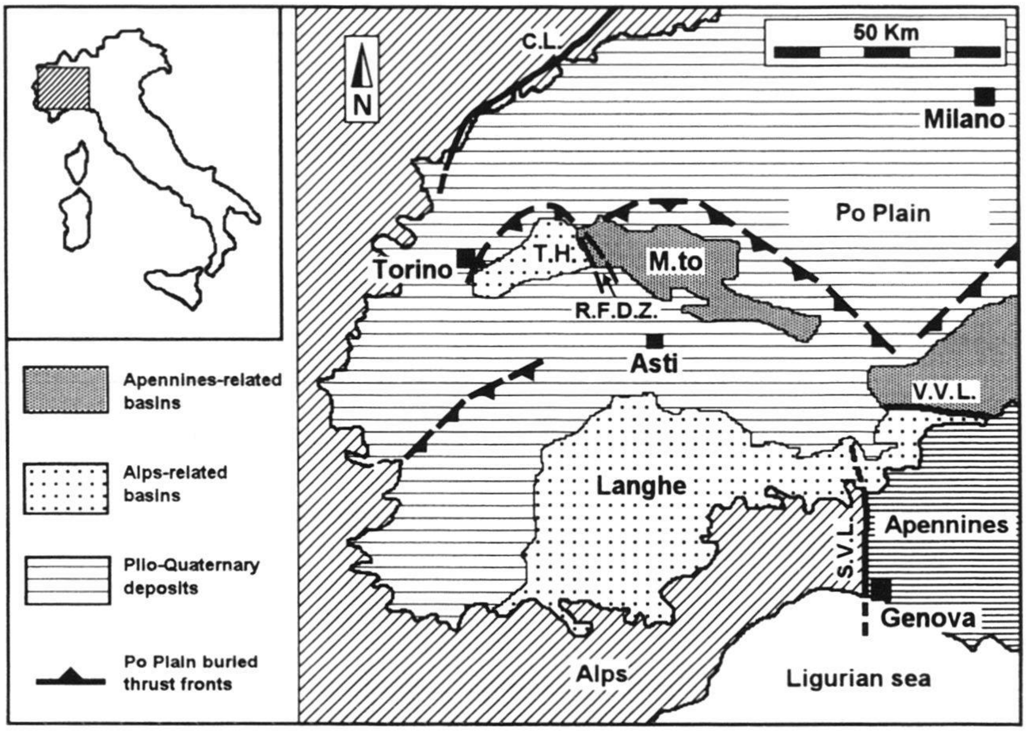


Fig. 1. Structural sketch map of the Tertiary basins at the Alps-Apennines junction zone (NW-Italy). **M. to:** Monferrato; **T. H.:** Torino Hill; **C. L.:** Canavese line; **V. V. L.:** Villalvernia-Varzi line; **S. V. L.:** Sestri-Voltaggio line; **R. F. D. Z.:** Rio Freddo convergent wrench zone. (Modified from Biella et al., 1992).

sandstones. They provide a valuable opportunity to investigate the Tertiary magmatism in the Alpine-Apennine domain, since their volcanic edifices have completely disappeared.

This paper reports the results of a multidisciplinary study on ten ash layers in the Oligocene-Miocene sediments of the Monferrato (NW Italy), which is currently regarded as the NW termination of the Apenninic thrust belt, and a key for understanding the Tertiary kinematics of the Alps/Apennine interaction. These layers thus provide an excellent source of information from which the Tertiary volcanic activity can be framed in the geodynamic Alpine context.

The stratigraphy and biostratigraphy of some of these layers (Clari et al. 1988, 1994; Ruffini et al. 1991; Bicchi et al. 1994), and two varieties of vitric tuffs (namely trachytic and rhyolitic tuffs), with different mineralogy and glass chemistry, have already been reported (Ruffini & Cadoppi 1994). The results of a biostratigraphical study, optical and microprobe analyses and typological study of zircon populations in ten ash layers enable a full assessment to be made of rhyolitic vitric tuffs (RVT) and trachytic vitric tuffs (TVT).

Geological setting

A thick succession of Tertiary sediments (Bacino Terziario Ligure Piemontese in the Italian literature: Sturani 1973, 1975; Cassano et al. 1986) crops out at the W border of

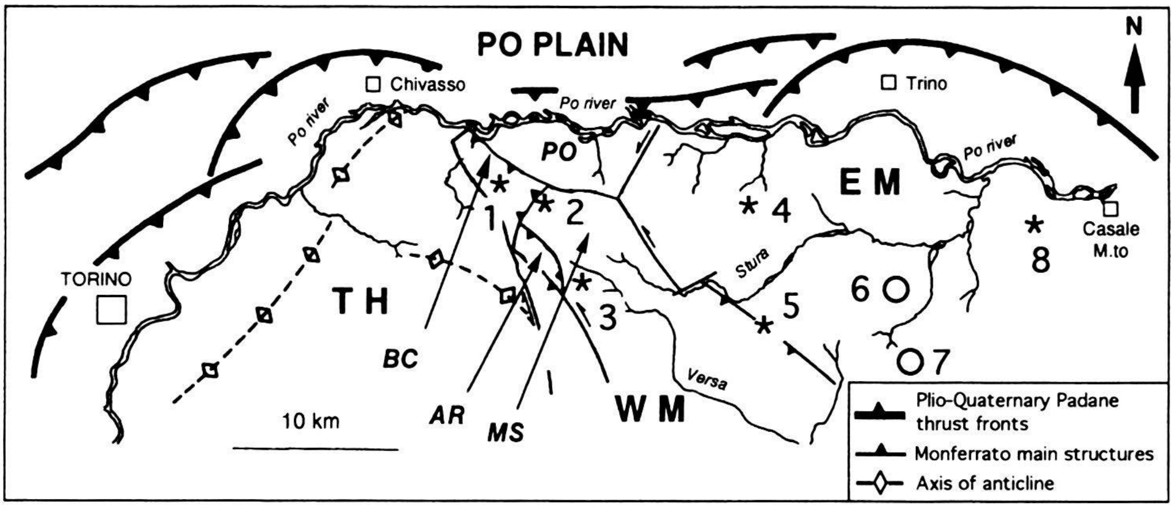


Fig. 2. Location of trachytic (circles) and rhyolitic (stars) vitric tuffs in Monferrato area. 1) Tonengo (TN); 2) Tonengo (LN); 3) Tabiella (TB); 4) Varengo (VR); 5) Villadeati (VD/GD, V15, VD1); 6) Starola (ST); 7) Ottiglio (OT); 8) Ozzano (OZ). **TH:** Torino Hill; **EM:** Eastern Monferrato; **WM:** Western Monferrato; **AR:** Aramengo-Marmorito unit; **MS:** Moransengo unit; **BC:** Bric Carrassa unit; **PO:** Po unit. (Modified from Clari et al. 1995).

the Po Plain (Fig. 1) and it represents the infilling of distinct Tertiary basins, named Torino Hill, Monferrato and Langhe. It masks the junction between the Alpine and Apenninic thrust belts (Bigi et al. 1990; Biella et al. 1992; Miletto & Polino 1992; Polino et al. 1992). The Monferrato consists of a Tertiary succession, resting on Apennine-related units, and overridden in turn by the Alpine basement (Polino et al. 1992). The superficial expression of this thrust is the Rio Freddo convergent wrench zone, which separates the Alpine-related Torino Hill domain from the Monferrato (Piana & Polino 1994).

