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Relationships between Campi Flegrei and Mt. Somma volcanism: evidence from melt inclusions in clinopyroxene phenocrysts from volcanic breccia xenoliths

L. V. Danyushevsky[1] and **A. Lima**[2]

[1] School of Earth Sciences, University of Tasmania, Hobart, Tasmania, Australia
[2] Dipartimento di Geofisica e Vulcanologia, University of Napoli "Federico II", Napoli, Italy

With 4 Figures

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Summary

We present compositions of reheated melt inclusions in clinopyroxene phenocrysts from three mafic xenoliths in Breccia Museo, Campi Flegrei, Italy. Melt inclusion compositions are remarkably different from the compositions of known contemporary Campi Flegrei lavas, being significantly enriched in K_2O and depleted in Na_2O. Some differences are also evident in FeO^* (total Fe as FeO) and TiO_2 contents. The clinopyroxene phenocrysts could not have crystallised from Campi Flegrei magmas. We suggest that they originated from a volcanic system genetically very similar to, and possibly linked with, the >14 ka volcanic system of Mt. Somma, another Campanian volcano ~30 km east from Campi Flegrei, from which Vesuvius subsequently developed. This result indicates a close relationship (or link) between the two volcanic systems which have until now been considered separate. We speculate that the link was established prior to eruption of the Neapolitan Yellow Tuff (NYT) (~12 ka). The xenoliths were derived from a volcanic system older than the host breccias themselves. We suggest that this older volcanism had close similarities with the volcanism of the older products of Mt. Somma (~25 ka).

Introduction

Volcanic activity on the Campanian Plain, southern Italy, receives continuing attention from Earth scientists, motivated by the proximity of active volcanoes to densely populated areas. Campi Flegrei, a volcanic center immediately west of

Naples, has been active since > 40 ka, and a number of studies have been devoted to understanding its activity (e.g., *Armienti* et al., 1983; *Di Girolamo* et al., 1984; *Rosi* and *Sbrana*, 1987; *Barberi* et al., 1991; *Melluso* et al., 1995; *Signorelli* et al., 1999a; *Pappalardo* et al., 1999; and references therein). This is important if we are to achieve a better estimate of the volcanic hazards associated with Campi Flegrei. According to current interpretations (e.g., *Pappalardo* et al., 1999 and reference therein), Campi Flegrei produced two powerful eruptions; the Campanian Ignimbrite (CI) and Neapolitan Yellow Tuff (NYT), at ~37 ka and 12 ka, respectively. This view has been questioned by recent work (*Gans* et al., 1999; *De Vivo* et al., in press), which indicates that in the Campanian Plain more than one ignimbrite eruption occurred in addition to that with an age of ~37 ka. Ar age dating of new ignimbrite outcrops indicates eruption ages of 205, 190, 157, 39 and 18 ka (*Gans* et al., 1999; *De Vivo* et al., in press). The latter authors speculate that the ignimbrites were erupted from fissures, activated along the neotectonic Apennine fault system parallel to the Tyrrhenian coast line, and were not confined to a unique event at a volcanic center located in the Campi Flegrei (*Rosi* and *Sbrana*, 1987; *Fisher* et al., 1993; *Orsi* et al., 1996). According to *De Vivo* et al. (in press), only the NYT was erupted within the Campi Flegrei source area, whereas the CI has a much wider source area. According to *Pappalardo* et al. (1999), the time interval between the CI (39 ka) and NYT (12 ka) eruptions is characterised by a large number of significantly less powerful events, which formed the volcanic breccias studied in this paper. One of these breccias, Breccia Museo, is believed to have formed between ~21 and 15 ka (*Melluso* et al., 1995; *Pappalardo* et al., 1999). According to new Ar age determinations, Breccia Museo has an age of ~39 ka (*De Vivo* et al., in press), and thus belongs to one of the ignimbrite events. No age determinations are available for the volcanic breccia studied at Punta Marmolite.

Important insights into the compositions of parental basaltic magmas fractionating in subvolcanic magma chambers can be obtained from the studies of melt inclusions in phenocrysts (e.g., *Sobolev* and *Danyushevsky*, 1994; *Portnyagin* et al., 1997; *Danyushevsky* et al., 1997). Recently, a number of such studies have addressed the nature of parental magmas in the Campanian volcanoes (e.g., *Vaggelli* et al., 1993; *Marianelli* et al., 1995, 1999; *Belkin* et al., 1995, 1998; *Lima* et al., 1999; *Cioni* et al., 1998; *Raia* et al., 1999; *Lima*, 2000).

