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RESEARCH ARTICLE

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Structural evolution of the Pleistocene Cimini trachytic volcanic complex (Central Italy)

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Abstract Structural, geomorphological, geophysical and volcanological data have been processed for the implementation of a dedicated GIS through which the structural evolution of the Pleistocene trachytic Cimini volcano (central Italy) has been reconstructed. The evolution of the Cimini complex includes three main close-in time phases: (1) intrusion of a shallow laccolith, rising along NW and NE trending faults and stagnating at the contact between the Mesozoic-Cenozoic and the Pliocene-Pleistocene sedimentary units constituting the bedrock of the volcano; (2) emplacement of lava domes along radial and tangential fractures formed by the swelling induced by the laccolith growth; (3) ignimbrite eruptions and final effusion of olivine-latitic lavas. Domes are both of Pelean and low lava dome type and their morphology was controlled by the location on the inclined surface of the swelled area. Some domes show to have uplifted upper Pliocene thermally metamorphosed clay sediments, suggesting a cryptodome-like growth. Comparison of the top of the Mesozoic-Cenozoic units with the top of the upper Pliocene-Pleistocene sedimentary complex, suggests that the laccolith emplaced in a graben of the Mesozoic-Cenozoic sedimentary complex filled by the Pliocene–Pleistocene sediments uplifted by the shallow intrusion. Stress patterns acting on the Cimini area have been deduced analysing the drainage network and the morphotectonic lineaments. Rose diagrams show a large dispersion of the lineaments reflecting the local presence of radial and tangential fractures. The most frequent extensional NW and NE trending lineaments have regional significance and controlled the magma uprise leading to the laccolith emplacement.

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Introduction

The Mt. Cimini trachytic dome complex (CDC), including lava domes and ignimbrites, is located in Central Italy between the eastern coastal margin of the Tyrrhenian Sea and the Apennines (Fig.1). The CDC, together with the Tolfa and the Ceriti-Manziate dome complexes, has been related to the emplacement of mantle magmas contaminated by crustal materials (Vollmer 1977; Clausen and Holm 1990; Coli et al. 1991; Pinarelli 1991; De Rita et al. 1994, 1997; Bertagnini et al. 1995; Perini et al. 2000). The geodynamic context of the volcanism is still debated (Serri et al. 1991 and references therein). At present there is a general agreement that these dome complexes are genetically related to the young alkali-potassic volcanism which affected central Italy since 0.6 Ma, almost in the same areas of the dome complexes emplacement (Perini et al. 2000). The age of these dome complexes is stratigraphically constrained by the presence of Upper Pliocene sediments involved in their emplacement processes (De Rita et al. 1994, 1997). A lava flow at the top of the CDC yielded a whole rock K/Ar age of 0.94±0.2 Ma (Nicoletti 1969). During this period Central Italy was subjected to extensional processes related to the formation of the Tyrrhenian Basin, which generated a main NW-oriented graben and a series of NE-trending transversal grabens (Barberi et al. 1994). The Tolfa and the Ceriti-Manziate dome complexes were emplaced within half grabens, with the main extensional NE-trending faults at their northern margin (De Rita et al. 1994, 1997). The graben into which the Tolfa dome complex developed is located within the Mt. Tolfa sedimentary horst; this structural setting induced the magma to be emplaced as cryptodomes, causing a general uplift, or up-arching, of the area, of up to about 200–400 m. Conversely, the half graben into which the Ceriti-Manziate dome complex formed, is at

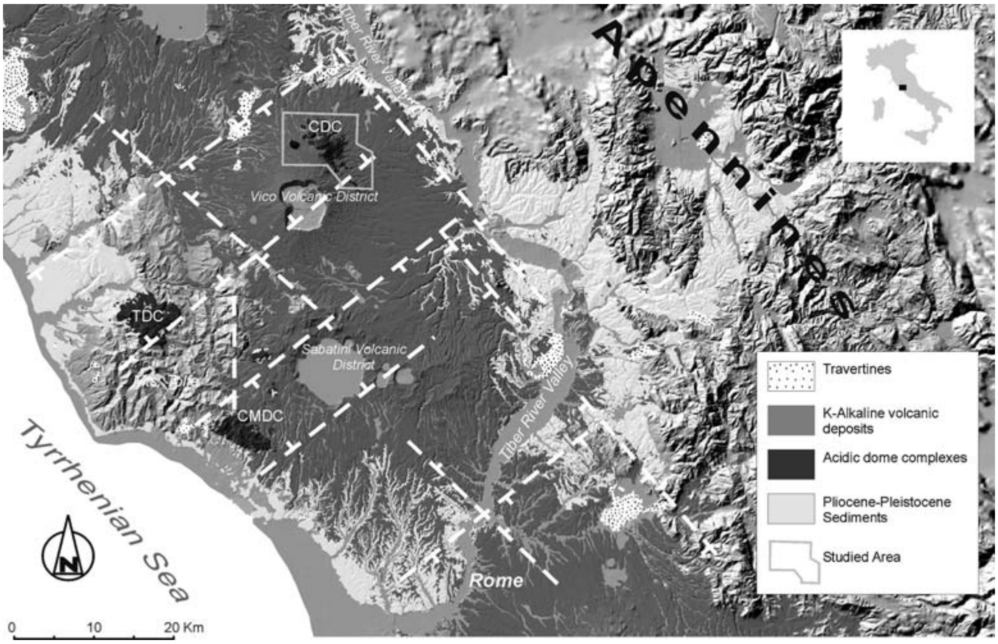

Fig. 1 Location of the Cimini dome complex (CDC), Tolfa dome complex (TDC) and Ceriti-Menziate dome complex (CMDC). Shaded relief map with geology draped on of northern Latium (central Italy). *White dashed lines* indicate main regional faults, bordering the NW and NE-trending grabens into which acid and alkali-potasssic volcanism developed

the southern margin of the Mt. Tolfa sedimentary horst. The Ceriti-Manziate complex includes mainly extrusive domes distributed along NE-trending fractures and characterised by a space-time evolution from west to east. This trend corresponds to a change in the chemical composition from rhyolites (to the west) to trachydacites (to the east), and therefore in the dome morphology from upheaved plug domes to the west to coulee (or low lava domes) to the east.