Tertiary deposits in the Monferrato domain show strong lateral facies and thickness variations (Bonsignore et al. 1969; Sturani 1973), indicating a complex evolution. Subdivision of Monferrato in a Western and an Eastern part (WM and EM in Fig. 2) is supported by recent stratigraphical (Clari et al. 1994, 1995) and structural data (Piana & Polino 1994). Furthermore, four tectono-stratigraphic units can be distinguished in the Western Monferrato (Fig. 1): they evolved in a wrench tectonic frame and were tectonically welded during Langhian times, as suggested by the uniform extent and the unconformable basal boundary of Langhian deposits (Clari et al. 1994, 1995).

Field Occurrences

Ash layers ranging in thickness from few centimeters to some meters crop out with a limited lateral continuity in both Western and Eastern Monferrato (Clari et al. 1988; Ruffini et al. 1991; Ruffini et al. 1993). Some differences in field occurrences of trachytic and rhyolitic layers were recognized.

Rhyolitic vitric tuffs (RVT). Three ash layers occur in Western Monferrato (TN in Bric Carrassa unit, LN and TB in Moransengo unit), whereas the other five (V15, VD/GD, VD1, VR, OZ) occur in Eastern Monferrato (Fig. 2). They are included within

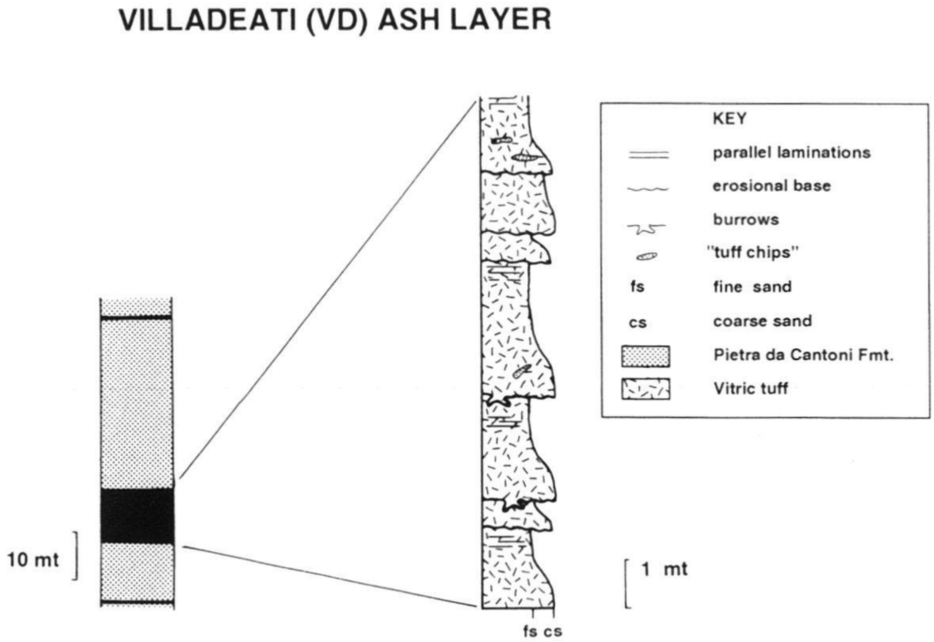


Fig. 3. Simplified section of the Villadeati (VD, n°5 in Fig. 2) multiple ash layer. Explanation in the text.

the following lithostratigraphic units (Clari et al. 1994, 1995): TN and TB are interbedded in the Marne a Pteropodi Formation (Early Burdigalian); V15-VD/GD-VD1 are within the calcarenites of the Pietra da Cantoni Formation (Late Burdigalian); VR crops out at the boundary between the Pietra da Cantoni Formation and the Tonengo Calcarenites (Early Langhian); OZ and LN are in the Tonengo Calcarenites.

RVT are mostly whitish friable rocks composed of glass shards with a coarse to fine-sand grain size. Thickness ranges from about ten centimeters (TV, LN, VD1) to several meters (VD/GD, VR, OZ). The base is always sharp, whereas the top is sharp to gradational, due to bioturbation. The thickest RVT are multiple layers, formed of several distinct strata (Fig. 3). Each stratum is decimeter-thick, coarser at the base (coarse-sand sized magmatic biotite and glass shards) and grading upward to dominantly fine to very fine-sand sized glass shards and occasional feldspar. Non-volcanic grains such as foraminifers and some metamorphic minerals (mainly blue amphibole and epidote) are usally less than 10%. Sedimentary structures, like parallel laminations, normal grading and burrowings, are widespread in each layer, as well as an enrichment of the crystalline component at the base. Fragments of unconsolidated fine-ash sediment, stripped from the lower ash stratum during an erosional event ("tuff chips"), are found in some strata.

Trachytic vitric tuffs (TVT). These layers have so far been found in Eastern Monferrato only (ST and OT, Fig. 2), within the Marne di Antognola Formation (Upper Oligocene–Lower Miocene). They display a strong alteration into zeolites, and can be recognized in the field by a typical yellow-pink colour. Thickness is a few decimeters in ST, and one meter in OT. They occur as discrete layers, generally with a sharp base, whereas the top is diffuse due to bioturbation. Parallel laminae about a few millimeters thick are recognized.

Biostratigraphy

A quantitative study of planktonic foraminiferal and calcareous nannofossil assemblages in sediments under- and overlying the vitric tuff beds has been carried out. Direct samples from ST and VD/GD were also analyzed. On the basis of the significant bioevents for the studied area (Bicchi et al. 1994), data are referred to the standard zonation (Blow 1969, emended in Spezzaferri 1994) for planktonic Foraminifera. Calcareous nannofossil data are referred to the standard zonation of Martini (1971) and Okada & Bukry (1980).

Biostratigraphical events are calibrated to the Geomagnetic Polarity Time Scale (GMTS) after Cande & Kent (1992). The calcareous plankton biochronology (Fig. 4) is from Berggren et al. (1985), Berggren & Miller (1988) and Young et al. (1994).