This study presents compositions of melt inclusions in clinopyroxene phenocrysts from three xenoliths from the Breccia Museo and the Punta Marmolite breccia. On the basis of these data, we suggest that the phenocrysts originated in a volcanic system genetically very similar to, and possibly linked with, the > 14 ka volcanic system of Mt. Somma, another Campanian volcano, ~30 km east from Campi Flegrei, from which Vesuvius developed (i.e., after 472 AD; *Rolandi* et al., 1998; *Webster* et al., this volume). These results have important implications for reconstructing the eruptive histories of, and the genetic links between, volcanic systems of the Campanian Plain.

Results

Two clinopyroxene-phyric xenoliths were collected from the Breccia Museo unit at the outskirts of the Campi Flegrei caldera rim: MT 3, from Acquamorta beach

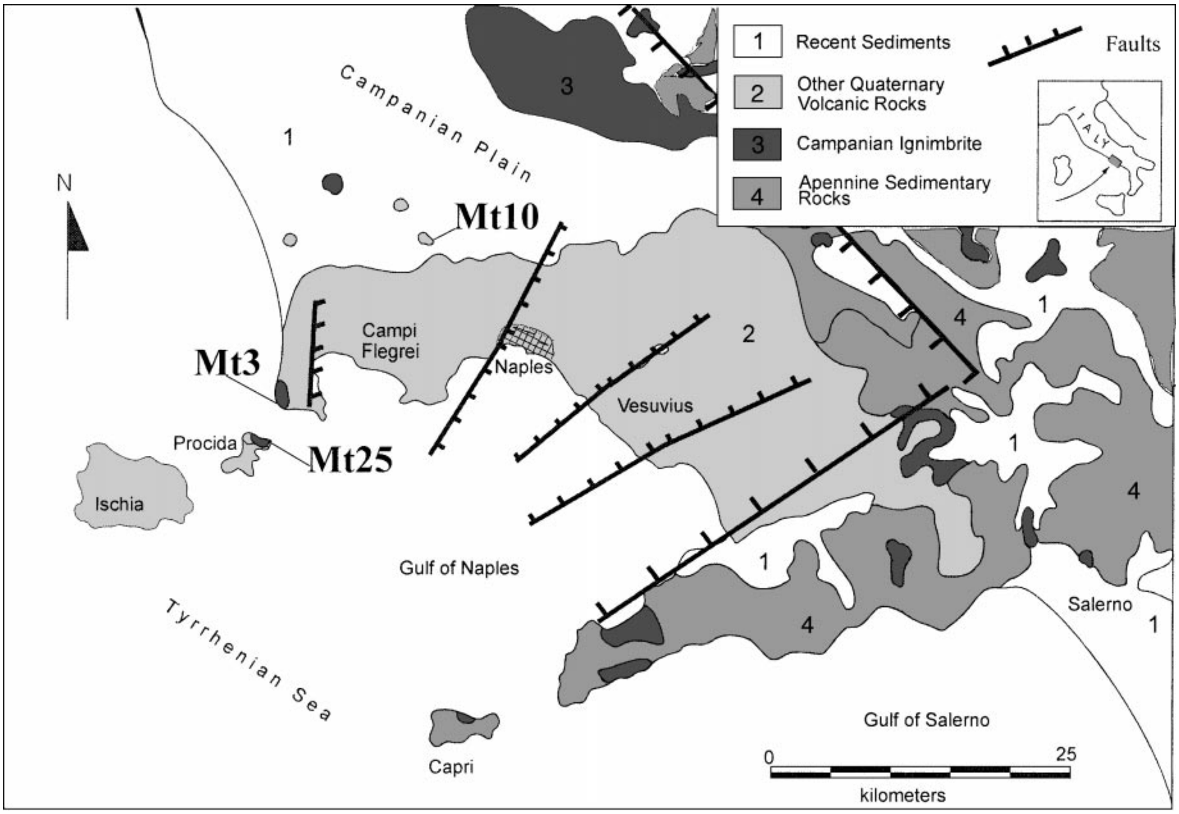

Fig. 1. Schematic geological map of a portion of the Campanian Plain and locations of the studied samples

(Monte di Procida) and MT 25 from Punta della Lingua (Procida Island). One further sample, MT 10, was collected from a volcanic breccia at Punta Marmolite (Quarto) (Fig. 1).

The samples studied have porphyric texture with clinopyroxene, often zoned, being the dominant phenocryst phase. Sample MT25 (leucite-tephrite) also has biotite phenocrysts, which is replaced by opaque phase(s) in varying degrees. Groundmass is composed of variable-size microlites of leucite (up to 0.3 mm in diameter), clinopyroxene, plagioclase and magnetite. Sample MT10 (basalt) has clinopyroxene phenocrysts up to 1 mm long, and rare olivine. The groundmass consists of microlites of clinopyroxene, plagioclase and magnetite. Sample MT3 (trachybasalt) has clinopyroxene phenocrysts up to 2 mm long, and minor biotite. Olivine is much less common and generally altered to iddingsite. The groundmass consists of microlites of clinopyroxene, K-feldspar, plagioclase and magnetite.