The Cimini Dome Complex (CDC), that is the object of the present paper, is located further north-west with respect to the Tolfa-Ceriti-Manziate dome complexes, almost at the centre of the NW-oriented main graben (Barberi et al. 1994), into which the Quaternary alkali-potassic volcanism of the Roman province developed (Fig. 1).

The CDC area is of key importance for understanding the relationships between regional extensional tectonics and volcanism at the inception of volcanic activity in the region and between the early rhyolite-trachydacite volcanism and the following alkali-potassic one.

Structural, geomorphological, geophysical and volcanological data have been processed using a GIS framework, through which the geological and structural evolution of the Cimini area has been reconstructed.

In this paper we will present and discuss our reconstruction of the evolution of the CDC, establish their relationships with the structural setting of the underlying sedimentary units and of the effects of regional tectonics and local stress field on domes emplacement.

Geology of the Cimini volcanic complex

The products of the Mt. Cimini volcanic complex, mainly lava domes and ignimbrites, are extensively covered by the K-alkaline pyroclastic deposits from the Vico volcano (Fig. 2).

Table 1 Stratigraphies proposed by different authors for the Cimini volcanic complex

Authors	Stratigraphy
Sabatini (1912)	Oligolabradorite lavas
	Oligoclasite lavas
	Ignimbrite
	Domes
Mittempergher and Tedesco (1963)	Ol-trachytic lavas
	Qz-latitic lavas
	Qz-latitic ignimbrite
	Qz-latitic domes
Mattias and Ventriglia (1970)	Radial lavas
	Ignimbrite
	Domes
Micheluccini et al. (1971)	Ol-latitic lavas
	Latitic lavas
	Domes
	Ignimbrite
Sollevanti (1983)	Latitic lavas
	2nd ignimbrite
	Endogenous domes
	1st ignimbrite
Lardini and Nappi (1987)	Surges
	Domes (2nd circle)
	Lower ignimbrite
	Domes (1st circle)
This work	Ol-latitic lavas
	2nd ignimbrite
	1st ignimbrite
	Domes

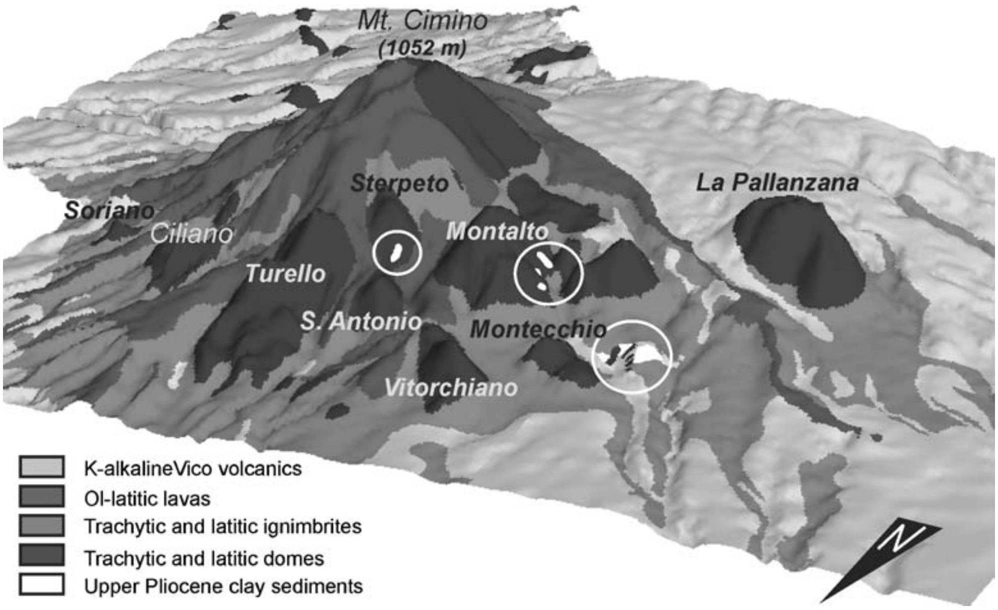

Fig. 2 Schematic geological map of the studied area draped on DEM. View from NW. *White circles* enclose outcrops of uplifted Upper Pliocene clay sediments. Toponyms of major domes are shown (geological map modified after Micheluccini et al. 1971)

A geochemical and petrographic study (Aulinas et al. 2004), indicates that the Cimini volcanic products include trachytic and latitic ignimbrites and lava domes, and olivine-latitic lavas. There is still debate on whether the ignimbrites were erupted before or after the emplacement of the domes and on the presence of one or more ignimbritic units interbedded with the lava domes (see Table 1).

The sedimentary complex below the volcanics consists of limestones and siliciclastic turbidites of Mesozoic and Cenozoic age, belonging to the Apennines Orogene. This belt has been dissected into horsts and grabens by post-orogenic extensional tectonics; grabens have been filled by Pliocene-Pleistocene marine sand and clay sediments (Brandi et al. 1970; Baldi et al. 1974). At the contact with the domes, clay sediments are deformed and locally uplifted more than 200 m (Fig. 2).

The age of the Cimini volcanism is not exactly constrained. Radiometric ages range between 1.35 ± 0.075 (ignimbrites) and 0.94 ± 0.2 Ma (final olivine-latitic lava; Nicoletti 1969; Aulinas et al. 2004). A lava dome gave an age of 1.01 ± 0.05 Ma (Nicoletti 1969), but as Nicoletti states in his paper, the number of analyses and the time range they cover are not sufficient to constrain the chronology of the events.

A negative gravimetric and a positive magnetic anomaly, characterizing the Cimini volcanic area, have been interpreted as due to the intrusion of a shallow magmatic body (La Torre et al. 1981; Sollevanti 1983).

