

# Magma chamber evolution prior to the Campanian Ignimbrite and Neapolitan Yellow Tuff eruptions (Campi Flegrei, Italy)

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**Abstract** The Campi Flegrei (Campanian Region, Italy) experienced two cataclysmic caldera-forming eruptions which produced the Campanian Ignimbrite (39 ka, CI) and the Neapolitan Yellow Tuff (15 ka, NYT). We studied the minor eruptions before both these large events to understand magma chamber evolution leading towards such catastrophic eruptions. Major, trace element, and Sr and Nd isotope compositions of pre-Campanian Ignimbrite and pre-Neapolitan Yellow Tuff products define distinct geochemical groups, which are here interpreted as distinct magma batches. These batches do not show any transitional trend towards the CI and NYT eruptions. The CI and NYT systems are decoupled geochemically and isotopically. At least one of the pre-CI and one of the pre-NYT erupted magma batches qualifies as mixing endmembers for the large CI and NYT eruptions, and thus, must have been stored in reservoirs for some time to remain available for

the CI and NYT eruptions. The least evolved, isotopically distinct magma compositions that are typical of the last phases of the NYT and CI eruptions did not occur before caldera-forming events. Based on the new data, we propose the following scenario: Multiple magma chambers with distinct compositions existed below the Campi Flegrei before the CI and NYT eruptions and remained generally separated for some time unless new magma was recharged. In each case, one of the residing magma reservoirs was recharged by a new large-volume magma input of intermediate composition from a deeper differentiating magma reservoir. This may have triggered the coalescence of the previously separated reservoirs into one large chamber which fed the cataclysmic caldera-forming eruption. Large magma chambers in the Campi Flegrei may therefore be ephemeral features, interrupted by periods of evolution in individual, separated magma reservoirs.

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## Introduction

The study of volcanic rocks emplaced before large caldera-forming eruptions is of great importance to understand the processes responsible for evolution, growth, and size of large magma chambers. These rocks should bear also essential clues on how magma systems evolve towards cataclysmic eruptions. As such, the products of the precursor activity of large caldera eruptions may provide information for assessing volcanic hazards that is of similar importance as the products of large caldera-forming events themselves.

The Campi Flegrei (Campanian Region, Southern Italy) is a nested caldera structure formed during two climactic eruptions (Orsi et al. 1996): the Campanian Ignimbrite (CI, 39.28 ka; De Vivo et al. 2001) and the Neapolitan Yellow Tuff (NYT, 14.9 ka; Deino et al. 2004). We try to understand how these large and potentially dangerous magma chambers formed and developed by studying the products of many individual eruptive events before 39 ka and between 39 and 15 ka.

In this paper, we present new geochemical and isotopical data of the pre-Campanian Ignimbrite (pre-CI) and pre-Neapolitan Yellow Tuff (pre-NYT) eruption products based on analyses of pumice clasts from two sections (Trefola quarry, TL and Ponti Rossi, PR).

### Geology of the Campi Flegrei area

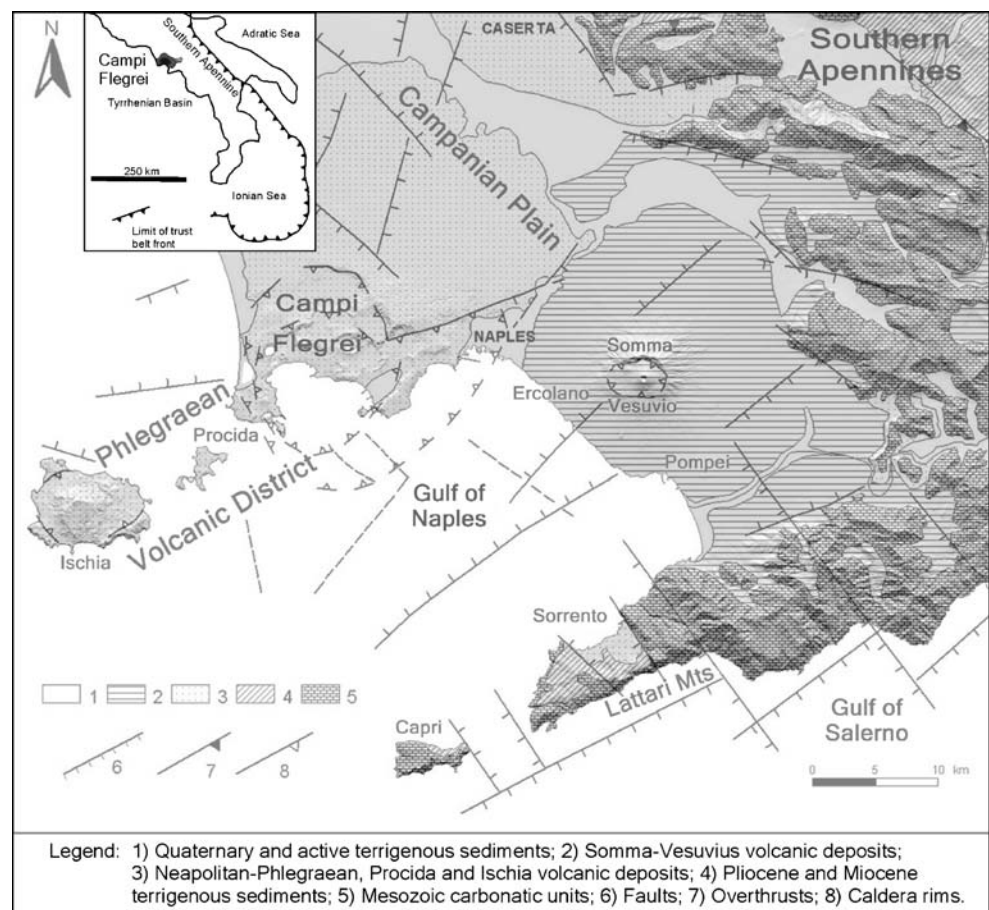
The Campi Flegrei caldera is located within the Campanian Plain along the western margin of the Southern Apennines mountain chain (Fig. 1). The Campanian Plain is composed of 2–3 km thick sequences of Plio-Quaternary continental, deltaic, and marine sediments intercalated with volcanic deposits. It is underlain by a graben formed during

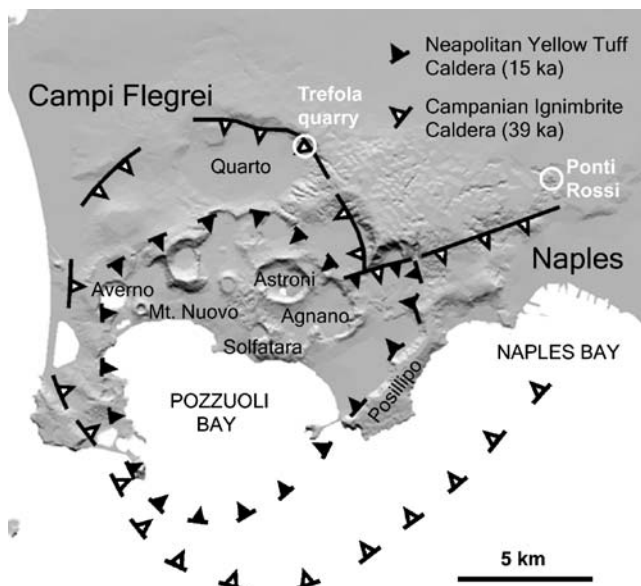
activation of NW–SE and NE–SW trending normal faults, which have downthrown the western Apennines during Quaternary times (Brancaccio et al. 1991).

Seismic data show that the top of the Mesozoic limestone basement beneath the Campi Flegrei caldera occurs at about 4 km depth (Zollo et al. 2003) above which no evidence of magma reservoirs of significant size ( $>1 \text{ km}^3$ ) has been found. Melt inclusion data of minerals in rocks younger than 39 ka indicate levels of crystallization at different depth: at about 10 and between 8 and 3 km, suggesting the occurrence of both deep and shallow magma reservoirs in the past (Cecchetti et al. 2001; Marianelli et al. 2006; Civetta and Rutherford, unpublished data).

The Campi Flegrei caldera includes a subaerial and a submerged part, which cover a total area of about  $230 \text{ km}^2$ . It is a resurgent nested structure (Fig. 2) formed during two major caldera collapses related to the eruptions of the Campanian Ignimbrite and the Neapolitan Yellow Tuff, respectively (Orsi et al. 1996). The geometry and dynamics of both large calderas, as well as of smaller volcano-tectonic collapses that occurred later, were deeply influenced by both local and regional stress regimes. Each large collapse affected the structural conditions of the system and constrained the vent locations of later volcanism. The onset of

**Fig. 1** Geological and structural sketch map of the Southern Campanian Plain (modified after Orsi et al. 2004)





**Fig. 2** Topographic map of the Campi Flegrei Region (modified after Orsi et al. 2004) with the Campanian Ignimbrite and the Neapolitan Yellow Tuff calderas and the sampling locations (Trefola quarry and Ponticcioli)

volcanism in the area is unknown. The oldest dated volcanic unit yielded an age of about 60 ka (Pappalardo et al. 1999) and is related to volcanism extending beyond the limits of the present caldera. Volcanic rocks older than the Campanian Ignimbrite are the product of both effusive and explosive eruptions. They are exposed only along the scarps that border the Campi Flegrei caldera and are mostly alkali-trachytic in composition (Pappalardo et al. 1999).