Major element compositions of the samples are presented in Table 1. Clinopyroxene phenocrysts were separated and mounted into epoxy, polished and examined for the presence of melt inclusions. Grains containing melt inclusions suitable for reheating experiments [see *Danyushevsky* et al. (2000) for detailed description of the reheating technique] were polished on both sides to form doubly-polished wafers $\sim$300 microns thick. Experiments were performed at the University

Table 1. *Major element compositions of samples studied (wt%)*

Sample	MT3	MT10	MT25
SiO_2	52.03	49.07	47.26
TiO_2	0.74	0.83	1.03
Al_2O_3	15.07	15.88	17.30
$Fe_2O_3^*$	6.89	8.14	8.81
MnO	0.16	0.16	0.18
MgO	5.09	5.99	4.55
CaO	9.81	11.36	9.97
Na_2O	3.23	4.50	2.97
K_2O	3.25	1.00	6.15
P_2O_5	0.47	0.61	0.89
LOI	3.12	2.61	0.61
Total	99.86	100.15	99.72

Analyses were performed by XRF at the University of Tasmania using standard analytical procedures; *P. Robinson* analyst. * – all Fe as Fe_2O_3

of Tasmania using a low-inertia heating stage designed at the Vernadsky Institute, Moscow (*Sobolev* and *Slutskii*, 1984). Reheating experiments were continued until the inclusions were deemed to be close to homogenisation (*Danyushevsky* et al., 2000), at which point they were quenched by switching the power off. A detailed description of the experimental procedures will be presented elsewhere (*Lima* et al., in preparation).

Representative compositions of reheated inclusions and their host clinopyroxenes are shown in Table 2. Host phenocrysts were analysed at distances of $\sim$20 μm from melt inclusions. No compositional variations exceeding the accuracy of microprobe analysis have been noted between individual points in each grain. All inclusions are characterised by low analytical totals (96.5 to 98.5%, Table 2). This is interpreted to reflect the presence of significant amounts of H_2O in the trapped melts. This interpretation is also supported by the analyses of volatiles in melt inclusions from clinopyroxene and olivine phenocrysts from the nearby Mt. Somma-Vesuvius lavas (*Belkin* et al., 1998; *Marianelli* et al., 1999; *Raia* et al., 1999), which showed H_2O contents in the range of 0 to 4 wt%.

Indirect support for high H_2O contents in the melt inclusions also comes from the calculated one-atmosphere (100 KPa) liquidus temperatures of clinopyroxene (Table 2). The calculated values represent liquidus temperatures of clinopyroxene for the analysed compositions under anhydrous conditions and are accurate within $\pm$15 °C (*Ariskin* et al., 1993). Since H_2O is known to suppress the liquidus temperatures of all anhydrous silicates (see *Danyushevsky* et al., 1996; *Danyushevsky* in press for a detailed discussion of the effects of H_2O on crystallisation of basaltic magmas), calculated anhydrous liquidus temperatures of the H_2O-bearing melts are higher than the actual liquidus temperatures. As can be seen in Table 2, all melt inclusions are characterised by higher calculated temperatures. This also indicates efficient quenching of melt inclusions.

Table 2. *Representative major element compositions (wt%) of reheated melt inclusions in clinopyroxene phenocrysts*