Thermally-metamorphosed sedimentary lithic clasts in the ignimbrite deposits indicate that melting processes

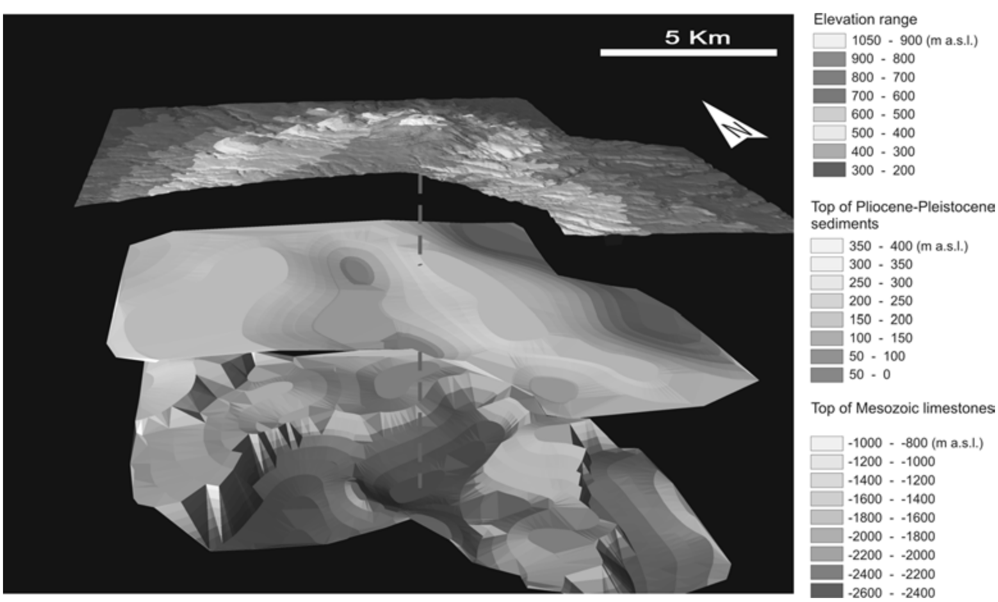

Fig. 3 Comparison between the top of the resistant complex (Mesozoic sedimentary units) and the top of the Cenozoic siliciclastic turbidites plus Pliocene-Pleistocene sediments. In correspondence of Mt.Cimino (*vertical dashed line*), the resistant complex shows a structural low, whereas the upper sediments are uplifted due to the intrusion of a laccolith

occurred at shallow depth (Di Sabatino and Della Ventura 1982).

Methodology of the study

In order to reconstruct the volcanic stratigraphy and the structural evolution of the CDC, a Digital Terrain Model (DTM) of the Cimini area has been constructed using aerial photographs and 1:10,000 topographic maps with a contour interval of 10 m. The geological map of Micheluccini et al. (1971) modified after new field data has been superimposed on the DTM (Fig. 2). Using the overlay technique the topographical data layer is superimposed to the structural-geological layers of the sedimentary substratum. The sedimentary substratum layers have been obtained by the analysis of the available geophysical data calibrated by shallow and deep boreholes data (La Torre et al. 1981; Borghetti et al. 1983). All the information has been processed using a GIS database. Two maps have been obtained and compared: the map of the top of the Pliocene-Pleistocene clay-sandy sediments associated with the Cenozoic siliciclastic turbidites and the map of the top of the resistant substratum made of Mesozoic limestones (see Fig. 3).

Structural data were derived combining morphotectonic lineaments and drainage network extracted by DTM spatial analysis.

The DTM allowed quantitative morphological analyses of the domes and determination of their spatial distribution. The aim of these analyses was to identify the main morphological characteristics of each dome such as slope, aspect ratio, volume and eccentricity. Each of these characteristics has been quantified directly from the geological map and the DTM by means of the GIS.

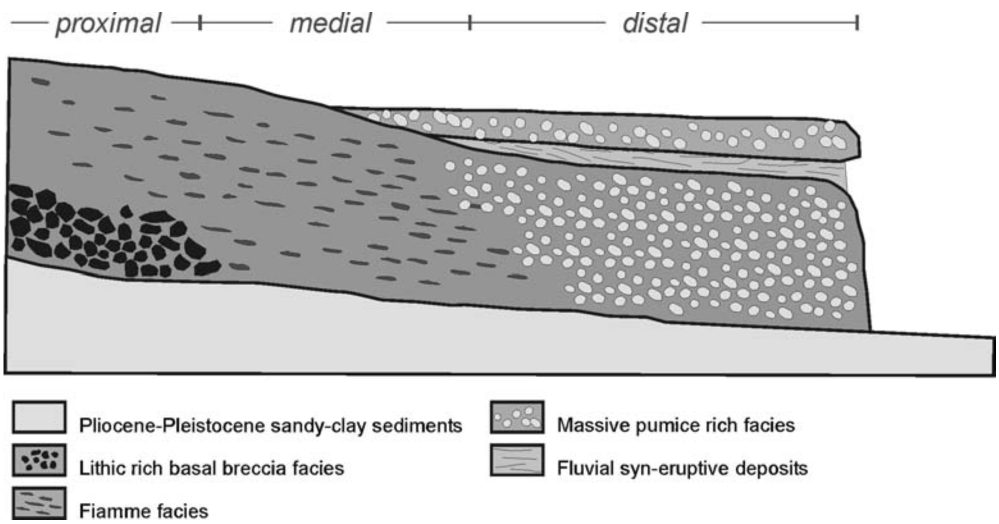

Fig. 4 Schematic radial section respect to Mt. Cimino (*left*). The sketch shows variation of proximal, medial and distal facies in the ignimbrite deposits (not to scale)