The CI eruption and caldera collapse (Fig. 2) was the earliest event to profoundly influence the present geological setting of the area. During this eruption, at least 200 km<sup>3</sup> of trachytic-to-phonotrichytic magma (DRE; Fedele et al. 2003) were emplaced as pyroclastic-fall and -flow deposits. An area of about 30,000 km<sup>2</sup> was covered by these highly mobile ignimbrites (Fisher et al. 1993). Volcanism between the CI and the NYT was confined within the caldera and characterized by explosive, mainly phreatomagmatic eruptions. Rocks related to this volcanism vary in composition from trachyte to alkali-trachyte to phono-trachyte (Pappalardo et al. 1999).

The NYT eruption and caldera collapse (Fig. 2) was the second more recent cataclysmic event in the history of the caldera and represents the largest known trachytic phreato-plinian eruption (Orsi et al. 1992). It emitted at least 40 km<sup>3</sup> (DRE) of latitic-to-trachytic magma emplaced as pyroclastic-fall and -flow deposits (Orsi et al. 1992, 1995). The latter deposits covered an area of more than 1,000 km<sup>2</sup> (Orsi et al. 1992). The resulting caldera covered an area of about 90 km<sup>2</sup> and was nested within the CI caldera (Orsi et al. 1996).

After the NYT eruption, both volcanism and deformation have been very intense within the caldera (Di Vito et al.

1999). There have been about 70 minor eruptions, the last of which occurred in A.D. 1538. The volcanic system is therefore still active, as also demonstrated by fumarolic and seismic activity and by recurrent repetitive episodes of unrest in the past 30 years (Orsi et al. 1999b and references therein). The volcanic rocks younger than NYT range in composition from shoshonite to peralkaline phonolite with trachyte and alkali-trachyte as the most abundant rocks (D'Antonio et al. 1999).

## Samples

Two volcanic successions at Trefola quarry (TL) and Ponticcioli (PR; Fig. 2), have been chosen and sampled, as they represent the most complete pre-CI and pre-NYT succession exposed in the area. Trefola quarry is situated in the northern Campi Flegrei area close to the northern border of the CI caldera. Ponticcioli is situated north of Naples near the outer margin of the CI caldera. Both stratigraphic sections were described in detail by Orsi et al. (1996), and we follow their stratigraphic nomenclature.

All collected samples are fresh, unweathered, and unaltered pumice and obsidian clasts. Trefola quarry exposes a thick sequence of pyroclastic deposits including twelve units below the CI (units TL<sub>a</sub> to TL<sub>n</sub>), five units between the CI and NYT deposits (units TL<sub>o</sub> to TL<sub>s</sub>), and five units above the NYT. The units are intercalated by reworked layers or palaeosols. The samples collected from units TL<sub>c</sub> and TL<sub>f</sub> are large pumice fragments (and in one case obsidian). Due to quarry conditions, the pre-CI units TL<sub>a</sub>, TL<sub>b</sub>, TL<sub>d</sub>, and TL<sub>e</sub>, as well as units TL<sub>g</sub> to TL<sub>n</sub>, were not sampled. Available geochemical data of these units will be taken from literature for the later discussions. The pre-NYT units TL<sub>o</sub> to TL<sub>s</sub> have been sampled completely. Orsi et al. (1996) described unit TL<sub>a</sub> as a pyroclastic-flow deposit, TL<sub>n</sub> is a succession of ashy pyroclastic-flow deposits, and units TL<sub>b</sub> and TL<sub>m</sub> are cross-laminated surge beds with minor fallout layers. The units TL<sub>c</sub> and TL<sub>f</sub> are complex sequences of pyroclastic deposits; units TL<sub>d</sub>, TL<sub>e</sub>, TL<sub>g</sub>, TL<sub>h</sub>, and TL<sub>i</sub> are distal fallout deposits (Orsi et al. 1996). The pre-NYT units TL<sub>o</sub> and TL<sub>s</sub> are pumice fallout deposits with minor surge beds, TL<sub>p</sub> is a distal ash fallout, TL<sub>r</sub> an ashy surge deposit, and unit TL<sub>q</sub> is an almost completely reworked ash deposit (Orsi et al. 1996).

Ponticcioli exposes a complete sequence between CI and NYT of nine units, which are intercalated by palaeosols. Units PR<sub>a</sub>, PR<sub>c</sub>, PR<sub>d</sub>, PR<sub>f</sub>, and PR<sub>h</sub> have been sampled (but not units PR<sub>b</sub>, PR<sub>e</sub>, PR<sub>g</sub>, and PR<sub>i</sub>). Available data of the missing units will be taken from literature for later discussion. Orsi et al. (1996) described unit PR<sub>a</sub> as a succession of distal surge beds with minor fallout layers. Units PR<sub>b</sub>, PR<sub>h</sub>, and PR<sub>i</sub> are described as surge beds, PR<sub>i</sub> also contains angular pumice clasts. The units PR<sub>c</sub>, PR<sub>d</sub>,

**Table 1** XRF and ICP-MS whole rock data of pre-CI and pre-NYT eruptions

Sample	TLe-1	TLe-2	TLe-3	TLe-4	TLe-5	TLe-6	TLe-7	TLe-8	TLf-9	TLf-10
SiO <sub>2</sub>	56.4	56.7	56.8	57.5	56.6	56.3	56.5	56.1	56.5	56.4
TiO <sub>2</sub>	0.40	0.41	0.41	0.41	0.41	0.40	0.41	0.41	0.41	0.42
Al <sub>2</sub> O <sub>3</sub>	18.7	18.9	18.8	19.2	18.9	18.8	18.8	18.6	18.4	18.6
Fe <sub>2</sub> O <sub>3</sub> tot	4.07	4.09	4.11	4.15	4.1	4.08	4.11	4.11	3.76	3.87
MnO	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.21	0.22
MgO	0.33	0.33	0.32	0.35	0.33	0.34	0.35	0.37	0.42	0.46
CaO	2.03	2.04	2.01	2.07	2.02	1.98	2.09	2.12	2.08	2.09
Na <sub>2</sub> O	6.61	6.61	6.67	6.79	6.56	6.52	6.54	6.31	5.44	5.38
K <sub>2</sub> O	7.17	7.2	7.25	7.32	7.29	7.19	7.15	7.05	7.39	7.26
P <sub>2</sub> O <sub>5</sub>	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.07	0.08
L.O.I.	2.70	2.62	2.39	1.17	1.96	2.96	2.97	3.46	4.15	4.35
Sum	96.03	96.60	96.68	98.12	96.53	95.94	96.27	95.39	94.68	94.77
Sc	4	3	1	1	1	4	6	<LLD	0	3
V	11	13	12	15	15	17	17	17	18	25
Ni	4	4	3	5	3	3	6	7	5	3
Zn	141	142	144	142	143	140	142	138	121	120
Ga	22	24	24	24	23	22	23	21	23	19
Rb	420	418	423	424	420	418	418	407	368	362
Sr	20	23	20	21	20	24	33	48	49	62
Y	71	68	71	72	73	73	72	69	53	54
Zr	733	735	751	745	740	741	738	721	541	550
Nb	131	134	135	131	130	130	130	127	97	97
Mo	6.60	6.97	7.31	6.39	7.45	7.27	7.20	7.05	6.57	6.45
Sn	8.66	8.72	8.91	8.90	9.03	8.76	8.89	8.91	6.56	6.69
Sb	2.10	1.73	1.98	2.27	2.20	2.11	2.26	2.09	1.18	1.51
Cs	36.5	35.1	37.2	36.6	37.9	36.3	37.2	36.4	27.1	27.0
Ba	23	33	32	8	20	13	41	66	39	54
La	114	95	107	61	114	111	123	112	60	85
Ce	225	204	209	171	223	198	234	216	151	166
Pr	22.6	19.1	21.9	12.8	22.4	21.9	23.9	22.4	12.5	17.0
Nd	77.0	65.1	74.0	44.9	77.7	75.3	82.1	76.8	43.5	58.0
Sm	13.7	11.6	12.8	8.7	13.5	13.2	14.4	13.3	8.0	10.2
Eu	1.30	1.14	1.24	0.85	1.29	1.25	1.37	1.29	1.03	1.33
Gd	13.9	12.0	13.2	9.0	14.0	13.5	14.6	13.6	8.3	10.4
Tb	1.85	1.63	1.74	1.29	1.80	1.75	1.94	1.74	1.15	1.37
Dy	10.20	9.14	9.90	7.49	10.20	9.77	10.60	9.89	6.49	7.48
Ho	1.98	1.76	1.82	1.47	1.95	1.87	2.04	1.83	1.24	1.41
Er	5.78	5.25	5.45	4.45	5.66	5.37	5.91	5.38	3.73	4.15
Tm	0.855	0.783	0.805	0.689	0.872	0.818	0.883	0.811	0.557	0.609
Yb	5.81	5.40	5.50	4.79	5.71	5.36	5.91	5.41	3.84	4.14
Lu	0.899	0.820	0.821	0.744	0.885	0.835	0.904	0.833	0.576	0.618
Hf	17.0	16.9	17.0	17.4	17.3	16.7	17.1	16.8	12.6	12.7
Ta	5.93	4.02	6.49	6.72	7.19	6.65	7.44	6.92	2.19	5.02
W	8.59	9.12	9.36	8.07	10.00	9.74	10.00	9.67	7.63	8.68
Pb	65.1	63.3	63.6	68.1	62.2	62.5	63.6	63.1	54.9	55.4
Th	57.2	49.4	51.5	37.8	53.0	52.3	56.7	53.1	31.2	37.9
U	18.9	15.4	14.9	11.1	16.1	15.7	18.2	16.6	8.3	10.9

and PRf are pumice fallout deposits, PRc also includes an ash bed. Unit PRe is described as a thin reworked ash deposit (Orsi et al. 1996).