Series and stages boundaries in figure 4 are approximated by well-established planktonic foraminiferal events. The Oligocene-Miocene boundary is placed at the first occurrence of *Paragloborotalia kugleri* (Steininger et al. 1994), while its last occurrence is used to mark the Aquitanian-Burdigalian boundary (Blow 1969; Berggren et al. 1985). In the literature, the base of the Langhian (base of Middle Miocene) is associated with the first occurrence of either *Praeorbulina sicana* (Iaccarino & Salvatorini 1982; Iaccarino 1985) or *P. glomerosa curva* (Jenkins et al. 1981; Berggren et al. 1985). The chronological error on the Burdigalian-Langhian boundary according to these two criteria is reported in figure 4. The Langhian-Serravallian boundary is placed at the first occurrence of *Orbulina universa* (Iaccarino 1985).

OTTIGLIO (OT) TVT – The calcareous nannofossil assemblage includes *Dictyococcites bisectus, Cyclicargolithus abisectus, Helicosphaera euphratis, H. compacta* and *H. recta.* The presence of both *Sphenolithus distentus* and *S. ciperoensis* assignes this TVT to Subzone CP19a, Late Oligocene in age.

The planktonic Foraminifera assemblage comprises *Globorotaloides suteri, Catapsydrax dissimilis, Dentoglobigerina* spp. and *"Globigerina" venezuelana* in the coarse fraction, and *Tenuitellinata angustiumbilicata, Cassigerinella chipolensis* and rare *Streptochilus pristinum* and *Paragloborotalia pseudocontinuosa* in the fine fraction. This association, together with the absence of both *Paragloborotalia opima opima* and *P. kugleri* suggests Zone P22, Late Oligocene in age.

STAROLA (ST) TVT – Samples from this vitric tuff are barren concerning planktonic Foraminifera. The nannofossil content is very poor, though the rare presence of *Dictyococcites bisectus, Helicosphaera compacta* and *Sphenolithus distentus* points to Zone CP18-CP19a, Oligocene in age. ST is not included in figure 4 on account of this uncertainty.

TONENGO (TN) RVT – In the TN calcareous nannofossil association *Dictyococcites bisectus* is absent or in very low frequency, suggesting an Early Miocene age. *Helicosphaera carteri* is the dominant helicolith, indicating Subzone CN1c, Early Burdigalian in age.

The microfauna is mainly rather poor and badly preserved. The planktonic Foraminifera association includes *Globoquadrina praedehiscens, Gq. dehiscens, "Globigerina" venezuelana* and *Catapsydrax dissimilis,* whose presence, together with the absence of *P. kugleri,* seems to indicate Zone N5/6, Early Burdigalian in age.

TABIELLA (TB) RVT – Samples from this vitric tuff are barren and it is not in-

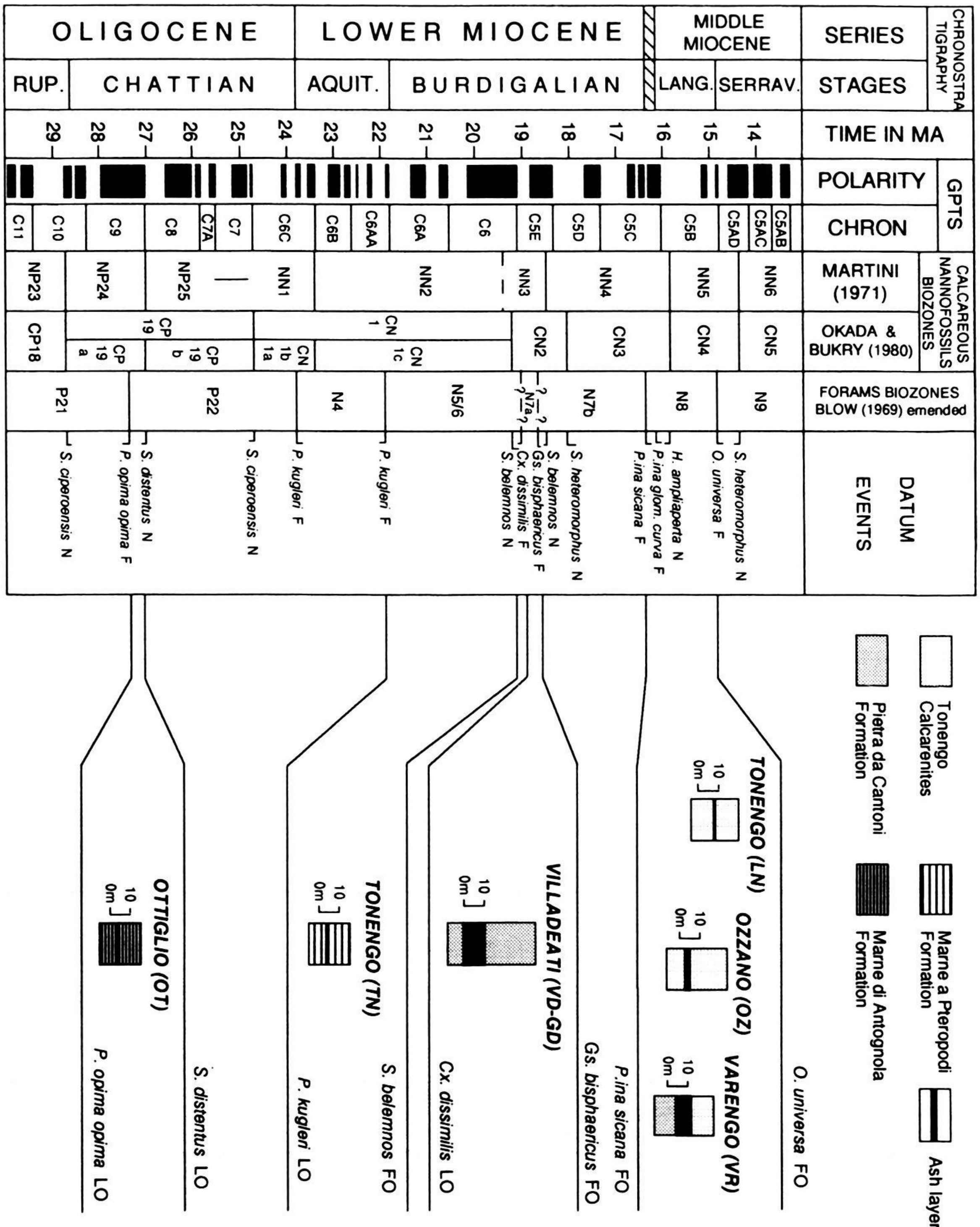


Fig. 4. Chronostratigraphy of studied sections based on calcareous nannofossil and planktonic Foraminifera data. FO=first occurrence; LO=last occurrence. Calcareous nannofossils (N): *S.=Sphenolithus; H=Helicosphaera.* Planktonic Foraminifera (F): *O.=Orbulina; P.ina=Praeorbulina; Gs.=Globigerinoides; Cx.=Catapsydrax; P.=Paragloborotalia.*

cluded in figure 4. Its host formation (Marne a Pteropodi Fm.) is Early Burdigalian, and this RVT may be of the same age.