Sample	MT3	MT3	MT3	MT3	MT10	MT10	MT10	MT25	MT25	MT25	MT25
Inclusion No.	31.1	30.2	32.1	29.2	16.1	20.1	17.2	28.2	21.2	22.1	25.1
Trun, °C	1160	1160	1160	1160	1185	1200	1190	1160	1195	1195	1160
Tcalc, °C	1203	1186	1203	1188	1243	1230	1220	1201	1244	1258	1186
Mg# host meas.	91.1	83.4	89.7	85.5	92.1	88.7	88.2	82.8	91.2	91.2	87.0
Mg# host calc.	90.1	86.9	88.2	87.6	94.5	92.2	91.0	89.7	92.3	93.0	88.7
SiO_2	48.77	48.46	47.84	48.09	52.84	51.86	49.61	48.03	50.20	49.99	48.55
TiO_2	0.87	0.88	0.85	0.87	0.65	0.88	0.88	1.10	0.87	0.74	0.92
Al_2O_3	14.43	14.69	13.58	14.91	13.02	13.12	13.33	13.73	11.30	10.37	14.89
FeO^*	6.51	7.54	7.63	7.51	4.13	5.82	6.47	6.47	6.48	6.24	6.22
MnO	0.15	0.16	0.19	0.19	0.07	0.14	0.20	0.16	0.16	0.15	0.19
MgO	7.46	6.42	7.10	6.85	8.10	8.17	7.91	7.01	8.71	8.90	6.18
CaO	12.35	12.92	13.41	12.54	12.10	13.10	13.33	12.52	13.21	13.77	11.23
Na_2O	1.76	1.66	1.46	1.63	1.89	2.01	1.60	1.77	1.34	1.25	2.13
K_2O	4.24	4.72	4.27	4.52	4.48	3.02	4.10	4.91	4.52	4.45	6.28
P_2O_5	0.46	0.55	0.52	0.45	0.57	0.34	0.52	0.84	0.67	0.64	0.91
Cr_2O_3	0.06	0.04	0.03	0.01	0.01	0.07	0.02	0.13	0.05	0.04	0.00
TOTAL	97.03	98.02	96.86	97.57	97.86	98.52	97.95	96.67	97.47	96.50	97.50

Trun – quenching temperature during experiments; Tcalc – 100 KPa liquidus temperature of clinopyroxene calculated after *Ariskin* et al. (1993) assuming fO_2 values corresponding to the Ni-NiO oxygen buffer; calculations were performed using software PETROLOG (*Danyushevsky*, in press); Mg# host meas. – analysed $100 * Mg/(Mg+Fe)$ values of host clinopyroxene; Mg# host calc. – $100 * Mg/(Mg+Fe)$ values of liquidus clinopyroxene calculated at 100 KPa after *Ariskin* et al. (1993). All analyses were performed using WDS on CAMECA SX50 electron microprobe at the University of Tasmania, using USNM 122142 and USNM 111240/52 standards for clinopyroxene and glass, respectively (*Jarosewich* et al., 1980); operating conditions used were 15 kV voltage, 20 nA beam current, ~5 micron beam size, counting times were 10 sec. on the peak and 5 sec. on backgrounds from each side; * – all Fe as FeO

Since the quenching temperature during reheating experiments does not reflect the true trapping temperature of the inclusions, the compositions of melt inclusions can be either depleted in the clinopyroxene component (if the quenching temperature is lower than the trapping temperature), or enriched in it (if the quenching temperature is higher). Variations in the amount of the clinopyroxene component in the melt affect its Mg# ($100 * Mg/(Mg+Fe^{2+})$), and thus affect the Mg# of the calculated liquidus clinopyroxene. Calculated clinopyroxene compositions are generally more magnesian than the actual hosts of inclusions (Table 2). This implies that most inclusions were overheated during experiments, i.e., the quenching temperatures were higher than the true trapping temperatures, and thus the analysed compositions are enriched in the clinopyroxene component relative to the original trapped compositions. A detailed description of the experimental results will be presented elsewhere (*Lima* et al., in preparation).

Comparison between the compositions of melt inclusions and Campi Flegrei volcanics

Figure 2 presents the compositions of Campi Flegrei volcanics older than 12 ky (pre NYT deposits). There are no compositional differences between samples from the Breccia Museo and other eruptions of this volcanic system (Fig. 2). The three