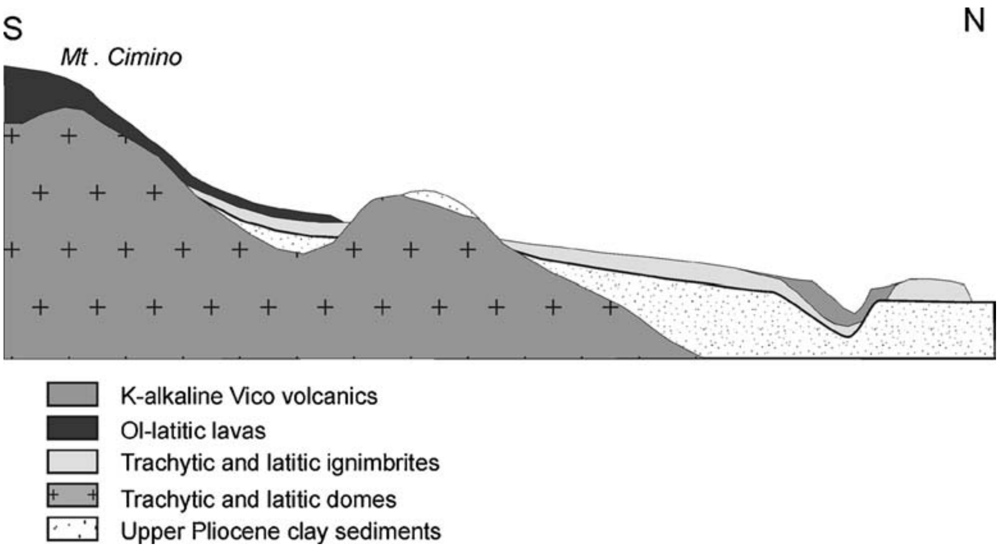

Fig. 5 Idealized N–S section illustrating the Cimini stratigraphy

Structure and evolution of the CDC

Data presentation

The Cimini domes outcrop over a NW-trending area, 16 km long and 7 km wide. The domes are aligned along NW and NE-trending fracture systems and are approximately distributed following a semi-radial and semi-annular pattern from the Mt. Cimino dome. The area of the domes constitutes a NW-trending topographic relief whose margins gently decline from the altitude of 1,052 m of Mt.Cimino to an average altitude of 290 m, which is also the average altitude of the young alkali-potassic volcanic cover of Vico volcano. The break in slope between the Cimini domes and the volcanic plateau of Vico is evident (Fig. 2).

The analysis of more than 70 stratigraphic sections indicates that at least two ignimbrite eruptions occurred. Ignimbrite deposits are separated by a 1 m thick, normal graded, gravel-to sand-size deposit, whose upper part show cross-bedded laminations and intercalations of lithic or pumice concentration lenses. Clastic component is monogenetic and derived from the lower ignimbrite, suggesting a syneruptive nature of the deposit. The ignimbrite deposits show lateral facies variations: proximal deposits are mainly made of massive coarse lithic rich breccia, medial deposits are generally welded and characterized by the presence of fiamme, while distal facies are made of massive pomiceous deposits (Fig. 4). Lateral facies variations are also caused by topographic irregularities due to the presence of domes: veneer facies developed at the margins or on top of lava domes, whereas massive valley ponded facies developed in the topographic depressions.

There is no evidence that ignimbrite deposits have been deformed by the emplacement of domes. Anywhere the contact between domes and ignimbrites is visible, the ignimbrites directly overlie the domes. No soils have been found between domes and ignimbrites. Olivine latitic lavas, mostly emplaced in the northeastern sector of the Cimini complex, represent the final effusive episode. Stratigraphical relationships of the Cimini area are represented in Fig. 5.

Comparing the top surfaces of the main sedimentary complexes below the volcanics it is possible to evaluate the relationship between the Cimini volcano and its sedimentary substratum (Fig. 3).

The sedimentary succession made of the Mesozoic calcareous units (resistant complex) appears dissected in horsts and grabens bordered by NE and NW-trending faults. The upper complex made of Pliocene-Pleistocene post-orogenic sediments and by Cenozoic siliciclastic turbidites shows lateral thickness variations. There is an apparent structural high of the upper sedimentary complex in the Mt. Cimino area, over the graben of the Mesozoic complex.

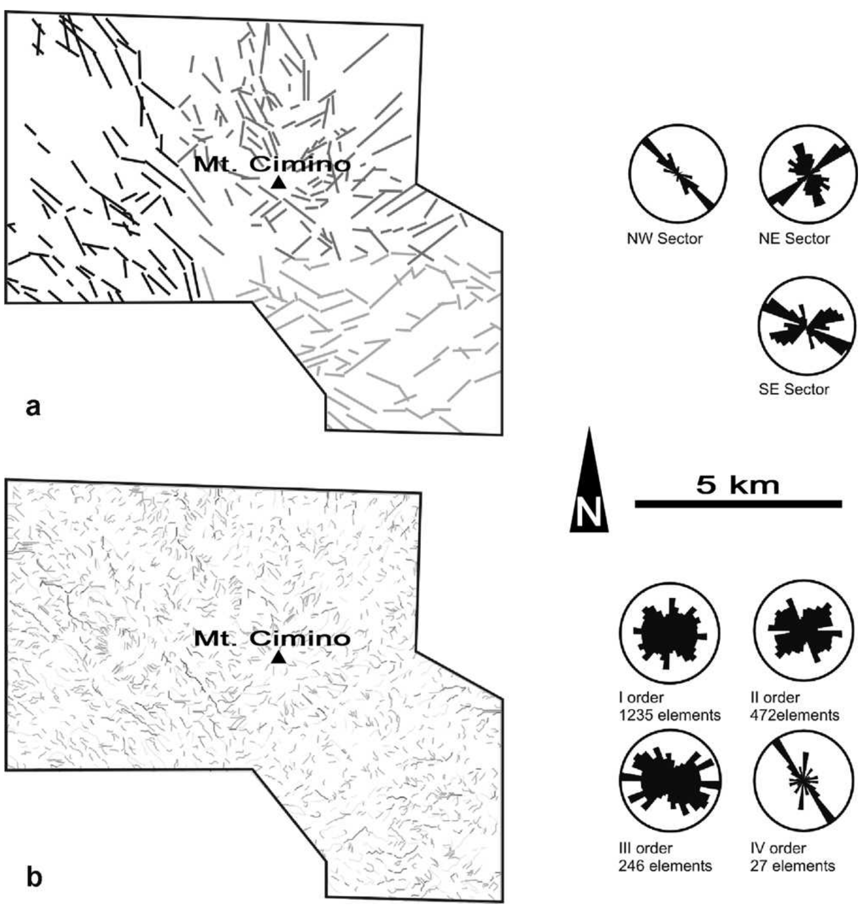

Fig. 6 Morphotectonic lineaments and rose diagrams for different sectors of the Cimini area **a**. Drainage network of the Cimini area and rose diagrams for different orders of the drainage lines **b**