VILLADEATI-GODIO (VD-GD), VILLADEATI (V15) AND VILLADEATI (VD1) RVT – These RVT contain a calcareous nannofossil assemblage with very frequent *Helicosphaera carteri* and *H. ampliaperta.* The presence of *Sphenolithus belemnos* points to the lower part of Zone CN2, Late Burdigalian in age.

As regards the planktonic Foraminifera, assignment to Subzone N7a (Late Burdigalian) is possible owing to the abundance of *Globigerinoides (G. trilobus, G. subsacculifer, G. quadrilobatus, G. subquadratus, G. trilobus-bisphaericus transition), Paragloborotalia (P. acrostoma, P. mayeri* gr., *P. siakensis),* and of (to a lesser extent) *Globoquadrina dehiscens, Globigerinella obesa* and *Globorotalia scitula* gr., and the absence of typical *Gs. bisphaericus.*

VARENGO (VR) - TONENGO (LN) - OZZANO (OZ) RVT – The calcareous nannofossil associations of these RVT are similar and poorly preserved. *Helicosphaera ampliaperta* is absent or in very low frequency, whereas *Sphenolithus heteromorphus* is abundant. The assemblage, however, is not distinct enough to allow attribution to the upper part of Zone CN3 or the lower part of Zone CN4. The planktonic foraminifers, on the other hand, give more detailed information. The three associations are very similar with abundant *Globigerinoides (G. trilobus, G. bisphaericus, G. subquadratus),* and *Dentoglobigerina (D. altispira, D. langhiana). Paragloborotalia siakensis, Globorotalia scitula* gr. are also present. *P. sicana* has been recognized in VR, and even in OZ together with *P. glomerosa curva.* Typical specimens of *P. glomerosa circularis* and transitional specimens towards *O. suturalis* occur in LN. VR can thus be assigned to the upper part of Subzone N7b, OZ to the lower part and LN to the upper part of Zone N8, Langhian in age.

Petrography

The rhyolitic types show a well-preserved vitroclastic texture with glass shards and mineral fragments. The vitric fraction is up to 70%, and is composed by fresh, colourless, Y-shaped glass shards and pumices. The grain-size of shards ranges from 50 μm to 600 μm, and they are flat to slightly curved with sharp angular edges. The 400–600 μm pumices are vesicular with well-developed elongated vesicles.

All crystals with a thin coating of glass are regarded as essential volcanic components; they are (Tab. 1): plagioclase, biotite, quartz, sanidine and scarce amphibole. TN alone has a less evolved mineral assemblage that lacks biotite and quartz, and contains orthopyroxene and clinopyroxene associated with a calcic plagioclase and minor amphibole.

This phenocryst assemblage is typical of subalkaline rocks. The occurrence of quartz and biotite in most samples and the presence of sanidine indicate that these ash layers are derived from "highly differentiated" or "felsic" melt compositions, in agreement with the rhyolitic composition of glass shards (Tab. 4).

The trachytic types display a vitroclastic texture almost completely obliterated by autigenic formation of zeolites. The usual phenocryst assemblage is (Tab. 1): anorthoclase and/or sanidine, andesitic plagioclase and Ti-Ba-rich phlogopite, with minor Al-clinopyroxene, kaersutite and aegirine. Quartz is present in a very small amount, but volcanigenic origin is uncertain. The shards are almost completely replaced by zeolitic materials, with predominant Ba-zeolite (harmotome).

Tab. 1. Main petrographical features of trachytic and rhyolitic vitric tuffs from Monferrato.

Type of vitric tuff	*Samples*	*Feldspars*				*Mafic minerals*					*Accessory minerals*			*Age*
		Plg	Sa	Ant	Qz	Cpx	Opx	Aeg	Amp	Bt	Ox	Zr	Ap	
Trachytic vitric tuffs	ST	++	+++	++		++		++	++	++	++	++	+	Oligocene
	OT	++	+++	++		++		++	++	++	++	++	+	Upper Oligocene
Rhyolitic vitric tuffs	TN	+++				+++	+++		++		+		+	Lower Burdig.
	V15	+++	+		+	++				++		+		Upper Burdig.
	VD	+++	+		+++				+	+++	+	++	++	Upper Burdig.
	VD1	+++			++				++	++	+	+	+	Upper Burdig.
	TB	++	+		++	+			+	++		+	+	Burdigalian?*
	VR	+++			++				+++	++	+	+	+	Langhian
	OZ	+++	+		++				+	+++	+	+	+	Langhian
	LN	++	+		++					+++	+	++	+	Langhian

Abbreviations: Plg = plagioclase; Sa = sanidine; Ant = anorthoclase; Qz = quartz; Cpx = clinopyroxene; Opx= orthopyroxene; Aeg = aegirine; Amp = amphibole; Bt = biotite; Ox = oxides; Zr = zircon; Ap = apatite.
Assemblage abundances indicated approximately by: +++ common; ++ some; + few.
The ages are referred to the biostratigraphic data of this work.
* Ruffini et al., 1991.

Tab. 2. Representative microprobe analyses of main minerals in rhyolitic vitric tuffs from Monferrato. Sample location in figure 2. Structural formulae are calculated on the basis of 8 oxygens for feldspars, 6 oxygens for pyroxene, 15 cations ((N_{cat}–K=15) and 23 oxygens for amphibole, 22 oxygens for biotite; n.c. = not calculated.

	RHYOLITIC VITRIC TUFFS						
	TN	**LN**	**VD**	**TN**	**TN**	**VD1**	**LN**
	Pl	**Sa**	**Pl**	**Cpx**	**Opx**	**Amp**	**Bt**
SiO2	47.57	64.93	60.31	51.86	53.27	46.50	35.85
TiO2	0.00	0.00	0.00	0.41	0.39	1.49	3.64
Al2O3	32.97	19.06	24.69	1.39	1.34	8.23	14.15
FeO T	0.51	0.00	0.00	11.86	17.37	17.14	28.84
MnO	0.00	0.00	0.00	0.51	0.56	0.00	0.44
MgO	0.00	0.00	0.00	13.75	24.98	12.05	5.88
CaO	16.50	0.00	6.98	20.86	1.52	10.91	0.32
Na2O	2.27	3.32	7.42	0.00	0.56	1.42	0.62
K2O	0.00	11.98	0.58	0.00	0.00	0.58	8.44
Tot.	99.82	99.29	99.98	100.64	99.99	98.32	98.18
Si	2.19	2.98	2.69	1.95	1.94	6.70	5.56
Ti	0.00	0.00	0.00	0.01	0.01	0.16	0.43
AlIV	1.79	1.03	1.30	0.04	0.04	1.09	2.44
AlVI	0.00	0.00	0.00	0.02	0.02	0.30	0.15
Fe3+	0.02	0.00	0.00	0.01	0.09	1.16	n.c.
Fe2+	0.00	0.00	0.00	0.34	0.44	0.90	3.74
Mn	0.00	0.00	0.00	0.03	0.02	0.00	0.06
Mg	0.00	0.00	0.00	0.77	1.35	2.59	1.36
Ca	0.81	0.00	0.33	0.84	0.06	1.69	0.05
Na	0.20	0.30	0.64	0.00	0.04	0.40	0.19
K	0.00	0.70	0.03	0.00	0.00	0.11	1.67

The assemblage is typical of alkaline rocks. The very few shards that have escaped zeolitic alteration show a trachytic composition (Tab. 4). Identical layers completely converted into Ba-zeolites are well known in the Apennines as Ba-zeostones (Minguzzi et al. 1987).