Pumice samples of eruptions older than CI (pre-CI) tend to have a gray to dark gray color and are angular and

relatively large in size (up to 8 cm). The CI eruption marks a change in pumice characteristics. Between the CI and NYT eruptions (pre-NYT), pumice samples are denser with small vesicles, light beige in color, and more rounded in shape with respect to pre-CI pumices.

TLf-11	TLo-1	TLo-2	Tlo-3	TLp	TLq	TLr	TLs-1	TLs-2	TLs-3	TLs-4
56.6	60.7	59.9	60.5	60.1	58.7	57.9	59.6	59.7	59.8	58.4
0.41	0.40	0.40	0.41	0.43	0.42	0.41	0.42	0.42	0.42	0.42
18.5	17	16.8	17	17.2	17.5	17	17.4	17.5	17.5	17.6
3.84	2.67	2.65	2.74	2.93	3.2	2.89	2.89	2.94	2.89	3.33
0.21	0.18	0.17	0.17	0.18	0.13	0.15	0.15	0.15	0.16	0.14
0.43	0.22	0.23	0.27	0.33	0.48	0.35	0.3	0.33	0.32	0.55
2.07	1.5	1.51	1.53	1.57	2.16	1.84	1.87	1.88	1.87	2.33
5.58	5.58	5.57	5.62	5.23	4.3	4.79	4.9	4.93	4.94	4.22
7.41	6.73	6.71	6.78	6.8	8.14	7.5	7.62	7.62	7.61	8.18
0.08	0.04	0.04	0.04	0.05	0.09	0.06	0.05	0.05	0.06	0.09
3.88	3.98	4.05	3.95	4.26	3.80	4.00	3.72	3.58	3.70	3.75
95.13	95.00	93.98	95.06	94.82	95.12	92.88	95.20	95.53	95.57	95.26
<LLD	<LLD	1	1	<LLD	<LLD	3	2	0	<LLD	5
24	19	25	23	31	48	36	36	39	36	54
3	3	8	3	6	5	5	2	2	4	5
122	90	88	92	94	78	82	86	87	86	78
19	20	20	13	21	18	17	20	18	18	17
363	448	444	448	430	331	374	374	374	360	335
54	1	38	34	56	265	114	71	76	70	290
57	61	59	63	69	43	47	47	51	51	27
547	730	694	716	672	367	471	477	483	477	364
96	102	98	104	96	51	71	73	75	75	54
6.53	6.38	7.15	6.80	6.83	6.73	7.20	6.94	7.20	7.11	6.28
6.86	7.31	7.45	7.55	7.33	4.46	5.68	5.56	5.48	5.59	4.53
1.25	2.08	2.00	2.08	2.08	0.97	1.45	1.40	1.30	1.36	0.97
27.4	41.6	40.7	42.0	39.4	20.1	27.8	27.0	27.3	26.9	20.5
32	18	17	21	47	193	69	24	31	18	171
62	74.2	111	64.5	116	68	95	83	77.5	97	39.6
151	151	196	141	208	134	165	156	146	169	96.3
12.7	14.0	21.1	12.5	21.8	13.9	18.6	16.5	15.4	19.8	8.2
45.1	45.4	69.6	41.7	74.8	49.4	66.1	58.2	54.2	68.8	30.3
8.1	7.8	11.6	7.1	12.6	8.8	11.6	10.5	9.8	12.0	5.6
1.07	0.78	1.16	0.74	1.39	1.80	1.68	1.53	1.44	1.76	1.16
8.6	8.12	11.8	7.54	12.9	8.7	11.4	10.3	9.68	11.6	5.76
1.14	1.09	1.54	1.00	1.60	1.11	1.43	1.33	1.24	1.49	0.73
6.68	6.15	8.59	5.96	8.95	5.85	7.71	7.08	6.68	7.98	4.04
1.27	1.24	1.65	1.16	1.72	1.09	1.44	1.35	1.28	1.48	0.76
3.74	3.89	4.98	3.69	5.09	3.15	4.12	3.90	3.63	4.35	2.17
0.572	0.613	0.757	0.575	0.792	0.454	0.627	0.575	0.544	0.627	0.328
3.88	4.33	5.28	4.10	5.33	3.10	4.11	3.90	3.60	4.23	2.16
0.610	0.672	0.808	0.623	0.843	0.465	0.645	0.598	0.561	0.641	0.334
12.8	16.8	17.4	16.7	16.2	8.9	11.8	11.7	11.5	12.0	8.34
2.29	5.02	5.01	5.26	5.32	2.74	4.23	4.29	3.76	4.19	2.77
7.54	8.28	8.42	7.98	8.80	7.38	8.42	8.61	8.24	8.68	7.16
56.9	61.1	60.8	62.2	61.9	51.1	57.7	57.9	57.1	58.0	51.6
32.2	43.8	65.3	38.5	64.7	33.7	47.9	41.8	38.0	48.5	19.1
8.9	13.3	19.2	11.7	19.1	9.6	14.6	10.8	10.9	14.9	5.91

## Analytical procedure

Analyzed samples are whole-rock composites of pumices from individual layers. Each sample comprises representative pumices (~500 g) which are similar in color, texture, and crystal content. All samples were washed in distilled water, crushed to lapilli-size particles, then ground and homogenized in an agate mortar. Powders were molten to

glass discs for major and trace elements by X-ray fluorescence spectrometry (XRF) at Geowissenschaftliches Zentrum Göttingen (GZG). Solutions of sample powders were analyzed for trace elements by inductively coupled plasma-mass spectrometry (ICP-MS) at GZG. The analytical precision for major elements analyzed by XRF is better than 1%, but varies between 1 and 2% for Na, Mg, and P. The error ranges from 5 to 10% for trace elements detected

**Table 1** (continued)

Sample	PRa	PRc1	PRc2	PRd1	PRd2	PRf1	PRf2	PRh
SiO <sub>2</sub>	57.8	58.6	59.1	58.8	56.8	58.8	57.1	57.9
TiO <sub>2</sub>	0.40	0.41	0.42	0.41	0.48	0.42	0.41	0.42
Al <sub>2</sub> O <sub>3</sub>	17.2	17.5	17.6	17.6	17.7	17.2	16.8	17.4
Fe <sub>2</sub> O <sub>3</sub> tot	2.98	3.17	3.21	3.13	4.45	2.82	2.74	3.24
MnO	0.129	0.135	0.134	0.134	0.118	0.153	0.151	0.134
MgO	0.46	0.51	0.51	0.48	1.04	0.33	0.32	0.53
CaO	1.97	2.06	2.19	2.12	3.35	1.89	2.11	2.72
Na <sub>2</sub> O	4.19	4.06	4.11	4.06	3.2	4.69	4.73	4.03
K <sub>2</sub> O	7.86	7.94	8.14	8.03	8.47	7.54	7.43	8.07
P <sub>2</sub> O <sub>5</sub>	0.07	0.08	0.09	0.09	0.20	0.05	0.05	0.09
L.O.I.	3.95	3.93	3.39	4.04	2.91	4.11	4.15	4.25
Sum	93.06	94.46	95.49	94.85	95.81	93.89	91.84	94.53
Sc	9	7	4	9	8	2	2	8
V	45	55	55	50	102	37	41	54
Ni	5	4	4	5	3	1	5	4
Zn	78	81	78	76	72	89	83	80
Ga	18	18	20	18	17	19	18	17
Rb	314	324	317	321	279	366	356	321
Sr	184	215	273	229	882	69	76	291
Y	32	39	33	34	28	45	42	34
Zr	354	363	350	357	255	472	458	353
Nb	52	52	53	52	33	72	69	51
Mo	6.0	5.9	5.9	6.0	4.6	6.2	6.5	6.1
Sn	4.5	4.3	4.3	4.2	3.7	5.3	5.3	4.3
Sb	0.9	0.9	0.9	0.9	0.7	1.3	1.2	0.9
Cs	20.5	19.8	18.5	18.4	14.6	27.9	27.1	19.6
Ba	65	92	183	107	1950	4	21	152
La	60.6	60.5	52.4	49.7	49.9	66.7	55.5	65.5
Ce	132.0	132.0	120.0	118.0	109.0	173.0	149.0	142.0
Pr	13.4	13.3	11.7	11.1	11.4	14.3	12.0	14.3
Nd	46.5	46.0	40.8	38.4	41.3	49.3	41.4	49.7
Sm	8.5	8.4	7.5	7.1	7.7	9.0	7.5	9.0
Eu	1.7	1.7	1.5	1.4	2.1	1.3	1.1	1.8
Gd	7.4	7.3	6.6	6.3	6.8	8.1	6.8	8.0
Tb	1.0	0.9	0.9	0.8	0.8	1.1	0.9	1.0
Dy	5.6	5.5	5.1	4.9	4.6	6.3	5.6	6.0
Ho	1.1	1.0	1.0	0.9	0.8	1.2	1.1	1.1
Er	3.0	3.0	2.8	2.6	2.4	3.5	3.2	3.2
Tm	0.4	0.4	0.4	0.4	0.3	0.5	0.5	0.5
Yb	3.0	2.8	2.7	2.6	2.2	3.5	3.3	3.1
Lu	0.5	0.4	0.4	0.4	0.3	0.6	0.5	0.5
Hf	8.4	8.3	8.0	8.1	5.9	11.0	10.7	8.2
Ta	1.9	2.0	1.9	2.0	1.5	2.9	2.4	2.3
W	6.2	6.1	6.2	6.3	5.1	5.2	5.7	6.5
Pb	50.5	49.8	50.3	49.7	41.9	58.2	56.9	51.7
Th	28.9	28.3	27.6	25.9	21.4	34.3	29.6	32.4
U	7.7	7.0	6.2	6.0	6.1	7.9	8.0	8.6

Nomenclature after Orsi et al. (1996)

<LLD Below detection limit

by XRF. The precision for trace elements analyzed by ICP-MS varies between 1% for most elements and 3.6% for Lu.