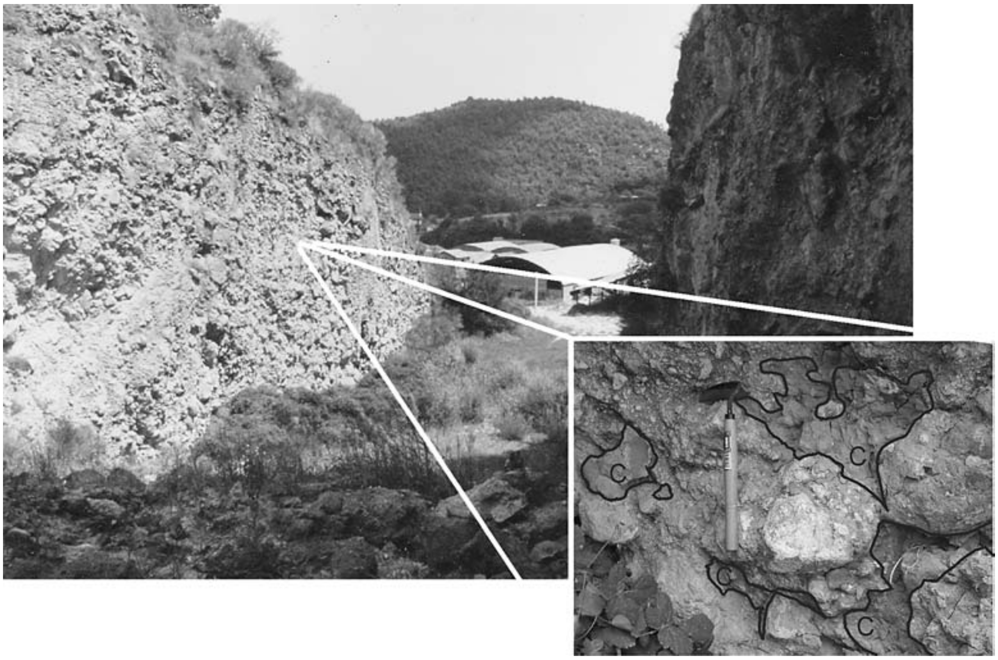

Fig. 7 Quarry cut at Fornace Pacifici. The dome, here, shows a thick carapace. Blocks of the lava dome are mingled with blocks of thermally metamorphosed clayey sediments (C). At present, the contact between the lava dome and the uplifted clayey sediments is not more visible. This contact is testified by the photo (Fig. 6) in the work of Mittempergher and Tedesco (1963)

The apex of the structural high coincides with the location of Mt. Cimino, where geophysical data indicate the presence of negative gravimetric anomaly and positive magnetic anomaly (La Torre et al. 1981; Borghetti et al. 1981, 1983). These data indicate the presence of an intrusive body at shallow depth.

To estimate the size of the magmatic body we have considered the entity of the deformation shown by the GIS and we have compared it with geophysical data (La Torre et al. 1981). We estimated a thickness of the magmatic body around 2,000 m, taking into account that the AGIP data indicate a depth of less than 1,000 m for the top of the Cenozoic siliciclastic turbidites. Considering that the upswelled area has an almost circular shape whose minimum and maximum radius are respectively of 3 and 11 km, we obtain a volume in the range of 60–100 km^3.

Fig. 8 Photo of Mt. Monterone lava dome. A succession of lava flows indicates the extrusive nature of the dome

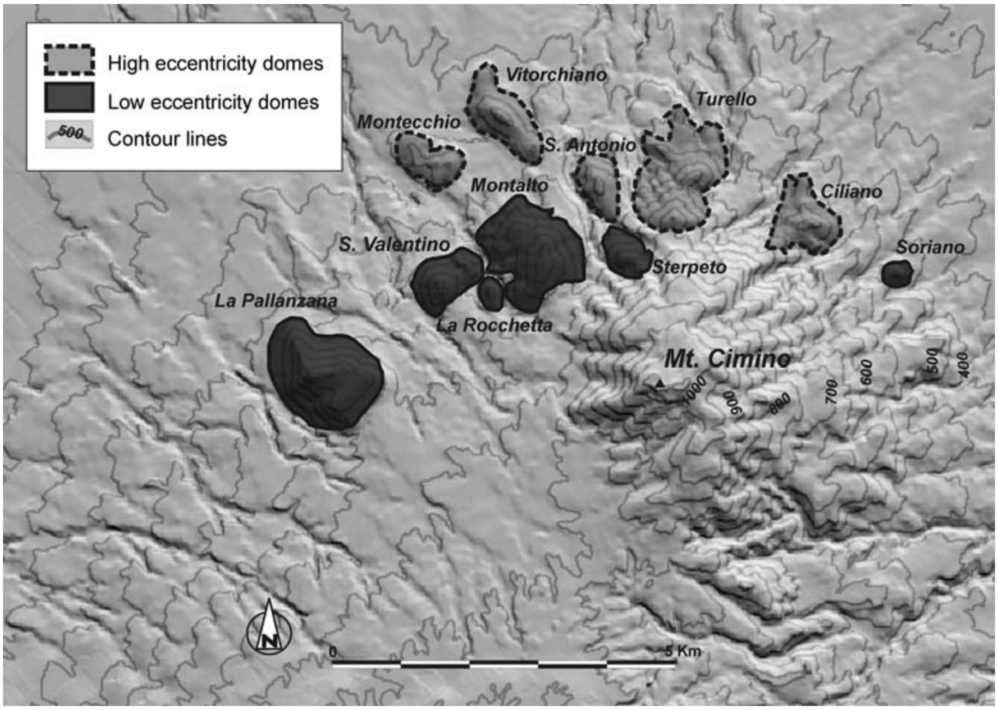

Fig. 9 The 11 domes identified by GIS analysis and their location in the Cimini area. Domes with low eccentricity (*dark gray domes*) are mainly located at the center of the Cimini area close to Mt. Cimino (*solid point* of Fig. 10b), whereas those with high eccentricity (*light gray* color) occupy a more external position (*open circles* in Fig. 10b)