Mineral chemisty

The main phenocryst phases and glass shards were analyzed with a Cambrigde SEM equipped with a Link EDS system 860 using an online reduction system with ZAF-4 correction procedures (analytical conditions were: 15 kW acceleration voltage, 15nA beam current and 50 sec counting time). Pure oxides were used as standards. Representative analyses of main phenocryst phases of both vitric tuffs are given in table 2 and table 3 respectively.

Tab. 3. Representative microprobe analyses of main minerals in trachytic vitric tuffs from Monferrato. Structural formulae are calculated on the basis of 8 oxygens for feldspars, 6 oxygens for pyroxene, 23 oxygens for amphibole, 22 oxygens for biotite; n.c. = not calculated.

	TRACHYTIC VITRIC TUFFS						
	ST	**ST**	**OT**	**OT**	**OT**	**ST**	**ST**
	Pl	**Ant**	**Sa**	**Ae-aug**	**Cpx**	**Amp**	**Bt**
SiO2	56.93	64.02	65.72	52.68	47.87	40.27	36.40
TiO2	0.00	0.00	0.00	0.75	1.86	5.57	6.98
Al2O3	26.26	21.88	19.66	0.00	5.52	11.46	13.94
FeO T	1.03	0.48	0.00	20.25	7.02	11.27	13.80
MnO	0.00	0.00	0.00	1.43	0.00	0.00	0.39
MgO	0.00	0.00	0.00	6.02	13.64	13.23	13.97
CaO	9.10	2.62	1.04	8.35	22.58	11.52	0.00
Na2O	6.24	8.28	5.39	8.75	0.56	2.94	1.28
K2O	0.82	3.42	7.29	0.00	0.00	0.98	8.06
BaO	0.00	0.00	0.96	0.00	0.00	0.00	1.44
Tot.	100.38	100.70	100.06	98.23	99.05	97.24	96.27
Si	2.57	2.84	2.96	1.98	1.79	6.00	5.43
Ti	0.00	0.00	0.00	0.02	0.05	0.63	0.78
AlIV	1.40	1.15	1.04	0.02	0.18	1.99	2.45
AlVI	0.00	0.00	0.00	0.00	0.08	0.02	0.00
Fe3+	0.04	0.02	0.00	0.63	0.02	n.c.	n.c.
Fe2+	0.00	0.00	0.00	0.01	0.11	1.41	1.72
Mn	0.00	0.00	0.00	0.05	0.00	0.00	0.05
Mg	0.00	0.00	0.00	0.02	0.75	2.94	3.10
Ca	0.44	0.13	0.05	0.34	0.90	1.84	0.00
Na	0.55	0.71	0.47	0.64	0.05	0.85	0.37
K	0.05	0.19	0.42	0.00	0.00	0.19	1.53
Ba	0.00	0.00	0.02	0.00	0.00	0.00	0.08

Tab. 4. Microprobe analyses of volcanic glass shards from trachytic and rhyolitic tuffs. For CIPW norm calculations, Fe_2O_3 is standardized at 0.25 × FeO total.

	ST		TN		TB		VD		VD1		VR		OZ		LN	
	Av.(5)	St.Dev.	Av.(8)	St.Dev.	Av.(5)	St.Dev.	Av.(10)	St.Dev.	Av.(11)	St.Dev.	Av.(7)	St.Dev.	Av.(10)	St.Dev.	Av.(7)	St.Dev.
SiO2	58.79	2.11	69.26	0.63	73.65	1.45	72.58	1.17	73.32	0.96	72.31	0.75	74.64	1.54	74.10	1.07
Al2O3	17.87	0.61	13.40	0.85	12.25	0.64	11.86	0.18	11.86	0.30	12.04	0.33	12.41	0.48	11.98	0.37
TiO2	1.09	1.34	0.15	0.20												
MnO			0.04	0.10												
MgO	0.97	0.29	0.25	0.15							0.04	0.11				
FeO	3.90	1.73	1.83	0.27	1.29	0.20	0.96	0.19	1.08	0.14	1.01	0.22	0.99	0.25	1.03	0.09
CaO	2.37	0.79	1.48	0.21	1.04	0.29	0.69	0.10	0.93	0.11	0.99	0.12	1.04	0.11	0.57	0.05
Na2O	6.20	0.60	2.30	0.71	2.65	0.16	2.08	0.66	2.10	0.14	2.01	0.15	2.04	0.22	2.22	0.61
K2O	5.09	1.44	2.59	1.52	2.95	0.05	3.92	0.62	3.61	0.29	3.03	0.26	3.22	0.27	1.80	0.38
BaO	0.13	0.25														
TOT	96.41		91.30		93.83		92.09		92.90		91.42		94.42		91.71	
CIPW NORM																
Q			45.48		46.96		47.20		48.16		50.67		50.51		57.30	
C			4.52		2.99		3.19		3.03		4.39		3.90		5.83	
Or	31.14		16.78		18.56		25.18		22.93		19.56		20.15		11.58	
Ab	48.70		21.32		23.86		19.12		19.12		18.62		18.28		20.48	
An	6.14		8.04		5.51		3.72		4.96		5.36		5.46		3.08	
Ne	3.09															
Ol	2.10															
Di	5.05															
Hy			2.82		1.61		1.22		1.36		1.38		1.24		1.31	
Mt	1.46		0.72		0.49		0.38		0.42		0.39		0.38		0.41	
Il	2.15		0.30													

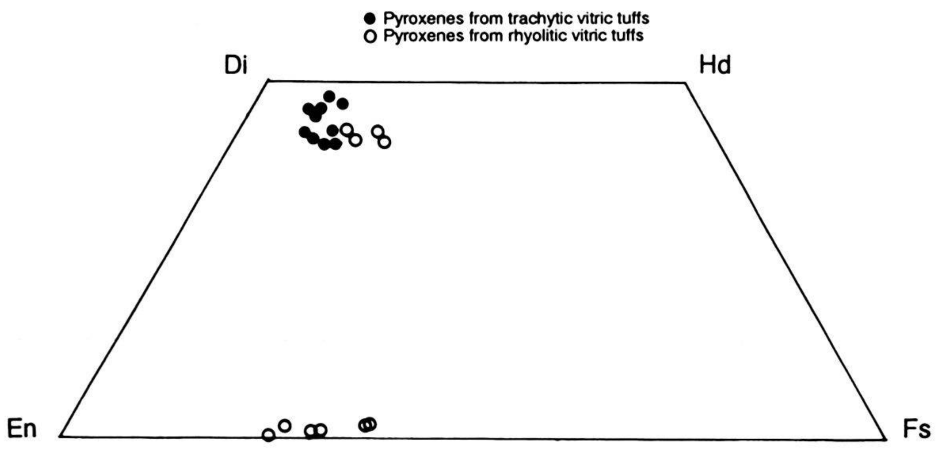


Fig. 5. Di-Hd-En-Fs diagram for Ca-rich and Ca-poor pyroxenes from trachytic and rhyolitic vitric tuffs.