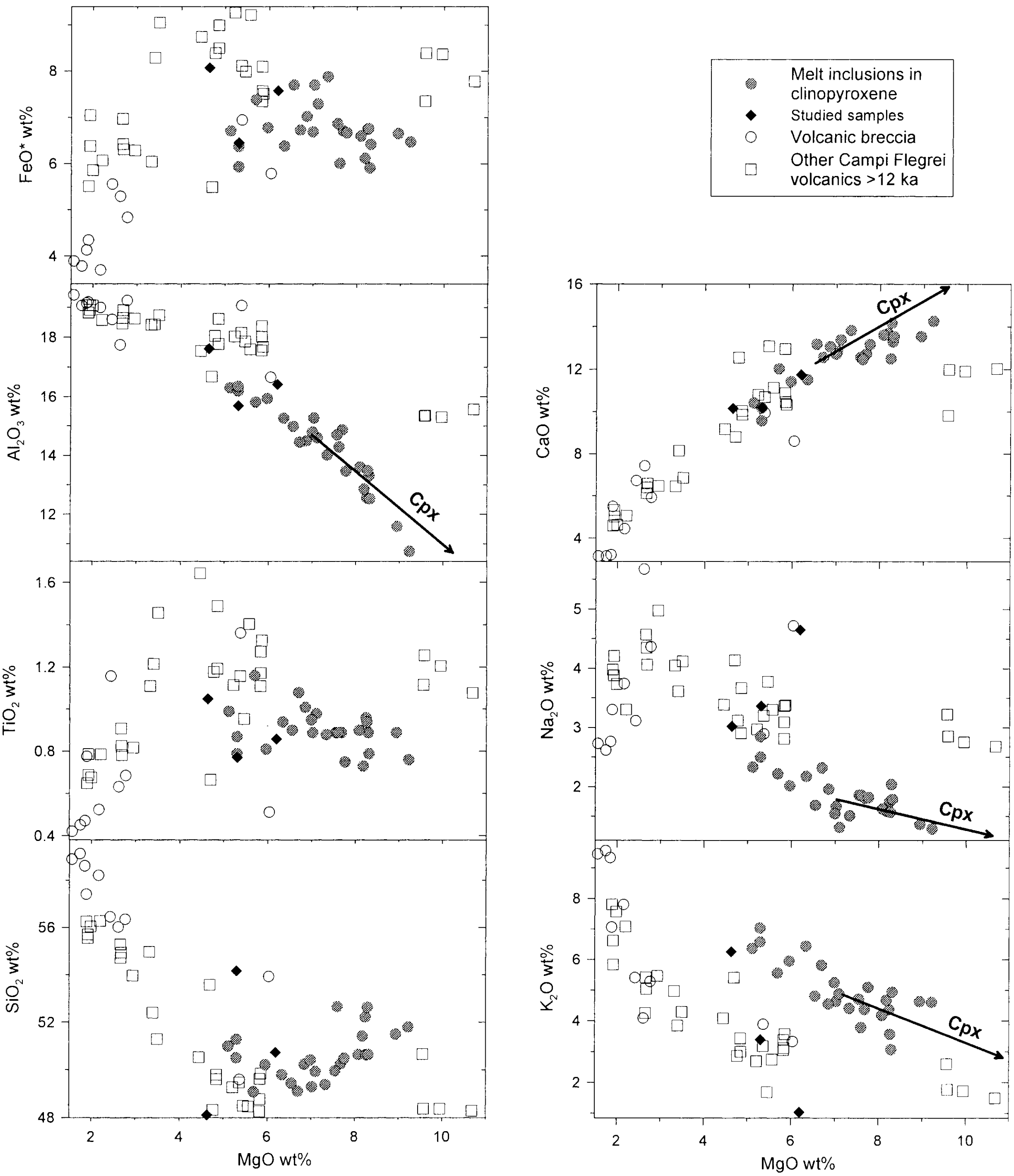

Fig. 2. Compositions of Campi Flegrei volcanics older than 12 ky and reheated melt inclusions in clinopyroxene from this study. Samples from within the Breccia Museo Unit and three samples from this study are shown separately. Data from *Armienti* (1981), *Di Girolamo* et al. (1984), *Melluso* et al. (1995), *Pappalardo* et al. (1999), *Paone* et al. (this volume). Black arrows on Al_2O_3, CaO, Na_2O and K_2O plots point toward the composition of the host clinopyroxene. All data are recalculated to 100% anhydrous. See text for discussion

samples from this study generally also plot within the field of old Campi Flegrei volcanics. The crystallisation of Campi Flegrei parental magmas has been studied in detail previously (e.g., *Armienti* et al., 1983; *Rosi* and *Sbrana*, 1987). Despite some significant scatter on Fig. 2, the major element trends defined by samples from Campi Flegrei are consistent with initial fractionation of olivine, joined by clinopyroxene and plagioclase between 6–8 wt% MgO. Fe-Ti oxide started crystallising at ~ 4 wt% MgO. Despite the common presence of sanidine phenocrysts in trachytes (e.g., *Armienti* et al., 1983), its fractionation is not required by compositional variations in samples with $MgO > 1.5$ wt%.

Compositions of reheated melt inclusions in clinopyroxene from the three samples studied (Fig. 2) are remarkably different from the compositions of Campi Flegrei lavas. Although differences in Al_2O_3 and CaO contents are consistent with overheating during experiments (see the previous section), differences in Na_2O and K_2O are not. As can be seen on plots with K_2O and Na_2O on Fig. 2, any variations in the amount of the clinopyroxene component in the compositions of melt inclusions are unable to return them to the whole rock trend. In other words, melt inclusion compositions from the Museo and Punta Marmolite breccias are significantly enriched in K_2O and depleted in Na_2O compared to any known contemporary eruptive products of Campi Flegrei. Some differences are also evident in FeO^* (total Fe as FeO) and TiO_2 contents. Thus we conclude that clinopyroxene phenocrysts from these breccias could not have crystallised from Campi Flegrei magmas.