Table 2 Morphological characteristics of the Cimini domes

No.	Domes	Diam. (m) Max.	Min.	Med.	Elev. (m) Eccentricity	Max	Min	Volume (m^3)	Aspect ratio
1	Ciliano	1056	558	870	0.52	590	450	8436673	0.16
2	Rocchetta	444	263	339	0.59	670	560	2206600	0.32
3	Montalto	1416	834	1242	0.58	780	520	45344031	0.20
4	La Pallanzana	1490	1043	1265	0.7	800	540	79954900	0.20
5	Montecchio	864	325	679	0.37	540	460	5481606	0.11
6	S.Antonio	900	405	590	0.44	610	470	7728937	0.23
7	S.Valentino	926	541	744	0.58	710	520	15360328	0.25
8	Soriano	374	277	292	0.7	500	430	1636533	0.23
9	Sterpeto	723	411	553	0.56	770	570	7014614	0.36
10	Turello	1524	785	1248	0.51	750	430	36800425	0.25
11	Vitorchiano	1329	474	826	0.35	750	430	19163523	0.38

The morphotectonic lineaments and the drainage network obtained from the DTM (Fig. 6) have been analysed to evaluate the effect of the local vs regional stresses on the development of the Cimini dome complex.

Rose diagrams show a large dispersion of the lineaments. Nevertheless, it is possible to observe that NW and NE trending lineaments are the most frequent. According to Sollevanti (1983), they have regional significance. NW-trending faults acted also after the end of the Cimini volcanism: they lowered the south-western part of the volcanic complex, which is now covered by the Vico volcanics.

Another question concerns the endogenous or exogenous nature of the lava domes. Field data indicate that both types exist. At Fornace Pacifici (S. Valentino dome, see Figs. 2 and 7) it is evident that the dome, there, was emplaced as a cryptodome with an endogenous growth mechanism, causing the uplift of the overlying Pliocene clay sediments. A quarry cut, over 20 m thick, shows the intrusive contacts between the lava of the dome and the clay sediments: blocks of the dome carapace are mingled with thermally metamorphosed clay sediments and covered by the veneer facies of the ignimbrite. A photo in the paper of Mittempergher and Tedesco (1963) clearly shows the clayey sediments on top of the lava. Unfortunately, this part of the quarry has been destroyed. This type of dome has thick carapace breccia, probably formed by the autobrecciacion of the lava stressed by the internal extrusion of fresh magma.

Conversely, at Mt. Monterone the dome shows an exogenous growth mechanism, evidenced by its inner structure constituted by the superimposition of thin lava flows gently dipping away from the top of the dome. The dome shows a coulée morphology (Fig. 8).

Unfortunately, there are not clear exposures of the internal structures of each dome. However, the GIS analysis has allowed to evidence the morphological characteristics of 11 domes (Fig. 9).

Most of the domes are enclosed inside the 430 m contour line and their average median slope is 14%. On the base of these two parameters and through the comparison with the geological map, the GIS allowed the determination of the aspect ratio, eccentricity and volume (Table 2). Aspect ratio and volume range from 0.11 to 0.38 and from 1.6×10^6 to 79.9×10^6 m^3, respectively.

In the classification scheme proposed by Blake (1990) the Cimini domes plot between the lines corresponding to Pelean and low lava domes (Fig. 10a).

By comparing aspect ratio and eccentricity (Fig. 10b), the domes are of two types displaying high or low eccentricity, the former displaying a wider range of aspect ratio. The domes just around Mt. Cimino have low eccentricity; they are sub-circular with steep slopes, and are enveloped by a thick carapace of breccias. High eccentricity domes are located furthest from Mt. Cimino (Fig. 9). They have more irregular morphologies: lower elevations, gentle slopes and usually show a preferential direction of development. Their maximum diameters are oriented radially from Mt. Cimino area.

Discussion of the data

Data presented so far allow to reconstruct a new model for the evolution of the CDC. The overlay technique of the GIS system has evidenced a deformation of the upper sedimentary complex below the CDC. According to the geophysical data this deformation may be interpret as due to the presence of a laccolith body whose intrusion produced the swelling of the area. The intrusion of the laccolith occurred in a structural low that can be interpreted as a minor NE-trending transversal graben (respect to the main NW-trending graben). The intrusion occurred at the contact between the Cenozoic siliciclastic turbidites and the Pliocene-Pleistocene sandy-clayey sediments (Fig. 11).

In fact, these last sediments are outcropping at an altitude of 400 m on top of some domes. Conversely no siliciclastic turbidites sediments are ever outcropping. They are present as lithic clasts in some domes lavas. The dimensions of the laccolith and the structural framework into which it developed are comparable with those evaluated for the Tolfa area, south-west of the Cimini area (De Rita et al. 1997). Domes developed after the emplacement of the laccolith, as the consequence of extensional stresses related to the swelling of the area, in turn due to the shallow magmatic intrusion. The high eccentricity of the external domes is controlled by