Sr and Nd isotopes were determined by thermal ionization mass spectrometry at Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano using a

Thermo Finnigan Triton TI multicollector mass spectrometer. Whole rock powders were leached with cold 6 N HCl for 10 min and with warm 6 N HCl for 10 min then rinsed several times in pure sub-boiling distilled water and finally dissolved with suprapur HF–HNO<sub>3</sub>–HCl mixtures. Sr and

Nd were separated by conventional ion-exchange chromatographic technique. The mean measured values of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  for NIST-SRM 987 and La Jolla standards were  $0.710240 \pm 0.000009$  ( $2\sigma$ ) and  $0.511846 \pm 0.000007$  ( $2\sigma$ ), respectively. The Sr and Nd blanks were negligible during the period of measurements. The measured  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of the Sr-poor pre-CI rocks has been corrected for Rb decay since eruption (Table 2). No age-correction is necessary for the younger pre-NYT trachytes.

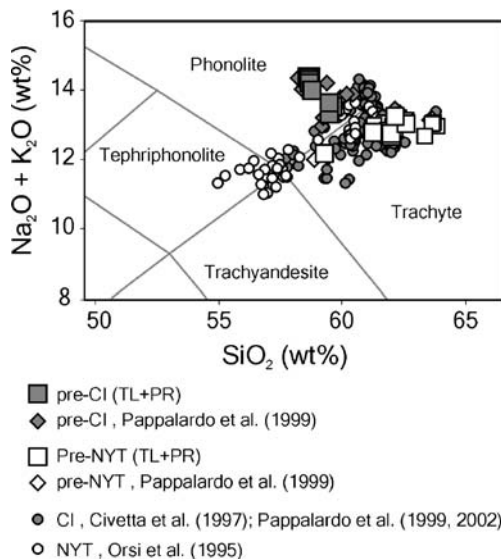
## Geochemistry

New whole rock major and trace element data and Sr–Nd isotope data from volcanic rocks erupted before CI and NYT eruptions are reported in Tables 1 and 2. Figure 3 compares our samples with previously published pre-CI, CI, pre-NYT, and NYT data in a TAS diagram. The pre-CI rocks are phonolites, whereas the pre-NYT rocks are trachytes. The two major eruptions are more diverse in their geochemistry:

**Table 2** Sr and Nd isotope data of pumice samples of pre-CI and pre-NYT

	$^{87}\text{Sr}/^{86}\text{Sr}$	Error	$^{143}\text{Nd}/^{144}\text{Nd}$	Error
LM1 (NYT)	0.707503	0.000005	0.512461	0.000003
0304 (NYT)	0.707507	0.000008	0.512458	0.000003
PRh	0.707539	0.000005	0.512466	0.000008
PRf-2	0.707438	0.000005	0.512473	0.000005
PRf-1	0.707436	0.000005	0.512473	0.000007
PRd-2	0.707571	0.000006	0.512457	0.000007
PRd-1	0.707351	0.000006	0.512475	0.000009
PRc-2	0.707321	0.000006	0.512468	0.000007
PRc-1	0.707318	0.000005	0.512466	0.000007
Pra	0.707289	0.000005	0.512468	0.000004
TLs-4	0.707517	0.000005	0.512464	0.000005
TLs-3	0.707431	0.000005	0.512461	0.000006
TLs-2	0.707437	0.000005	0.512468	0.000005
TLs-1	0.707424	0.000007	0.512468	0.000005
TLr	0.707461	0.000006	0.512468	0.000006
TLq	0.707466	0.000006	0.512471	0.000006
TLp	0.707533	0.000004	0.512463	0.000006
Tlo-3	0.707403	0.000006	0.512461	0.000005
Tlo-2	0.707373	0.000006	0.512455	0.000005
Tlo-1	0.707372	0.000007	0.512455	0.000005
S.Marco (CI)	0.707316	0.000008	0.512472	0.000006
Cdt 202.2 (CI)	0.707368	0.000008	0.512497	0.000003
Cdt 201.7 (CI)	0.707374	0.000007	0.512494	0.000003
Mond.152a2 (CI)	0.707375	0.000007	0.512498	0.000004
TLm base	0.707226	0.000005	0.512501	0.000005
Tli	0.707697	0.000005	0.512505	0.000005
TLh	0.707697	0.000006		
TLg	0.706978	0.000005	0.512515	0.000018
TLf-11	0.706992	0.000005	0.512512	0.000005
TLf-10	0.707367	0.000005	0.512520	0.000009
TLf-9	0.707194	0.000006	0.512516	0.000006
TLc-8	0.707311	0.000005	0.512514	0.000006
TLc-7	0.707396	0.000006	0.512519	0.000004
TLc-6	0.707259	0.000007	0.512517	0.000006
TLc-5	0.707058	0.000006	0.512518	0.000007
TLc-4	0.707045	0.000008	0.512519	0.000007
TLc-3	0.707127	0.000005	0.512512	0.000008
TLc-2	0.707280	0.000006	0.512521	0.000005
TLc-1	0.707284	0.000006	0.512518	0.000006

Isotope data of CI and NYT (from D'Antonio et al. 2007 and Arienzo et al., personal communication) are reported for comparison. All pre-CI and CI Sr-isotope values are age-corrected



**Fig. 3** Total alkalis versus silica diagram for igneous rock classification, after Le Maitre et al. (1989)

The Campanian Ignimbrite has phonolitic–trachytic composition; the Neapolitan Yellow Tuff is phonolitic-trachytic and tephriphonolitic-trachyandesitic.

#### Chemostratigraphy

When plotting whole rock major and trace elements to stratigraphic position within the Trefola quarry (Fig. 4), we do not find any obvious or simple compositional trends before the CI and NYT eruptions. Rather, the pumice compositions define distinct compositional groups. Combining our data with those from other authors (Civetta et al. 1997; D’Antonio et al. 1999; Orsi et al. 1995; Pappalardo et al. 1999; 2002) enhances and supports this interpretation (Fig. 4).

The studied *pre-Campanian Ignimbrite* rocks from Trefola quarry can be divided geochemically into three distinct groups: (1) TLc-unit, here defined as group pre-CI 1, (2) TLf, TLg, TLh, and TLi units (TLg, h, i from Pappalardo et al. 1999), here defined as group pre-CI 2, and (3) TLM unit (data from Pappalardo et al. 1999), here defined as group pre-CI 3.

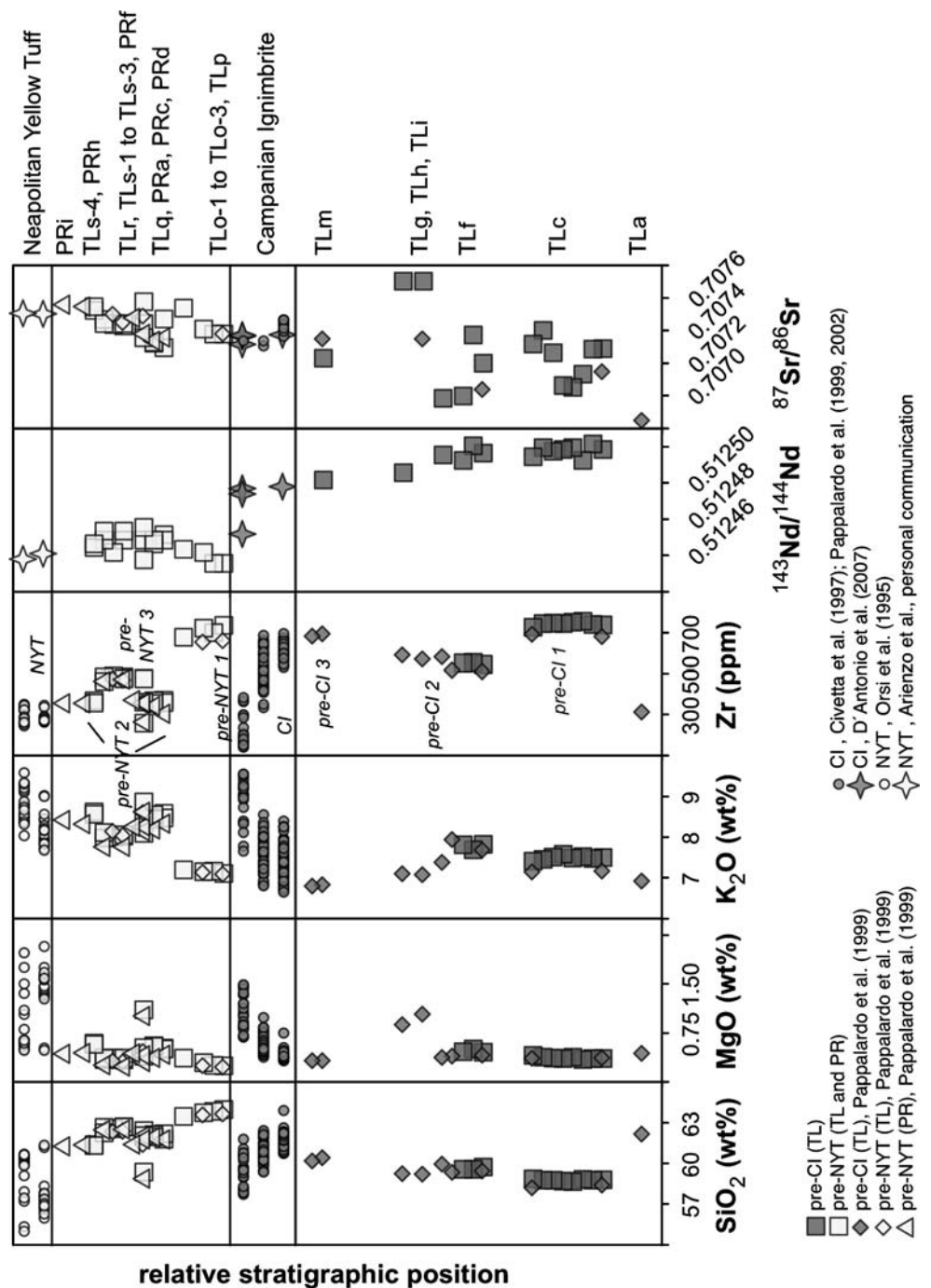
As the investigated rocks have generally high and similar SiO<sub>2</sub> contents, CaO, MgO, and Zr contents were found to better reflect the degree of differentiation. Group pre-CI 1 shows the lowest SiO<sub>2</sub> content of all pre-CI rocks, but is a highly evolved phonolitic magma (Fig. 4) as is shown by its high Zr content. The lowermost unit TLc (Pappalardo et al. 1999) is different with SiO<sub>2</sub> > 62 wt% and low Zr content, and thus, cannot be correlated to group pre-CI 1 or any other pre-CI group. Pre-CI 2 has a slightly higher SiO<sub>2</sub> and MgO, but significantly lower Zr content compared to pre-CI 1. Group pre-CI 3 again has high Zr concentration like pre-CI 1, but has a slightly higher SiO<sub>2</sub>