Between $\sim$25–14 ka Mt. Somma, another Campanian volcano in the vicinity of Campi Flegrei (east of Napoli), was also active, and in the following section we investigate whether the clinopyroxene phenocrysts studied from the Museo and Punta Marmolite breccias could have originated from a volcanic system genetically related to the Mt. Somma system. We distinguish here the Mt. Somma from Vesuvius becase the latter grew within the Mt. Somma caldera (*Rolandi* et al., 1998; *Webster* et al., this volume) later on, during the interplinian activity following the 472 A.D. plinian eruption.

Comparison between the compositions of melt inclusions and Mt. Somma-Vesuvius volcanics

Temporal variations in major element contents of Mt. Somma-Vesuvius volcanics

The volcanic products of the Mt. Somma-Vesuvius have been studied extensively (e.g., *Santacroce*, 1987; *De Vivo* et al., 1993; *Spera* et al., 1998; *Signorelli* et al., 1999b; and references therein). The major element compositions of Mt. Somma-Vesuvius rocks display significant temporal variability (*Ayuso* et al., 1998). Plots of major elements for the overall Mt. Somma-Vesuvius activity (Fig. 3) confirm this temporal variability. The most recent Vesuvius eruptions (post $\sim$472 AD) are characterised by higher K_2O and FeO^*, and lower Na_2O and SiO_2 contents. Volcanic products of the 17 ka–472 AD eruption have higher SiO_2, Na_2O and lower K_2O and FeO^* contents. Old (> 17 ka) Mt. Somma volcanics can be divided into two compositional groups. The first resembles the 17 ka–472 AD volcanics, whereas the second is unique. It is characterised by high K_2O and low Na_2O contents, similar