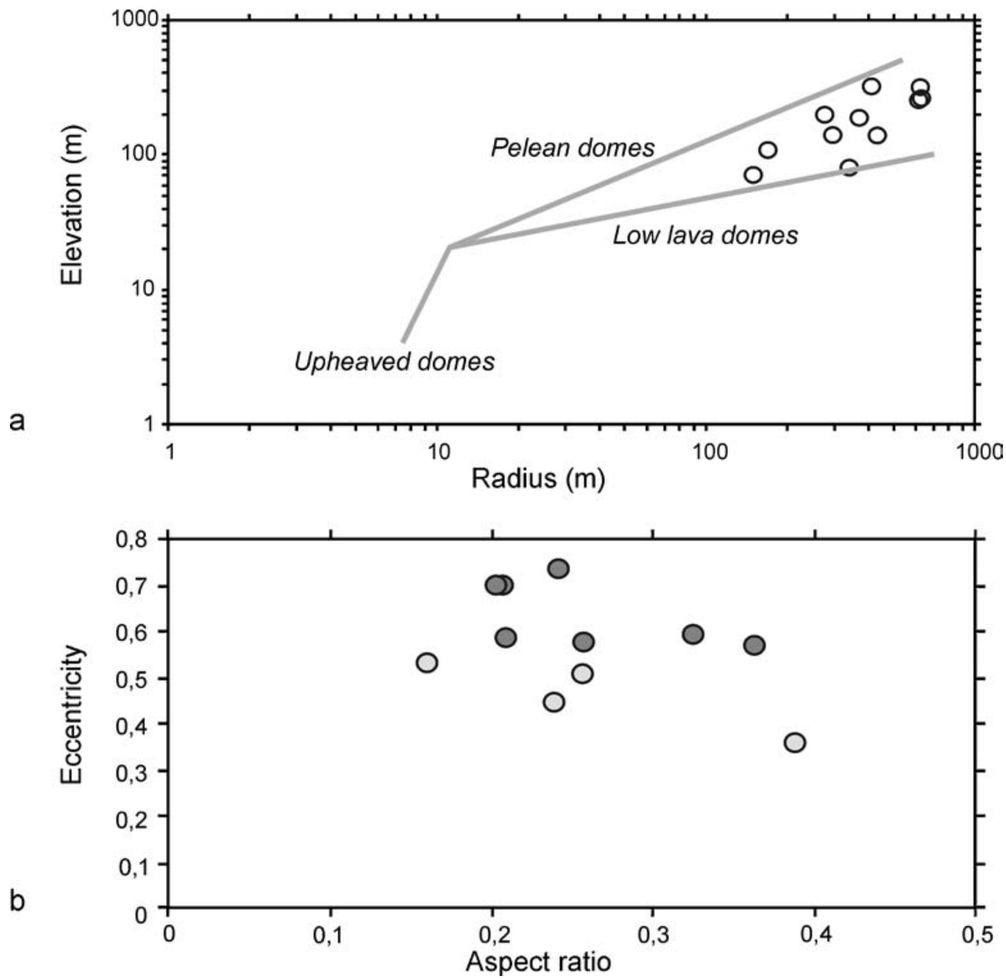

Fig. 10 In the Blake (1990) morphological classification of lava domes, the Cimini domes range from Peleean to low lava dome type **a**. Plot of Cimini domes in eccentricity vs. aspect ratio diagram. On the base of their eccentricity (ratio of maximum and minimum diameters) the Cimini domes can be grouped in two types **b**

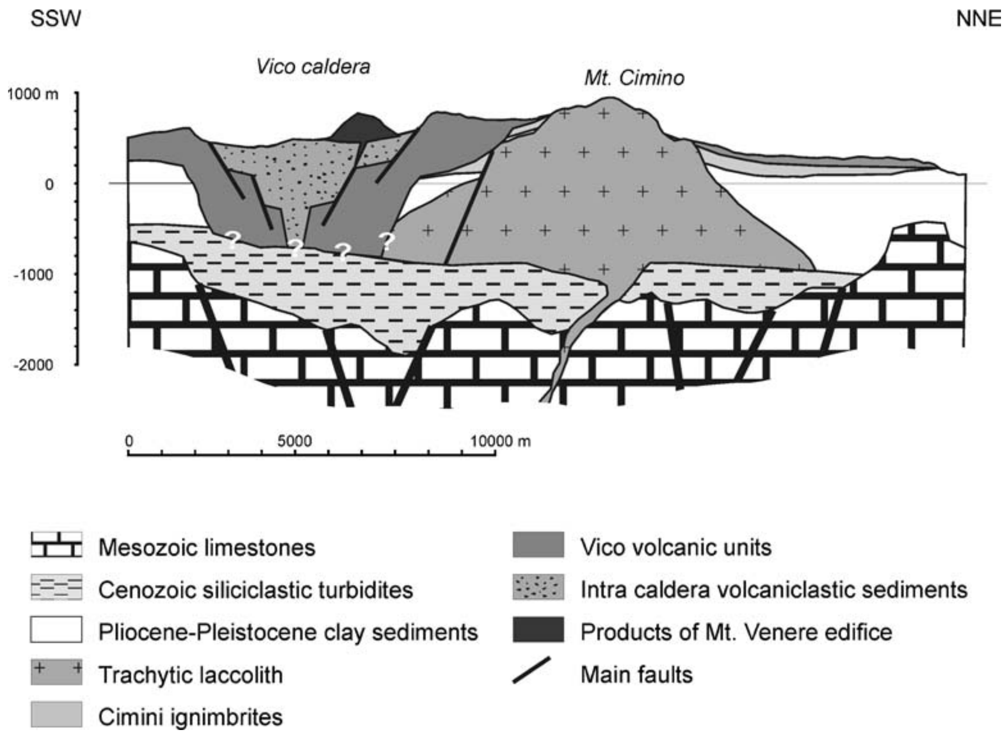

Fig. 11 Interprertative cross section illustrating the relationship between the Cimini laccolith and the sedimentary substratum

the inclined surface produced by the laccolith. The endogenous or exogenous nature of the domes may be related to the rate of the local extension controlling the effusion rate of the emplacing lava domes. Accordingly, the exogenous domes prevail where the maximum extension occurred. The final evolution of the CDC was the explosion of the two ignimbrites. The ignimbrites were erupted shortly after the dome emplacement and their emplacement had to be close in time. In fact no soils or erosional surfaces are present between domes and ignimbrite deposits. Moreover, the two ignimbrites are separated by syneruptive fluvial deposits. This conclusion is also supported by (1) ignimbrites and domes have the same chemical-petrographic composition (Puxeddu 1971; Aulinas et al. 2004); (2) ignimbrites contain lithic clasts of the lava domes; (3) no ignimbrite xenoliths have been found in the lava of the domes.