Pyroxenes – These are present in the TN RVT only. Bronzite to hyperstene and augite (Fig. 5), with low content of TiO_2 and Al_2O_3, are the most common, and indicate a subalkaline magma.

The composition of TVT clinopyroxenes ranges from titanaugite to salite and subordinate aegirine and aegirinaugite. Titanaugite (TiO_2 between 1% and 2%, and Al_2O_3 > 2%) may indicate an alkaline character of the magma (Le Bas 1962). This is confirmed by the presence of aegirine, typical in late crystallization stages of peralkaline melts.

Feldspars – Slightly normally zoned plagioclase (mainly andesine and labradorite) is the most abundant phenocryst phase in RVT, whereas sanidine is subordinate. Phenocryst compositions follow a normal trend of differentiation, showing a gradual enrichment in albitic component from the oldest (Lower Burdigalian) to the youngest (Langhian) layers (Fig. 6a).

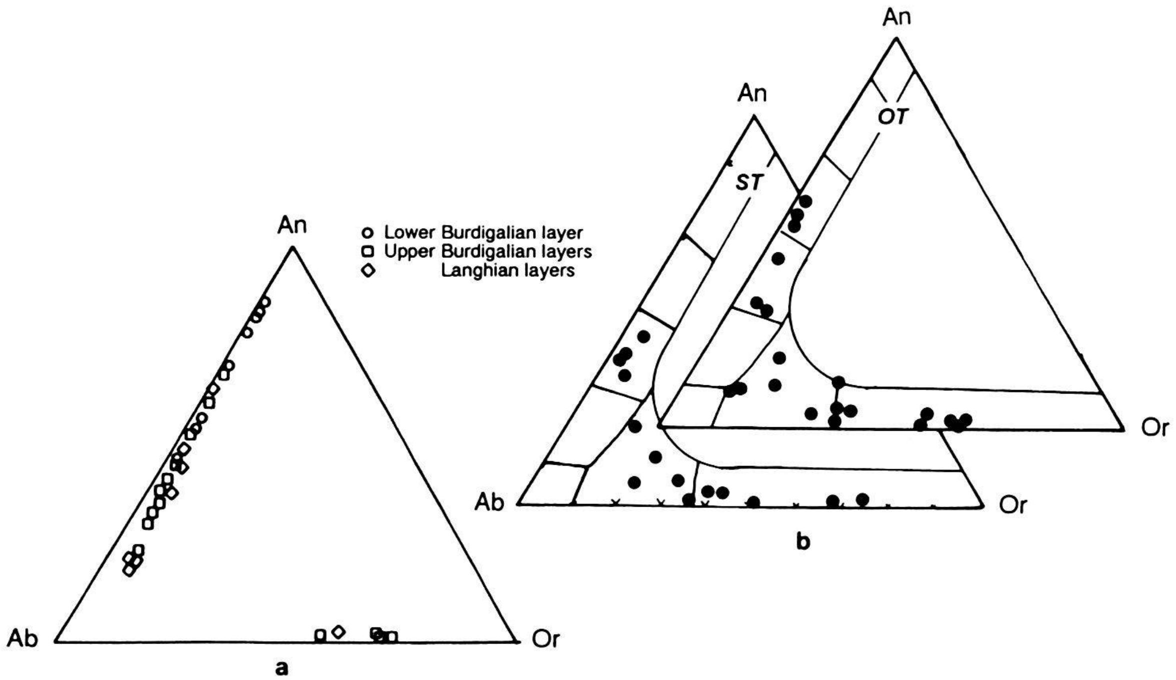


Fig. 6. Ab-An-Or (wt%) plot of plagioclase and K-feldspar for rhyolitic (a) and trachytic (b) ash layers.

The TVT contain three types of feldspars (Fig. 6b): sanidine, anorthoclase and andesine. Anorthoclase ($An_{21}Ab_{66}Or_{13}$) overgrows on plagioclase, whereas sanidine is present as separated crystals ranging in composition from $An_{02}Ab_{24}Or_{74}$ to $An_2Ab_{61}Or_{37}$. Both anorthoclase and sanidine contain up to 1.5 wt% BaO.

Amphiboles – Crystals observed in some RVT (generally occurring as euhedral phenocrysts) are calcic, mostly edenitic-hornblende, edenite and magnesian-hastingsitic hornblende, according to the nomenclature of Leake (1978). They are common in calc-alkaline series (Gill 1981).

Amphibole from TVT occurs as small, anhedral grains containing up to 5% wt TiO_2. It can be defined as kaersutite.

Ferromagnesian mica – Biotite is ubiquitous in RVT, though absent in the lowermost layer (TN). It is a typical titan-biotite (Ti > 0.25 p.f.u. according to Rock 1982), with constant Al concentration and nearly constant Fe/Mg ratio (Ruffini & Cadoppi 1994). It is noteworthy that biotite from the youngest layer has the highest total Fe content.

Ferromagnesian mica from TVT has high TiO_2 and MgO content so that it can be defined as phlogopite. It characteristically contains up to 1% wt BaO.

Glass composition – Electron microprobe analyses of RVT and TVT shards are given in table 4. The total oxide components range from 91% to 96%. The deficit may come from the initial volatile content, loss of light components during analysis and from hydration and post-depositional alteration. The peraluminous character shown by RTV (C-normative) can be ascribed to alkali loss during analysis or by interaction with seawater (Ruffini & Cadoppi 1994).

Zircon typology

A typologic study of zircon populations was carried out on eight samples according to Pupin (1976, 1980). When possible (Fig. 7), a population of over one hundred crystals for each sample was separated in order to define a statistically representative zircon population. This method corroborates the petrographical and mineral chemistry data, especially in the most weathered ash layers, and gives more precise information about the composition and the characteristics of the magma.