content. It is important to note that from TLc at the bottom to TLM at the top, and thus towards the initial CI eruption products, SiO<sub>2</sub> increases slightly and in a stepwise fashion from group to group. In contrast, MgO and K<sub>2</sub>O first increase and then decrease, whereas Zr first decreases and then increases from group to group. Within a given group, the different stratigraphic layers show a constant composition. Only from the uppermost TLf upwards to TLM, there is a compositional trend for K<sub>2</sub>O between samples. The TLc and TLM units (pre-CI 1 and 3) are geochemically similar to the most evolved CI magma. The <sup>143</sup>Nd/<sup>144</sup>Nd ratio is similar within the three pre-CI groups with values of 0.51251–0.51252. But from TLg (pre-CI 2) to TLM (pre-CI 3), the ratio decreases to a value similar to the first-erupted most differentiated CI. The <sup>87</sup>Sr/<sup>86</sup>Sr ratios show a large isotopic range (0.70700–0.70740) for all pre-CI. The pre-CI units TLh and TLi (part of pre-CI 2) have a relatively high MgO (and CaO) content and are significantly more enriched in radiogenic Sr, indicating that the magma of these units is somehow different to the rest of the pre-CI rocks (Fig. 4).

The studied *pre-Neapolitan Yellow Tuff* deposits from both Trefola quarry and Ponti Rossi are also divided into three distinct groups: (1) stratigraphic units TLo and TLp represent a coherent compositional group, here defined as group pre-NYT 1, (2) units TLq, TLs-4, PRa, PRc, PRd, PRh, and PRi (PRi data from Pappalardo et al. 1999) define the pre-NYT 2 group, and (3) TLr, TLs-1 to TLs-3, and PRf define group pre-NYT 3. There is a good stratigraphic correlation between Trefola quarry and Ponti Rossi (Fig. 4). The lowermost group pre-NYT 1 has the highest SiO<sub>2</sub> content (>63 wt%) and is the most evolved of all the pre-NYT rocks. It is also characterized by high Zr concentration. Group pre-NYT 2 is less evolved, with lower Zr and low SiO<sub>2</sub>, but with higher MgO and K<sub>2</sub>O contents. Only sample PRd-2, a black pumice, has much lower SiO<sub>2</sub> and much higher MgO with respect to pre-NYT 2. This difference to the other samples of the group can be seen in most major and trace elements as well as in slightly higher Sr and slightly lower Nd isotope ratios. Group pre-NYT 3 compositions fall between groups 1 and 2. Pre-NYT 2 erupted both before and after pre-NYT 3. As the composition of pre-NYT 2 and pre-NYT 3 samples is quite similar (e.g., MgO), the discrimination between these groups cannot be seen for all elements. A very good indicator for the grouping in this case is Zr (Fig. 4). But also, SiO<sub>2</sub>, K<sub>2</sub>O, and Na<sub>2</sub>O can be used to clearly distinguish the groups. The pre-NYT rocks tend to show an alternating but decreasing degree of differentiation towards the NYT eruption. The NYT erupted the least evolved magmas with SiO<sub>2</sub> content of <62 wt%. Pre-NYT 2 and 3 rocks have similar Nd isotopes, but pre-NYT 1 group has values slightly lower compared to pre-NYT 2+3.



**Fig. 4** SiO<sub>2</sub>, MgO, K<sub>2</sub>O, Zr contents, and Sr and Nd isotopes vs stratigraphy, position, and relative deposit thickness (according to Trefola quarry section). The thickness of the deposit is not in scale with the erupted volume. Stratigraphy after Orsi et al. (1996). Analytical uncertainty is within symbol size. Literature data are for comparison. The age of the lowermost TLa unit is 60 ka; CI and NYT were dated to 39 and 15 ka, respectively

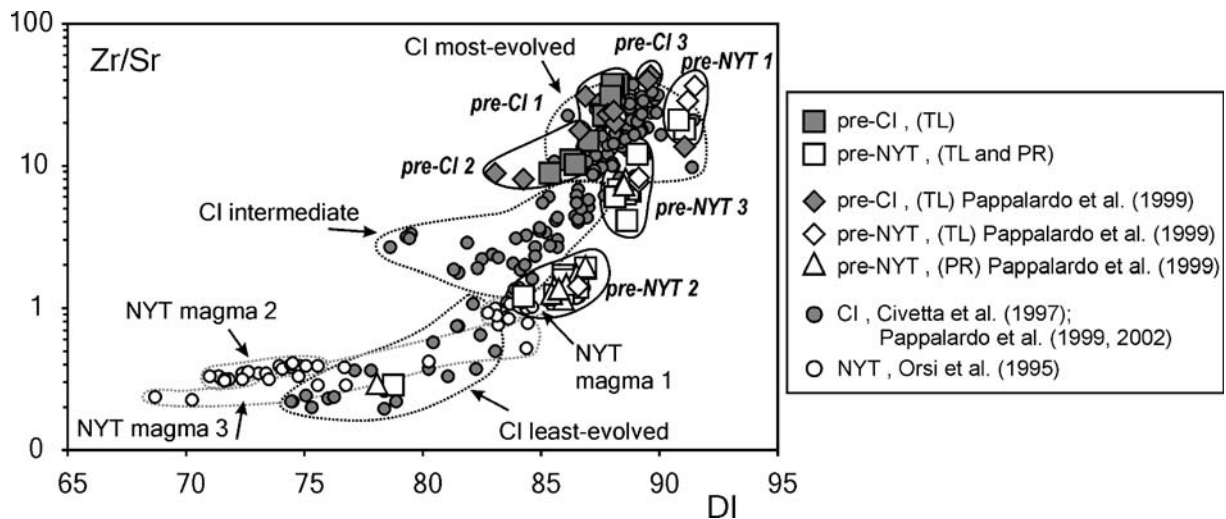


Nd isotopes of pre-NYT range from 0.51246 to 0.51248, whereas Sr isotopes range from about 0.70729 (value similar to the isotopic ratio of the last-erupted least differentiated CI trachytic magma) to 0.70754 (value close to the Sr isotopic ratio of NYT).

Although data of some units are missing (lack of access), the compositions with stratigraphic sequence clearly indicate that there is no continuous trends in pre-CI and pre-NYT towards the CI and NYT magmas, respectively.

### Compositional variations

Before discussing the pre-CI and pre-NYT compositions and their relation to CI and NYT magmas, we need to recall the compositional variation of the Campanian Ignimbrite and the Neapolitan Yellow Tuff. A common presentation of Campi Flegrei volcanic rocks is the DI vs Zr/Sr as a discrimination diagram (Fig. 5, e.g., Civetta et al. 1997). Civetta et al. (1997) and Pappalardo et al. (2002) showed



**Fig. 5** DI vs Zr/Sr ratio for pre-CI/CI, pre-NYT/NYT. Circles highlight the pre-CI and pre-NYT magma batches and the CI (by Civetta et al. 1997) and NYT (by Orsi et al. 1995) magmas

that the CI deposits can be divided into three compositional groups of different degree of differentiation. They described most evolved, intermediate, and least evolved pumices with  $Zr/Sr=9-35$  (and  $DI=88-90$ ) for the most evolved pumices and  $Zr/Sr \leq 1$  (and  $DI=75-83$ ) for the least evolved pumices (Fig. 5). The intermediate pumices resulted from mixing between the most and least evolved magmas. These two endmember magmas also have distinct Sr and Nd isotope composition (Table 2 and Arienzo et al. 2007). Orsi et al. (1992, 1995) also distinguished three magma groups in the Neapolitan Yellow Tuff, each separated by a compositional gap (Fig. 5). The NYT rocks mainly have  $Zr/Sr \leq 1$  (and  $DI \leq 87$ ) and, thus, are less evolved than most CI rocks. DI vs Zr/Sr (Fig. 5) supports the discrimination of the CI and NYT rocks. The NYT rocks display a very narrow range of Sr and Nd isotopes, 0.70750–0.70752 and 0.51246, respectively (Table 2 and D'Antonio et al. 2007).