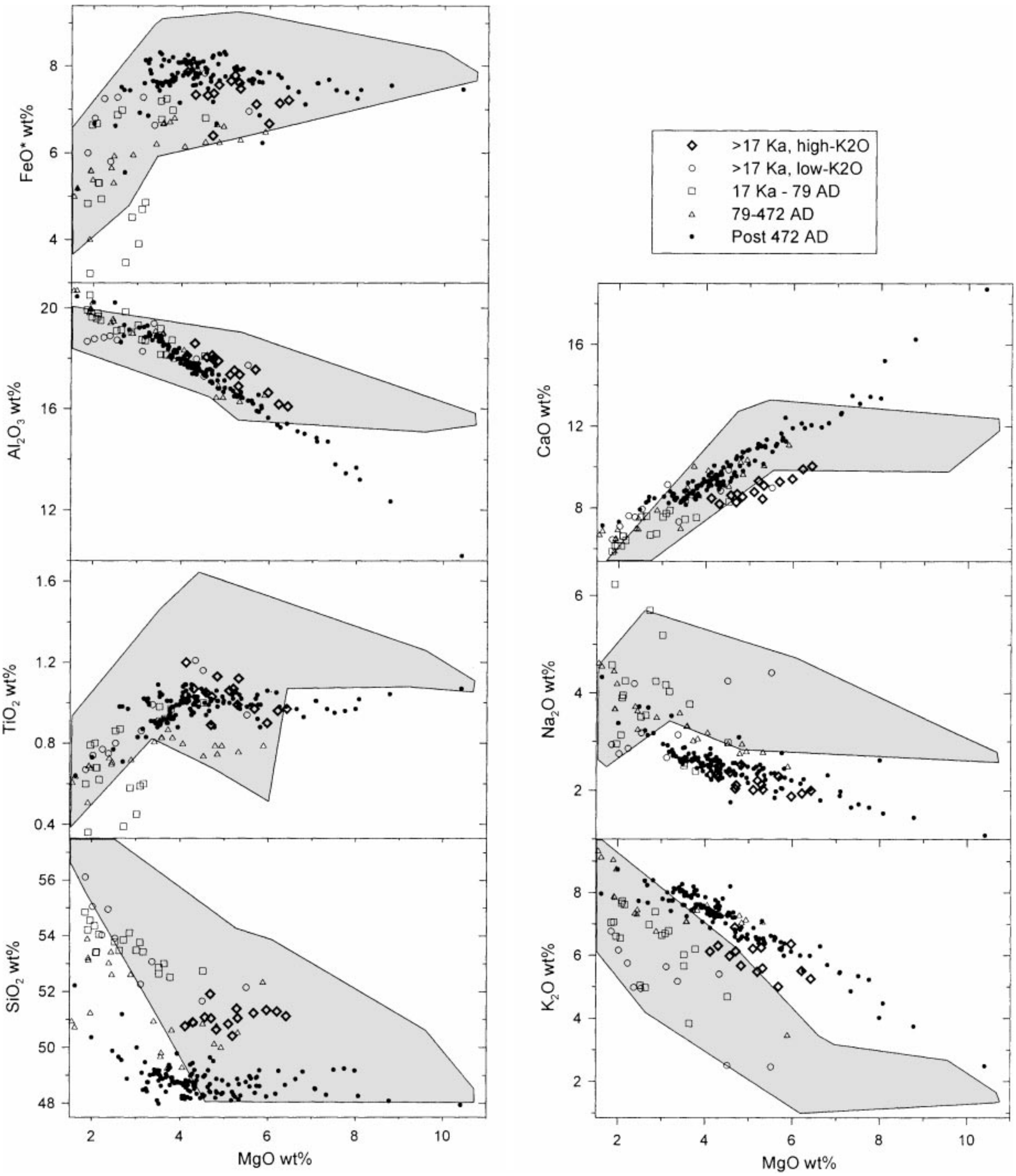

Fig. 3. Temporal variations in the compositions of Mt. Somma-Vesuvius volcanics. Data from *Villemant* et al. (1993), *Belkin* et al. (1993), *Ayuso* et al. (1998) and this volume. The light grey field corresponds to the Campi Flegrei volcanics from Fig. 1. All data are recalculated to 100% anhydrous. See text for discussion

to the recent volcanics, but the SiO_2 contents are higher, similar to the 17 ka–472 AD volcanics.

An interesting feature of recent Vesuvius volcanics is that they form very tight compositional trends at MgO > ~ 4 wt% (Fig. 3). These trends have been interpreted by *Marianelli* et al. (1999) to reflect the accumulation of clinopyroxene phenocrysts. This is also consistent with the petrographical data of *Trigila* and *De Benedetti* (1993), which display a good correlation between rock MgO contents and the abundance of clinopyroxene phenocrysts. These observations imply that the compositions of the recent Vesuvius volcanics at MgO > ~ 4 wt% do not reflect true melt compositions. Instead, these rocks represent magmas formed by evolved melts (MgO < 4 wt%) and variable amounts of clinopyroxene phenocrysts that these melts picked up from cumulate layers in the magma chamber(s) during eruption. Very tight trends formed by 'basaltic' recent Vesuvius rocks (Fig. 3) indicate that the composition of the erupting evolved melts has changed little since ~ 472 AD, and that the magma chamber supplying these inter-plinian eruptions is essentially in a steady-state condition.

Compositions of melt inclusions in pyroxene phenocrysts from Breccia Museo and from volcanic breccia of Punta Marmolite resemble the high-K_2O group of pre-17 ka Mt. Somma volcanics

As discussed above, the older volcanics of Mt. Somma (> 17 ka), which might be broadly contemporaneous with the Breccia Museo Unit (~ 39 ka), form two compositional groups. Whole rock compositions from the high-K_2O group are compared with the compositions of melt inclusions in clinopyroxene from this study on Fig. 4. There is a close match between the compositions of melt inclusions and high-K_2O group rocks. CaO and Al_2O_3 contents are not included in this comparison since their contents in melt inclusions are significantly distorted by overheating (CaO is significantly higher, Al_2O_3 is significantly lower; see Fig. 2). We thus conclude that the pyroxene phenocrysts from the breccia xenoliths originated in a volcanic system genetically very similar to the feeding system of the older Mt. Somma eruptions. The Ar ages of the Breccia Museo outcrop (~ 39 ka) (*De Vivo* et al., in press), are very similar to the ages of the older products of Mt. Somma, which, though not precisely dated, range from 14 ka to > 25 ka. This result is important because it is suggested that a close relationship (or link) existed between the volcanic products of Mt. Somma, situated about 10 km east of Napoli, with the volcanic products of the Campi Flegrei area, about 15 km west of Napoli. The Mt. Somma-Vesuvius volcanic system has always been considered as separate from the volcanic system active to the west of Napoli. We invoke here a close link between the volcanism of Mt. Somma and volcanism in the Campi Flegrei area prior to the NYT eruption (~ 12 ka). The xenoliths sampled in the ~ 39 ka (*De Vivo* et al., in press) Breccia Museo and the breccia at Punta Marmolite were derived from a volcanic system older than the breccia units themselves. We suggest that this older volcanism had close similarities to the volcanism of the older products of Mt. Somma (> 25 ka). A perfect overlap of the Pb isotopic compositions of the Breccia Museo, Campanian Basalts and Mt. Somma volcanics confirms this (*Paone* et al., in