Conclusions

The evolution of the Cimini volcanic complex can be summarized in four main phases (Fig. 12)

- Phase 1: intrusion of a laccolith, rising along NW and NE trending faults, at the contact between the Mesozoic-Cenozoic and Pliocene-Pleistocene sedimentary units. We estimated a volume of the laccolith in the range of 60–100 km^3. The size of the laccolith and the structural framework into which it developed are comparable with those evaluated for other laccoliths emplaced in Latium area (De Rita et al. 1997).
- Phase 2: emplacement of the domes following radial and tangential fractures formed as consequence of the swelling induced by the laccolith intrusion. Gudmundsson et al. (1997) suggested that sill-like magma chambers located in areas of doming are likely to generate stress fields that encourage the initiation of ring faults.
- Phase 3: ignimbrite eruptions. Ignimbrite eruptions seem to occur mainly from the central Mt.Cimino dome, located at the apex of the updomed area. The eruptions could have been triggered by decompression related to the local extension of this sector. It is also possible that some ignimbrite deposits at a distance of more than 10 km from the central area, and characterized by the presence at the base of basal lag breccia are related to eruptions from ring faults.
- Phase 4: effusions of the final olivine latitic lavas.

The evolution of the Cimini volcanism occurred in a very short time as indicated by the absence of soils and of inter-eruption deposits between the volcanics. The lack of inter-eruption deposits probably induced previous authors to think that only one ignimbrite eruption occurred. On the other hand, it justifies the radiometric age data that are superimposed in the range of the analytical error. The last more basic lava flows indicate a deeper provenance of the magma, possibly reflecting an increasing rate of regional extension and/or the uprise of a deeper less evolved part of a stratified magma chamber.

This reconstruction is based on the interpolation of interdisciplinary data through a dedicated GIS and answers many questions concerning the evolution of the Cimini dome complex. The use of GIS has allowed an explanation of the different morphologies of the domes as due to their location on the swelled area, and to discriminate local

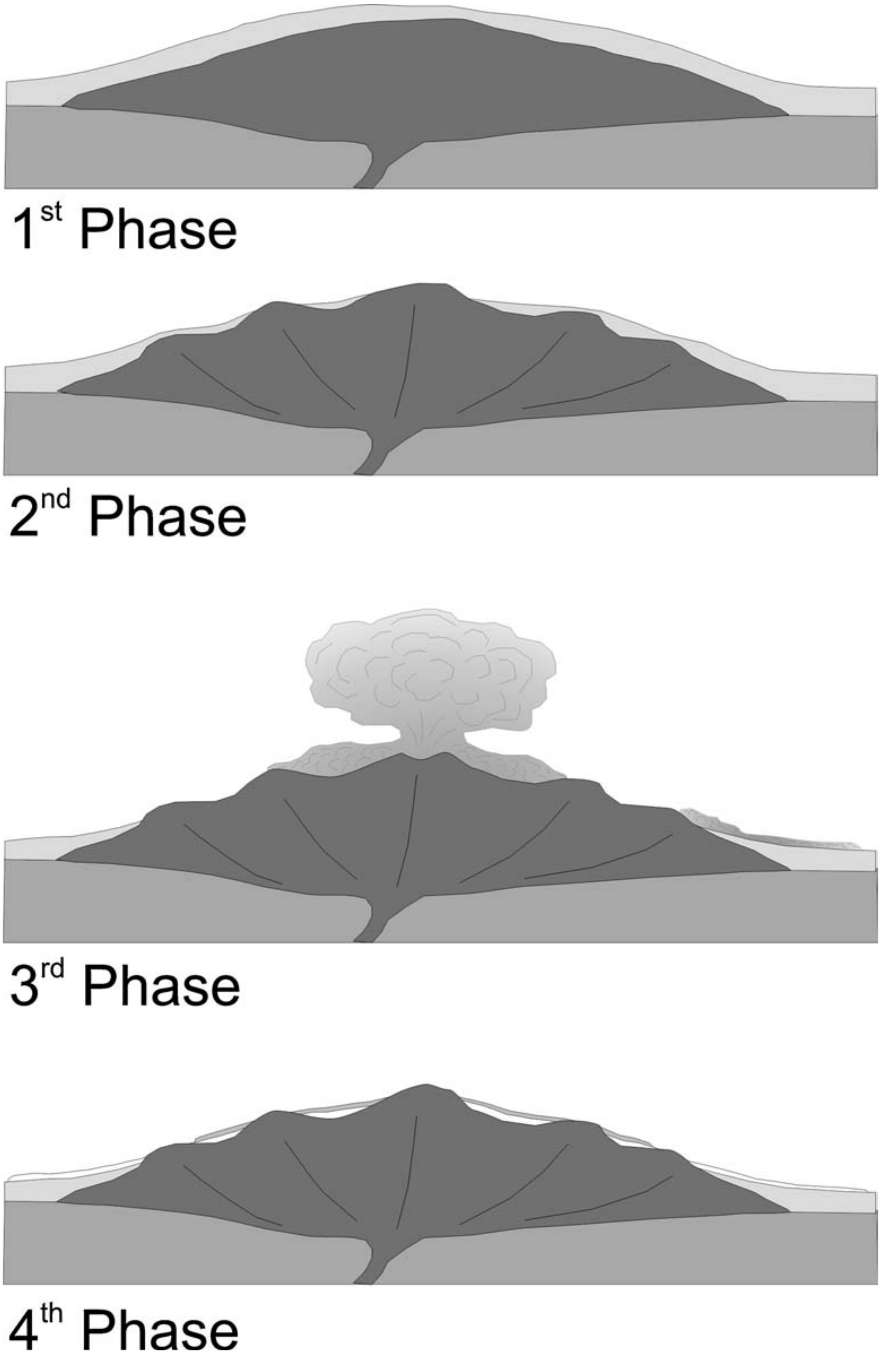

Fig. 12 Conceptual model of the evolution of the Cimini volcanic complex (not to scale). Phase 1: intrusion of a laccolith at the contact between the Mesozoic-Cenozoic and the Pliocene-Pleistocene sedimentary units. Phase 2: emplacement of the domes following radial and tangential fractures formed because of the swelling of the area. Phase 3: ignimbrite eruptions. Phase 4: effusions of the final ol-latitic lavas

deformations caused by the laccolith emplacement from those related to the regional tectonics.

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