The pre-CI and pre-NYT rocks are highly evolved ( $DI > 78$ ), but show a variable Zr/Sr ratio. Pre-CI and pre-NYT rocks plot on different trends. Only sample TLa (pre-CI, Pappalardo et al. 1999) fails. Variation diagrams (Fig. 6) also show that the products of the CI and NYT eruptions form continuous compositional fields. By contrast, the pre-CI and pre-NYT products form distinct compositional clusters. The pre-CI and CI rocks plot across the trends of pre-NYT and NYT rocks.

**Pre-CI/CI magmas** Element vs CaO plots (Fig. 6) clearly indicate that the pre-CI rocks do not show a trend of increasing differentiation with stratigraphy; the rocks rather form a compositional field. With decreasing degree of differentiation, the CI magmas show an increase of  $Fe_2O_3$ , MgO,  $K_2O$ , and  $P_2O_5$  (and V, Sr, Ba, Sc, Eu), but a decrease of  $SiO_2$ , MnO, and  $Na_2O$  (and Zr, Y, Nb, Rb, Zn, La, Ce, Pr, Nd, Sm, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Th).

$TiO_2$  and  $Al_2O_3$  show more or less constant concentrations with changing CaO. The pre-CI rocks match well with the highly evolved CI endmember for MnO, MgO,  $Na_2O$ ,  $K_2O$ ,  $P_2O_5$  and for most trace elements, as well as for Nd isotopes (Fig. 7). Although pre-CI rocks are highly evolved (low CaO, high DI), they are characterized by significantly lower  $SiO_2$  content compared to the most evolved CI rocks.

**Pre-NYT/NYT magmas** The pre-NYT/NYT magmatic system is clearly different from the pre-CI/CI system. The pre-NYT samples define three distinct clusters (Fig. 6) close to the most evolved NYT rocks. Generally, with decreasing degree of differentiation, the pre-NYT magmas decrease in  $SiO_2$ , MnO, and  $Na_2O$  (and Zr, Y, Nb, Rb, Zn, and REE), but increase in  $TiO_2$ ,  $Al_2O_3$ ,  $Fe_2O_3$ , MgO,  $K_2O$ , and  $P_2O_5$  (and V, Sr, Ba and Sc, Eu) contents (Fig. 6). The NYT rocks are less evolved than the pre-NYT rocks; however, for most elements, the NYT and pre-NYT rocks show the same geochemical trend. Nd isotope composition of pre-NYT and NYT are identical (0.51246–0.51247, Fig. 7). The least evolved pre-NYT rocks (pre-NYT 2, Figs. 5 and 6) generally overlap with the evolved end of the NYT trend. In addition, the  $^{87}Sr/^{86}Sr$  ratio of the last erupted pre-NYT 2 is similar to NYT.  $TiO_2$ , MnO, and  $Na_2O$ , but especially  $K_2O$ , contents emphasize that the NYT rocks are nevertheless distinct from the pre-NYT rocks.

As the Zr/Sr ratio has been used by Civetta et al. (1997) and Pappalardo et al. (2002) to document compositional characteristics, we use this element ratio to further compare pre-CI and pre-NYT rocks to the large-volume CI and NYT products: The pre-CI rocks are all highly evolved with  $Zr/Sr=8-40$  and  $DI > 83$  (Fig. 5). They do not show a trend but form compositional clusters. The pre-NYT rocks have intermediate to highly evolved Zr/Sr ratios from  $\geq 1$  to 35 and  $DI > 84$  (with PRd-2:  $DI < 79$  as an exception). They can

**Fig. 6** Variation of major elements and selected trace elements with CaO for pre-CI/CI and pre-NYT/NYT rocks. Relative errors for major elements vary between <0.1 and <1% and for trace elements between <1 to <5%. Data of this study agree with the data from Pappalardo et al. (1999) except for TiO<sub>2</sub>, Rb, and Y, which differ by up to 18%; their P<sub>2</sub>O<sub>5</sub> data are even up to 70% higher for rocks of equivalent stratigraphic position

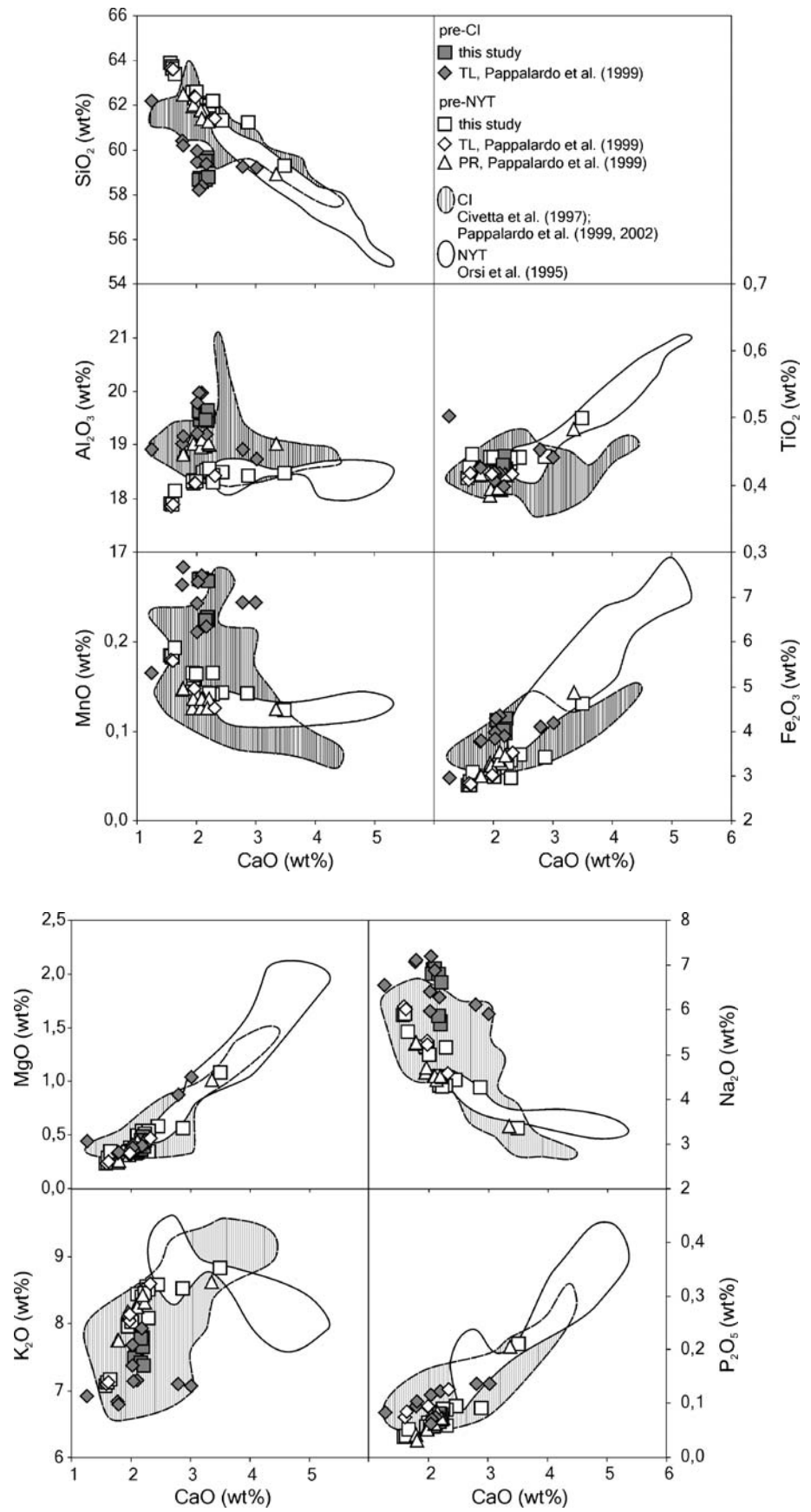
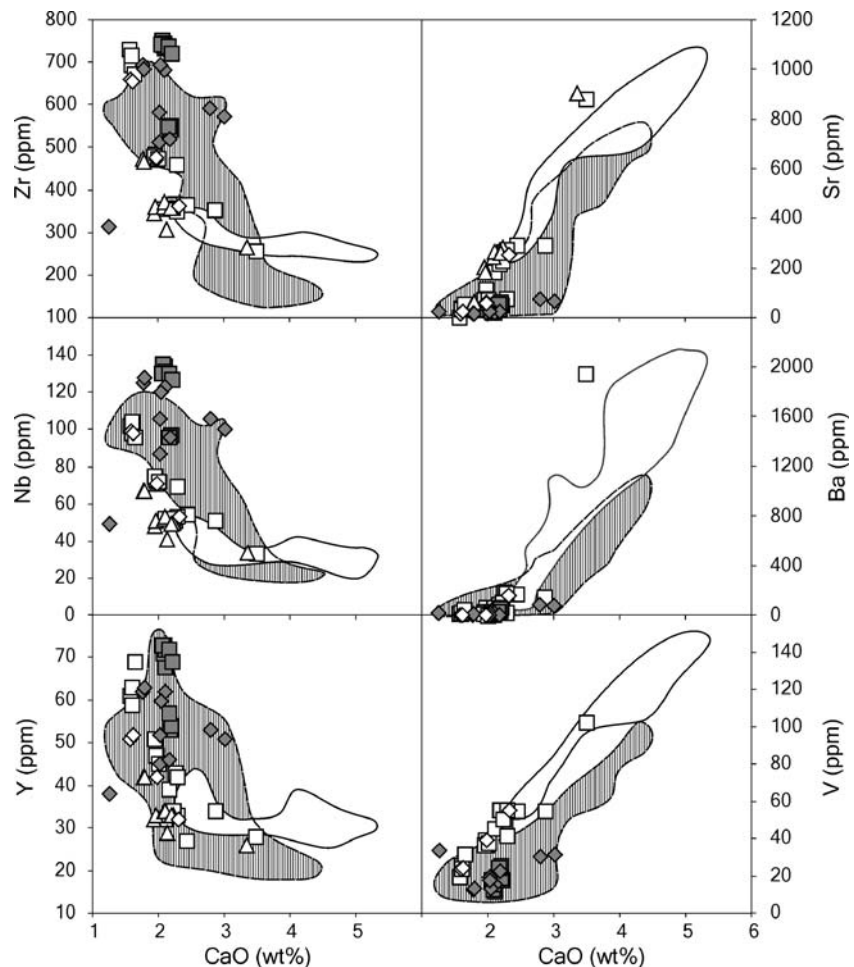


Fig. 6 (continued)



easily be divided into three distinct clusters as already demonstrated (Fig. 5). These pre-NYT clusters and the NYT rocks define a narrow curve of increasing DI with increasing Zr/Sr ratio that crosscuts the trend of the CI rocks (compare to Fig. 6).