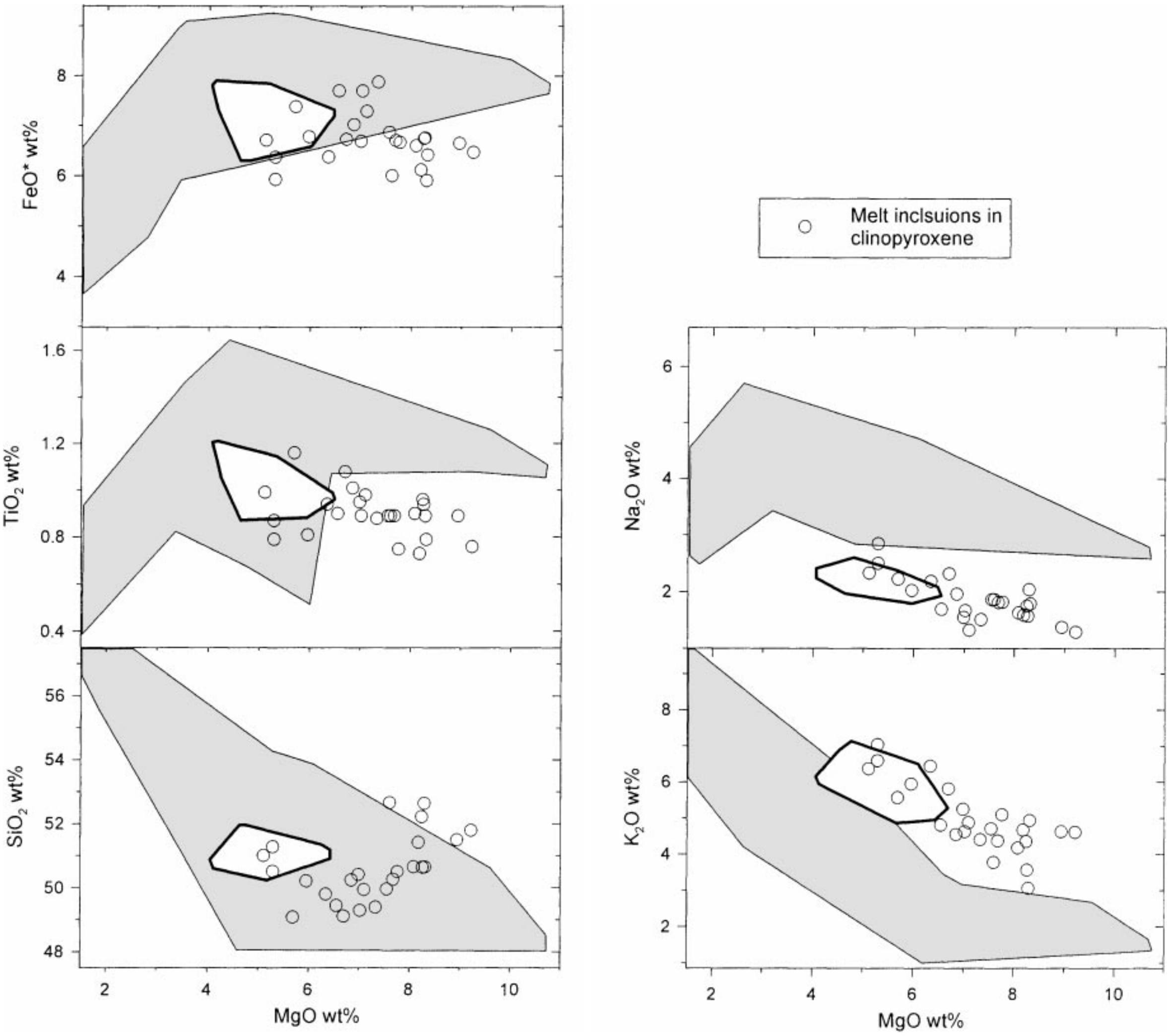

Fig. 4. Comparison of compositions of reheated melt inclusions in clinopyroxene from Breccia Museo and volcanic breccia of Punta Marmolite with the high-K_2O group of pre-17 ka Mt. Somma volcanics. The light grey field corresponds to the Campi Flegrei volcanics from Fig. 1. The white field corresponds to the high-K_2O group of pre-17 ka Mt. Somma volcanics from Fig. 3. All data are recalculated to 100% anhydrous. See text for discussion

preparation). Our conclusion is also supported by experimental results of *Trigila* et al. (1995) who demonstrated that the Campi Flegrei and Mt. Somma volcanics could have evolved from a similar parental magma.

Acknowledgments

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Authors' addresses: *L. V. Danyushevsky*, School of Earth Sciences, University of Tasmania, GPO Box 252-79, Hobart, Tasmania, 7001, Australia, e-mail: L.Dan@utas.edu.au; *A. Lima*, Dipartimento di Geofisica e Vulcanologia, University of Napoli "Federico II", I-80134 Napoli, Italy