Zircon morphology, mainly due to the arrangement of two bipyramids ({101} and {211}) and two prisms ({100} and {110}), reflects chemical composition and crystallization trend of magma. The relative development of bipyramids (A index: I.A in Fig. 7) is controlled by magma composition, whereas that of prisms (T index: I.T in Fig. 7) is controlled by the temperature and fluid pressure prevailing during crystallization (Pupin 1976; Pupin et al. 1978). Additional features, such as colour, inclusions, overgrowth, elongation, association, zonation etc. are also taken into account.

Since these tuffs are detrital, a part of zircons could derive from the terrigenous fraction: in this case, crystals are generally broken and show a rounded and corroded habitus. Only euhedral, unbroken crystals, therefore, were considered as primary and counted.

Zircon crystals from RVT are colourless or pale orange, clear, with a mild or pronounced elongation (generally > 1; frequently > 2); inclusions of needle-like crystals of apatite, opaque minerals, other zircon crystals and irregular or tube-like "bubbles" are common. Zircon types (Fig. 7) range widely from high-T (J_{2-3}, D) to low-T (S_{3-5}, P_1) subtypes and are compatible with a rhyolitic-rhyodacitic magma with several degrees of differentiation (Ruffini & Cadoppi 1994). From different I.A. values, VR has the most "aluminiferous" character, whereas LN is the most alkaline.

On the other hand, zircon crystals in TVT (ST, OT) are typical of a high-temperature magma and are compatible with a trachytic magma model. J_{2-5}, D and S_{22-25} are the main subtypes, indicating a crystallization temperature over 900°C (Fig. 7; Ruffini & Cadoppi 1994). Crystals are mildly or not elongated and show growth steps, growth gaps and different associations typical of volcanic-derived zircons.

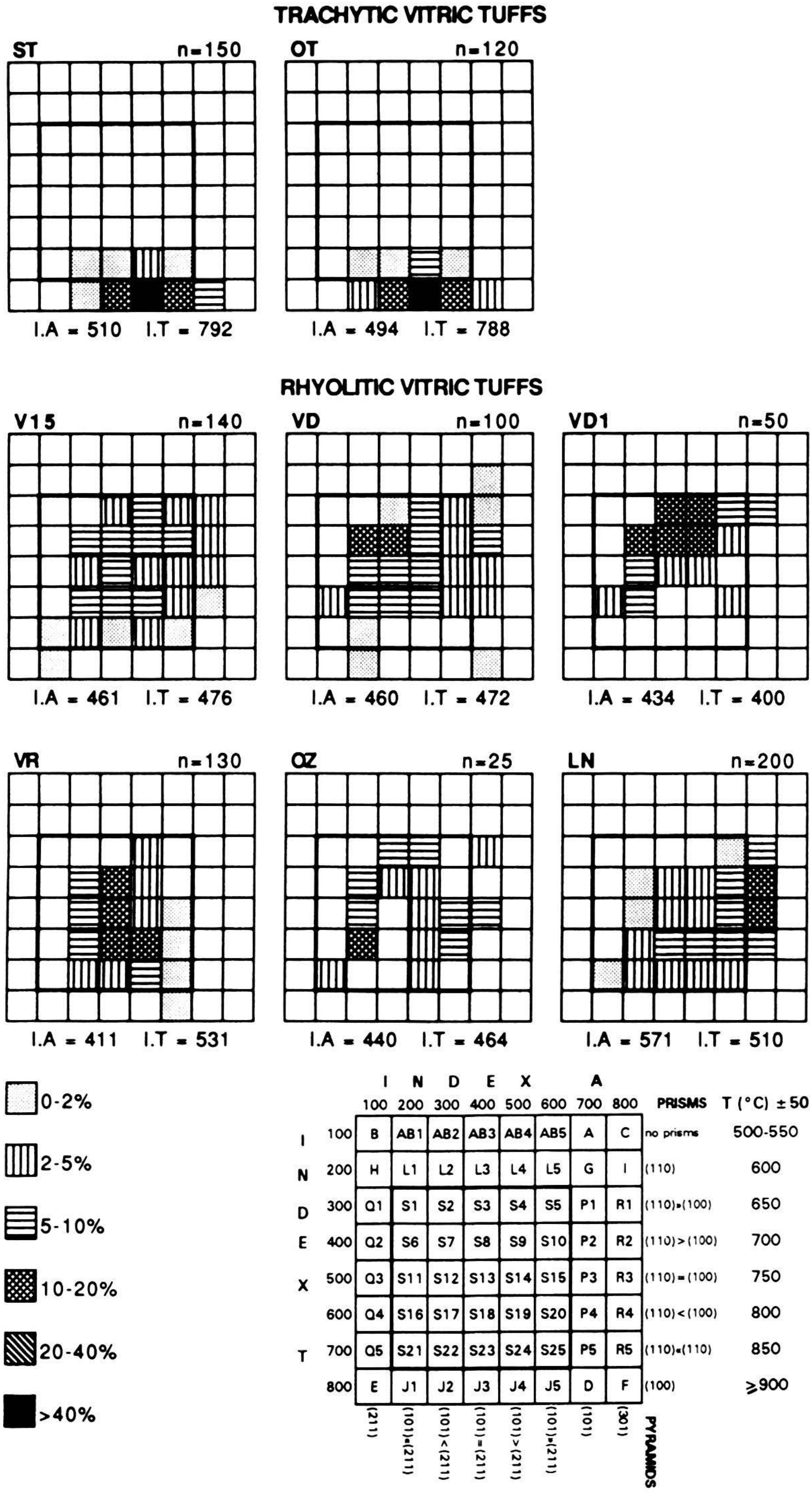
Discussion

The data presented here enable us to draw some conclusions about the origin of the Monferrato ash layers, and the mode and timing of their emplacement.

Mode of emplacement – Vitric tuffs can be interpreted as a product of explosive magmatic/phreatomagmatic subaerial eruptions. A subaqueous origin would imply the presence of an active intrabasinal volcanism, in contrast with the total absence of consistent volcanic traces, such as dikes or flows, in the whole Monferrato.

Sedimentological characters of the volcanigenic layers (erosional bases of the beds, normal grading and parallel laminations) strongly support the view that submarine cur-

Fig. 7 Typologic frequency distribution of zircon populations and mean point values (I.A, I.T) for trachytic and rhyolitic vitric tuffs in the diagram of Pupin (1976). The typological classification after Pupin (1976) and the corresponding geothermometric scale (Pupin & Turco 1972) are also shown.