We summarize that the pre-CI rocks form compositional clusters rather than a continuous trend. Their chemical and Nd isotopic compositions in general are similar to the most evolved CI rocks. The CI rocks themselves show a compositional trend from highly to less evolved rocks. The pre-NYT rocks also form distinct clusters lying on a compositional trend that, for most elements, extends the trend of the NYT rocks. The less evolved pre-NYT rocks always plot on the evolved end of the NYT trend and are isotopically similar (Sr and Nd isotopes) to the NYT rocks.

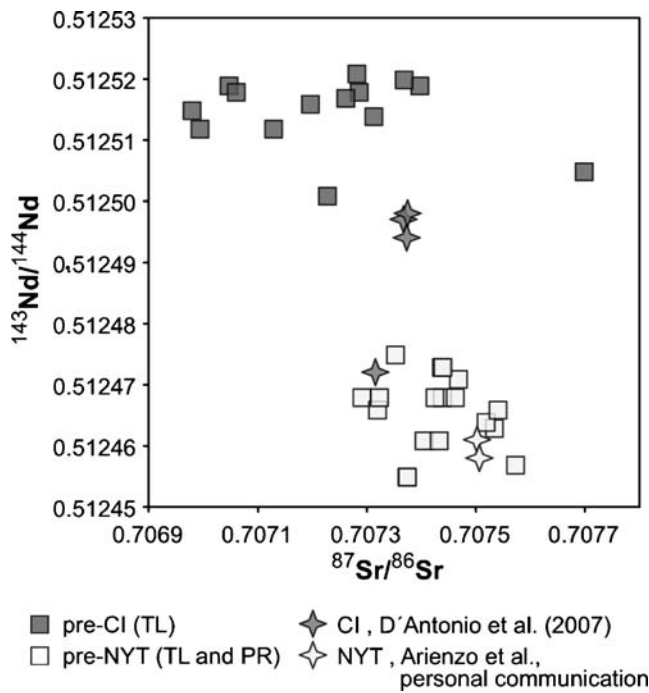
## Discussion

Our new data, together with previous published results, permit us to reconstruct the magmatic history of the Campi

Flegrei from about 60 ka ago to the NYT eruption in more detail (Fig. 8). Pappalardo et al. (1999) suggested that a magmatic system existed below Campi Flegrei that was replenished repeatedly during the past 60 ka. Our data support a different model of distinct magma batches feeding the pre-CI and pre-NYT eruptions. These magma batches evolved independently and were differently contaminated at shallow depths. As shown, they also did not evolve directly towards the CI and NYT endmember compositions. An important conclusion is that the pre-CI and pre-NYT magmas are not directly related genetically, being characterized by different geochemistry and particularly by different Nd isotope composition (Fig. 7). Based on our findings, the existence of a single, continuously zoned, and long-lived magma chamber is unlikely for the pre-CI and pre-NYT magmas.

## The Campanian Ignimbrite and its precursor activity

The pre-CI volcanic eruptions were fed by highly but differently evolved phonolitic magmas. The pre-CI eruptions have a much smaller volume than the following CI eruptions

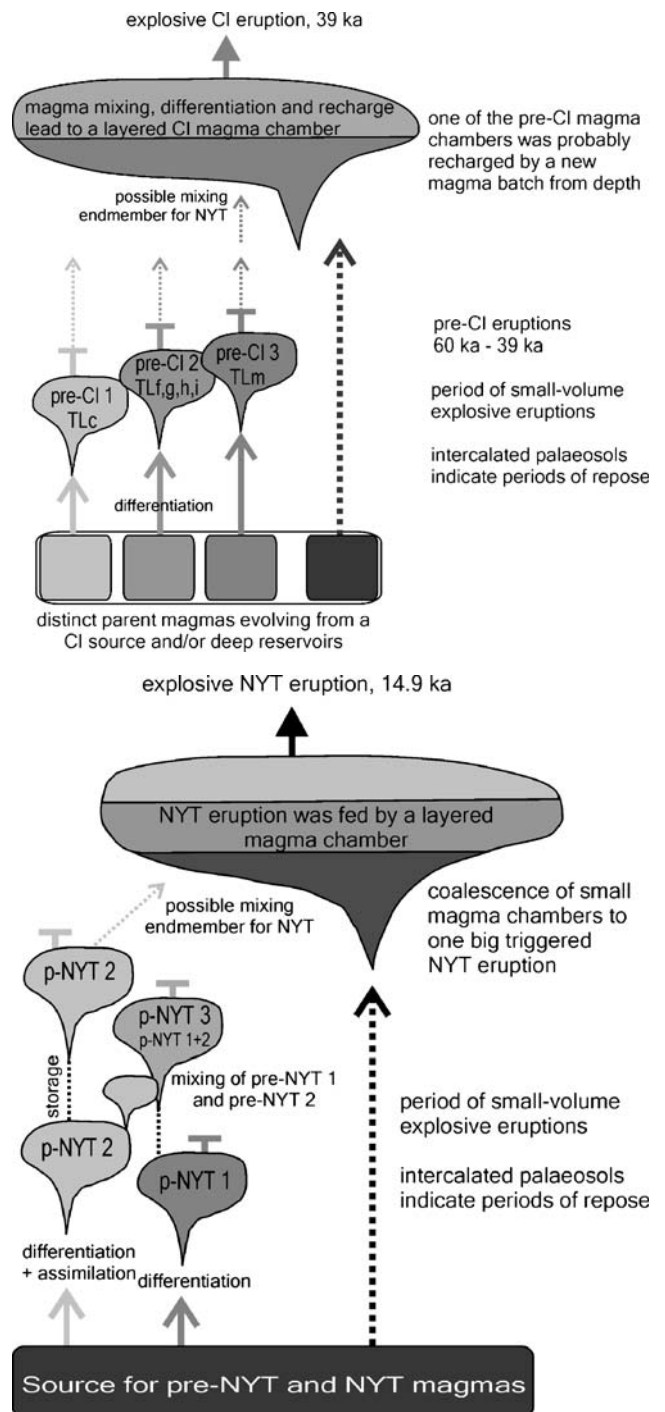


**Fig. 7** Sr vs Nd isotope diagram for pre-CI and pre-NYT of pumice samples. CI and NYT isotope data (from D’Antonio et al. 2007 and Arienzo et al., personal communication) are reported for comparison

and they erupted distinct batches from multiple centers (this work and Orsi et al. 1992, 1995, 1996, 1999a, b). Based on geochemical and Sr isotope variations observed between 60 and 44 ka ago, Pappalardo et al. (1999) proposed a model of a continuously growing magma chamber that was characterized by a process of fractionation, replenishment by fresh trachytic magma, and mixing with newly arrived magma. Our model differs from that of Pappalardo et al. (1999) in that we suggest the existence of distinct and separated magma batches. We have shown that the pre-CI rocks form distinct clusters and that the compositional variation and the degree of differentiation from cluster to cluster are not systematic with respect to stratigraphy, and thus, time. Interpreting these compositional clusters as magma batches, the pre-CI history started with the eruption of a highly differentiated magma batch (pre-CI 1). The following magma is only slightly more differentiated (batch pre-CI 2: higher SiO<sub>2</sub>, but lower K<sub>2</sub>O+Na<sub>2</sub>O and Zr contents). Towards the CI eruption, the degree of differentiation increases with respect to the pre-CI 3 batch (higher SiO<sub>2</sub> and Zr contents from the uppermost Tlf to Tlm unit).

Each depositional unit, i.e., each pre-CI magma batch, is geochemically homogeneous with no progressive trend of differentiation with stratigraphy. The constancy of Nd isotopes together with the observed variability of the Sr isotope ratio (Table 2 and Fig. 7) suggests the occurrence of open-system processes, such as contamination with material enriched in radiogenic Sr (but with low Nd content), acting on the Sr-poor pre-CI phonolitic magmas.

We assume that the different magma batches evolved in separated magma chambers, which were distinct with respect to degrees of differentiation, assimilation, and duration of storage (Fig. 8a). Intercalated palaeosols indicate periods of repose between the eruptions of these batches. Each batch erupted only once and did not appear later again. The distinct pre-CI magma batches are geochemically and isotopically (Nd isotopes) similar to



**Fig. 8** a Schematic representation of the pre-CI/CI magmatic system. b Schematic representation of the pre-NYT/NYT magmatic system

the first erupted CI magma. Thus, all the pre-CI and the first-erupted more differentiated CI magmas must have a geochemically similar source, probably a large heterogeneous deep reservoir (Fig. 8a).

The change from small individual magma batches to the large-volume CI eruption represents a sudden change in the magmatic regime. According to the model of Fisher et al. (1993), Civetta et al. (1997), Rosi et al. (1999), Pappalardo et al. (2002), and Arienzo et al. (2007), the CI magma chamber contained two isotopically distinct magma layers with different degrees of evolution separated by a compositional gap. The CI eruption began with phreatomagmatic explosions followed by the formation of a Plinian column that was fed by the simultaneous emission of both magmas. After column collapse, a multiple vent phase still erupted the uppermost evolved magma layer, accompanied by the onset of caldera collapse. The collapse was associated with pyroclastic flows that were also fed by the uppermost evolved layer. Mingling and simultaneous tapping of both magma layers occurred again during the main phase of caldera collapse. Towards the end of the eruption, only the deeper and least evolved magma erupted.

Considering this scenario and our results from the pre-CI eruptions, we conclude that: (1) the pre-CI magma reservoirs were ephemeral and separated, (2) one of the pre-CI magmas (pre-CI 3) may have resided in a magma chamber that later evolved into the larger reservoir from which the CI erupted, and (3) a recharge of entirely new magma preceded the cataclysmic CI event. Therefore, we argue that the pre-CI eruptions were fed from different smaller magma chambers and that no single large volume magma chamber existed for more than a few thousand years before the CI eruption.

#### Neapolitan Yellow Tuff and its precursor activity

We presented observations to argue that the pre-NYT magmas evolved independently from the preceding CI magmatic system. The pre-NYT rocks form highly evolved trachytic clusters that we again interpret as distinct magma batches.

Orsi et al. (1995) and Pappalardo et al. (1999) showed that the first erupted pre-NYT magma and the last-erupted (least evolved) CI magma have similar  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. They suggested that the least evolved CI magma, which remained in the chamber, differentiated in a closed system to produce an uppermost differentiated layer (the most evolved, first-erupted pre-NYT magma). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of the following eruption products, before the NYT eruption, increased through time and reached the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of the NYT. Thus, Pappalardo et al. (1999) suggested mixing between the newly arrived more radiogenic NYT magma with a resident fractionating magma similar to the least evolved CI magma.

Based on our new geochemical and isotopic results, we develop a more detailed model that links the pre-NYT magma batches to the range and endmembers of NYT magmas. As the pre-NYT batches and the range of NYT compositions define one differentiation path and are characterized by a similar Nd and Sr isotope composition (Fig. 7), we initially assume a common parent for these magmas. Differentiation of this parent magma, probably coupled with assimilation, resulted in the most evolved pre-NYT 1 magma batch (Fig. 8b). A new batch of the same parent magma underwent again differentiation coupled with assimilation to result in the pre-NYT 2 magma batch. Its youngest products are the most enriched in radiogenic Sr compared to all other pre-NYT rocks. Portions of pre-NYT 1 magma mixed during storage with pre-NYT 2 magma and formed the pre-NYT 3 magma batch. After pre-NYT 2, the new pre-NYT 3 magma erupted and was followed by further eruptions of a more contaminated (i.e., highest value in radiogenic Sr) pre-NYT 2 magma. The last erupted pre-NYT 2 magma has similar geochemical and isotopic signature compared to the first erupted NYT magma. Thus, we propose that the pre-NYT 2 magma was one potential mixing endmember for the NYT magma.

Our interpretations are supported by new data on the Sr and U/Th isotope systems. Scheibner et al. 2004, Arienzo et al. 2007, and confirm that (1) pre-NYT 1 magma batch cannot be a product of differentiation of the least evolved CI magma as suggested by Pappalardo et al. (1999) and (2) pre-NYT and NYT magmas have a common source that is different from the CI source.

Pre-NYT and NYT magmas thus evolved from one parent magma (Fig. 8b), which is similar to the later erupted most mafic NYT endmember. The other NYT magmas, however, evolved independently from the pre-NYT magmas. The Neapolitan Yellow Tuff eruption tapped three magma batches in a layered magma chamber (Orsi et al. 1992, 1995): NYT magma 1, magma 2, and magma 3 from the top of the reservoir downward. These layers were separated by compositional gaps interpreted as real gaps in the magma body. As regards the origin of the compositionally zoned NYT reservoir, Orsi et al. (1995) favored a stepwise filling of the NYT magma chamber by repeated arrivals of new trachytic magmas. NYT magmas 1 and 2 entered the chamber at distinct times coming from either a single or separate reservoirs. NYT magma 3 may have entered the magma chamber as a compositionally zoned body. Orsi et al. (1995) suggested mixing between NYT magma 2 and the upper more evolved part of NYT magma 3, which implies that the two magmas resided together in the chamber for a short time. The arrival of NYT magma 3 into the magma chamber triggered the NYT eruption. Orsi et al. (1992) argued that the NYT magmas erupted almost contemporaneously by simultaneous tapping of the three magmas in the chamber during the phreatoplilian explosion.

Combining published data with our geochemical and isotopic results from pre-NYT eruptions, we conclude that: (1) pre-NYT and NYT magmas evolved from a parent magma that is different from any CI magma, (2) pre-NYT magma chambers are ephemeral and separated, and (3) mixing between pre-NYT magmas occurred. Therefore, we argue that no single large volume magma chamber existed for a long time before the Neapolitan Yellow Tuff eruption.

Precursor volcanic activity, thus, did not “lead” to the formation of one large, long-lived and continuously growing reservoir (e.g., by input of new magma, mixing, and differentiation) that fed the large eruptions. Rather, when considering the chronology and compositional variations with time, we conclude that this change in the magma system from pre- to main eruptions (pre: single magma chambers, main: large layered magma chamber) probably occurred in less than a few thousand years (compare Fig. 4).

It is interesting to reconstruct the fate of the residual NYT magmas after the climactic NYT eruption. D’Antonio et al. (1999) also suggested that the magmas younger than NYT are isotopically similar to the least evolved NYT and less similar to the least evolved CI magmas. Less differentiated (shoshonite–latite) magmas were also erupted about 11–10 ka ago, along the fractures bordering N and NE the NYT caldera. They show the highest and most variable  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios and clear evidence of isotopic disequilibria (Morgan et al. 2005). D’Antonio et al. (1999, 2007) therefore suggested the existence of residual CI and NYT magma batches that mixed with a mafic recharge (Minopoli) magma. If so, there may be remnant batches from the CI and NYT large-volume reservoirs that can still provide evolved mixing endmembers as resident magma either for a new (mafic) magma input or as an increasingly differentiated (trachyte) magma. This scenario is entirely consistent with the observation by Morgan et al. (2005) that the mafic Minopoli shoshonitic magma is littered with debris from cumulates of earlier (and isotopically diverse) magma batches.

We showed that each caldera-forming event had its own distinct precursors. The switch from one (source and) magma regime to the next obviously occurred immediately after the CI caldera-forming eruption. We assume that the pre-CI and pre-NYT, as well as the CI and NYT magma batches, derived from a deep heterogeneous source where magmas resided and evolved separately. The magmas formed at different times, differentiated, assimilated, and were recharged during ascent. Each large caldera eruption (CI and NYT) is then characterized by a large volume of magma that is not recorded in any precursor activity. Therefore, we must assume that these large events were charged by a massive volume of magma that ascended relatively shortly before the cataclysmic eruptions from a deeper reservoir where differentiation occurred. While earlier models favored one large evolving magma chamber

feeding the pre- and main eruptions, which was more or less continuously recharged and eventually erupted in a caldera-forming event, we therefore argue for ephemeral systems that waxed and waned and finally coalesced into a large magma reservoir before the caldera-forming eruptions.

## Conclusion

Geochemical and isotopic analyses from pre-Campanian Ignimbrite and pre-Neapolitan Yellow Tuff pumice permit us to document the complete stratigraphy from the oldest pre-CI up to the NYT eruptions. Pre-CI/CI and pre-NYT/NYT magmas originated from different sources. The magmas that erupted before the CI and NYT eruptions have distinct compositions that allow us to distinguish individual magma batches. A complex history of storage and recharge probably led to the various magma batches that erupted.

Based on our data, we propose a model of several small magma chambers occurring below the Campi Flegrei before both the 39 and 15 ka cataclysmic eruptions and that these coalesced into a large reservoir only shortly (a few ka) before the large caldera-forming events.

These events were triggered by massive influx of relatively evolved magmas from a deeper differentiating magma reservoir. A large shallow magma chamber below the Campi Flegrei may therefore be only an ephemeral feature interrupted by periods of evolution in individual, separated magma reservoirs.

This scenario arises an important question: what ultimately triggers this regime change from ephemeral to a large-volume system? The answer to this question cannot be easily extracted from bulk chemistry of magmas, as their chemistry is the consequence of these processes and not their recorders. The most likely explanation, however, appears to be a strong thermal pulse probably triggered by a massive magma recharge event.

The magmatic history of the caldera and its more recent eruptive behavior suggests that the Campi Flegrei magma system is presently in a regime of ephemeral magma chambers from which small eruptions of trachytic and phonolitic magmas are to be expected. These will probably be fed by residuals of the CI and NYT magmas, possibly charged by new magma inputs from deeper reservoirs. Large caldera-forming explosive eruptions should be preceded by precursors that indicate massive recharge and magma chamber coalescence, which should be detectable by geophysical means.

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