TRACHYTIC VITRIC TUFFS
ST n=150
I.A = 510 I.T = 792
OT n=120
I.A = 494 I.T = 788
RHYOLITIC VITRIC TUFFS
V15 n=140
I.A = 461 I.T = 476
VD n=100
I.A = 460 I.T = 472
VD1 n=50
I.A = 434 I.T = 400
VR n=130
I.A = 411 I.T = 531
OZ n=25
I.A = 440 I.T = 464
LN n=200
I.A = 571 I.T = 510
0-2%
2-5%
5-10%
10-20%
20-40%
>40%
INDEX A
100 200 300 400 500 600 700 800
PRISMS
T (°C) ±50
INDEX T
100 B AB1 AB2 AB3 AB4 AB5 A C no prisms 500-550
200 H L1 L2 L3 L4 L5 G I (110) 600
300 Q1 S1 S2 S3 S4 S5 P1 R1 (110)»(100) 650
400 Q2 S6 S7 S8 S9 S10 P2 R2 (110)>(100) 700
500 Q3 S11 S12 S13 S14 S15 P3 R3 (110)=(100) 750
600 Q4 S16 S17 S18 S19 S20 P4 R4 (110)<(100) 800
700 Q5 S21 S22 S23 S24 S25 P5 R5 (110)«(110) 850
800 E J1 J2 J3 J4 J5 D F (100) ≥900
(211) (101)«(211) (101)<(211) (101)=(211) (101)>(211) (101)»(211) (101) (301)
PYRAMIDS

rents may have resedimented the volcanic ashes after their deposition. This is corroborated by a mixing with hemipelagic components (calcareous plankton and non-volcanic grains). Nevertheless, the high percentage of volcanic material (about 90%) suggests that reworking by currents was limited.

The evidence from the few sedimentary textures that survived strong zeolitization, suggests that the TVT may even have been deposited as fallout layers and then slightly reworked by turbidity currents in a marine environment. According to Bersani et al. (1986/87) and Tateo (1992), who studied similar sediments in Northern Apennines, the zeolites originated from a syn-depositional alteration of glass shards; later, fluids or gases enriched in Ba were responsible for the formation of Ba-zeolites (Minguzzi et al. 1987). Ba was actually available in the original magma, as suggested by its content in the phenocryst minerals and volcanic glass (Tab. 3, 4).

Timing – The biostratigraphical data fit both types of tuff into well-defined time spans. Owing to the strong alteration of trachytic tuffs, reliable results have only been obtained from one sample (OT), which is assigned to Zone P22 (Blow emended) and Zone CP19a (Okada & Burkry 1980), *i. e.* Upper Oligocene. The stratigraphical frame indicates that all TVT samples belong to the Upper Oligocene.

The RVT dominate the Miocene interval in the Monferrato succession, ranging from Lower Burdigalian to Langhian.

The mineralogy and time distribution of these tuffs suggest that two magmatisms (mildly alkaline and calc-alkaline) have taken place in well-defined times.

Volcanic source area – The source from which these ash layers originated have still to be located. Identification of the source of a vitric tuff requires evaluation of many variables: for example, direction of wind and marine currents at the time ashes were erupted (Fisher & Schmincke 1984; Bitschene & Schmincke 1990). Tectonic displacement of units containing the Monferrato ash layers must also be considered (Piana & Polino 1994). Coarse sand-size, decimetric thickness together with high percentage of volcanic material found in some levels, suggest an origin from nearby eruption centres at least for the RVT (Bitschene & Schmincke 1990).

Since the Oligocene volcanic activity of both calc-alkaline (*e. g.* Dal Piaz & Venturelli 1985 with references) and alkaline (*e. g.* De Vecchi et al. 1976) affinity has been reported for the whole Alpine chain; the Upper Oligocene TVT and Miocene RVT, recorded in the Monferrato, Langhe basin and Northern Apennines, demonstrate that both types of volcanism continued until these times. The Sardinian source area, suggested for the analogous Apennine rhyolitic ash layers (Mezzetti et al. 1991; Montanari et al. 1992), is ruled out in the Monferrato by the coarse grain-size and sedimentological and mineralogical characters of ash layers. So, the source areas of the Monferrato ash layers have to be searched at shorter distance. Nevertheless, apart from rare volcanic bodies buried in the near Po Plain foredeep (Cassano et al. 1986), volcanic edifices are almost completely disappeared in the Alps and Apennines.

The widespread distribution of ash layers in both Apennine-related (Northern Apennines and Monferrato) and Alpine-related domains (Langhe basin), suggest that the answer lies in the regional tectonic evolution of the Alpine/Apennine belt. Since the area was involved into the post-Oligocene underthrusting of the Insubric-Padane metamorphic crust and cover sediments behind the Apenninic thrust belt (Biella et al. 1992; Miletto & Polino 1992; Polino et al. 1992), it may be supposed that substantial volumes disappeared at depth into the northwestern edge of this belt after the Langhian (Piana & Polino 1995). The volcanic source of the Monferrato ash layers may have thus been passively transported by the underthrusting plate into the collisional belt and are now concealed at depth.

Final remarks

Two volcanic series have been distinguished in the Monferrato area (NW Italy) by a multidisciplinary study leading to the following five conclusions.

1) Two magmatic sources were active during the Oligocene-Miocene in the Alpine area: a mildly alkaline source supplied the trachytic vitric tuffs, whereas a calc-alkaline source contributed the rhyolitic vitric tuffs.
2) Sand-size, sedimentary structures observed in the field, cumulative thicknesses and the overall high glass percentage suggest that both types of volcanic ashes have an explosive origin, airborne dispersal and deposition in the basin, where they were slightly reworked by submarine currents.
3) The trachytic alkaline explosive cycle is Late Oligocene, consistently with the similar Ba-zeostones found in the Northern Apennines (Tateo 1992).
4) The rhyolitic calc-alkaline explosive cycle spanned from Early Burdigalian to Langhian. In the Late Burdigalian and Early Langhian, a period of intense explosive acidic volcanism is recorded by repeated thick beds of vitric tuffs (*e. g.* VD/GD, VR).
5) The volcanic sources are presently lost; they presumably disappeared during the Late Tertiary tectonic evolution of the Alpine/Apenninic junction.

Acknowledgments

Special thanks are given to B. Ricci, who introduced us to the ash layer problem in Monferrato, and to P. Clari, F. Dela Pierre, F. Piana and M. Timpanelli, who contributed pertinent stratigraphic and structural informations. The work was divided up as follows: calcareous nannofossils A. d'Atri, foraminifers A. Novaretti, petrography and mineral chemistry R. Ruffini, zircon typology P. Cadoppi. The authors are very grateful to P. Clari and R. Polino for the stimulating discussions. G. V. Dal Piaz and G. Venturelli are thanked for their constructive reviews.

The microprobe data were obtained with a Cambridge SEM–EDS installed and supported by CNR – C. S. Geodinamica Catene Collisionali, Dipartimento Scienze della Terra and Dipartimento di Scienze Mineralogiche e Petrologiche – Torino.

This work was financially supported by CNR – C. S. Geodinamica Catene Collisionali, Torino.

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Manuscript received December 1, 1994
Revision accepted March 21, 1995