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Triggering of Volcanic Pulses in the Campanian Area, South Italy, by Periodic Deep Magma Influx

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Geochemical fluctuations through time of the eruptions originating from Ischia island and from the Phlegrean Fields in the Campanian area have been analyzed in order to determine the relationships between the mechanisms responsible for compositional variations of the magmas and the fluctuations in eruptions. Geochemical fluctuations are derived from the detailed chronological and geochemical record of marine tephra in deep-sea sediment cores from the central Mediterranean Sea. Such fluctuations are marked by the repetition of similar compositional gradients during each eruptive cycle, as defined by a period of intense activity followed by a quiet eruptive period. Geochemical changes through time in both areas may be explained by magma evolution in a continuously crystallizing, tapped, and periodically refilled stratified magma chamber. Each eruptive and geochemical cycle starts by an influx of magma from depth into the shallow reservoirs, which leads to an increase in the frequency of the eruptions and maintains the activity in a particular volcanic area. This inflow may be controlled by changes of glacio-eustatic pressure, as suggested by its periodic occurrence every 24 kyr.

INTRODUCTION

Several causes for the fluctuations in eruptive rates in volcanic areas have been advanced, such as changes of rates of sea-floor spreading [Kennett *et al.*, 1977], solar activity [Stothers, 1989], lunar attraction [Dzurizin, 1980] and climatic changes [Rampino *et al.*, 1979; Matthews, 1969; Walcott, 1972; Kennett and Thunell, 1975]. Pressure variations on mantle would mechanically facilitate magma ascent through the lithosphere in response to changes in Earth's rotation, leading to readjustment of the rate of motion of the Earth's interior, and/or to changes in the distribution of water masses during Quaternary glaciations [Matthews, 1969; Walcott, 1972; Rampino *et al.*, 1979; Stothers, 1989]. Magma inflow from a deeper source into shallow reservoirs may produce an overpressure that is able to trigger an eruption, as has been observed during periods of inflation of some volcanoes prior to eruption. Such an influx of undifferentiated magma from depth would modify the geochemical evolution of residual evolved liquids within shallow magma chambers which is mainly controlled by fractional crystallisation [O'Hara, 1977; O'Hara and Matthews, 1981; Albarède, 1985]. Thus relationships between magma influx and eruptivity may be analysed by recording changes in the geochemical composition of erupted products through time and the fluctuations of the volcanic activity.

Temporal series of the explosive activity of the Campanian volcanoes has been developed for the past 190 kyr by detailed chronological and geochemical studies of marine ash layers of 5 deep-sea cores from the Tyrrhenian and Adriatic seas (Figure 1). Analysis of the frequency of the eruptions through time shows that eruptive cycles of about 23 kyr occur during this time period [Paterne *et al.*, 1990]. In this study, we have used the major and trace element composition of the Campanian ash layers to examine process of magma evolution. As

fractional crystallisation cannot entirely explain the observed geochemical trends through time, mixing processes either within a zoned magma chamber or during the filling of a shallow reservoir with magma from depth have been explored with respect to variations of relative erupted masses estimated for each eruption. Finally, the influence of such processes on the changes in rates of eruptions through time have been analysed.

METHODS

Methods of stratigraphical and geochemical identification of marine tephra layers, each one accounted for a unique eruptive event, have been previously published [Paterne *et al.*, 1986; 1988; 1990]. Major and trace element analyses were performed on glass shards, which are the only volcanic materials in marine sediments that can be traced over long distances. Furthermore, vitreous particles are representative of the magmatic liquid, its composition varying along with crystallisation, mixing or contamination processes.

Major element compositions, measured at 15 kV, 0.3 nA on large areas (20 to 50 μm^2) for 100 s with a Scanning Electron Microscope (SEM) coupled with an X ray Energy Dispersion Spectrometer (EDS) have been obtained on individual glass shards. Means and standard deviations have been calculated for each ash layer and some examples are given in Table 1. Each event, as defined by a chronostratigraphical position and by a chemically homogeneous composition has a mean value given in Tables 2 and 3 with a standard deviation which corresponds to a 2% error on SiO_2 , 5% on Al_2O_3 , and 20% on the other elements.

Trace element compositions were obtained by neutron activation analysis. Pure glasses, with crystal contents lower than 5%, separated from chemically homogeneous tephra layers were irradiated with a flux of 10^{14} n/cm²/s for 5 to 20 min. in Al vials and quartz tubes at the Centre d'Etudes Nucléaires de Saclay. Chemical measurements were made using an intrinsic Ge detector of 80 cm³, using granite and basalt

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Fig. 1. Location of the deep-sea cores and of the volcanic areas (shaded) of southern Italy. See text for explanations of the lines connecting marine cores.

TABLE 1. Average and Standard Deviation (1 σ) in Parentheses of Some Marine Ash Layers of Ischia Island and of the Phlegrean Fields

	Ash layer					
	70-04	C-16	C(i)-6	690-04	C-7	C-10
No*	21	53	20	20	43	42
SiO ₂	63.36 (0.31)	61.63 (0.93)	64.37 (1.08)	62.27 (0.64)	63.12 (0.90)	60.4 (0.55)
TiO ₂	0.6 (0.13)	0.31 (0.09)	0.13 (0.13)	0.56 (0.07)	0.25 (0.08)	0.23 (0.11)
Al ₂ O ₃	18.97 (0.26)	19.09 (0.22)	18.55 (0.07)	19.05 (0.22)	18.53 (0.21)	20.02 (0.41)
FeO	2.74 (0.42)	2.97 (0.47)	2.39 (0.22)	2.68 (0.13)	3.03 (0.39)	2.69 (0.41)
MgO	0.11 (0.07)	0.14 (0.07)	0.01 (0.02)	0.09 (0.05)	0.14 (0.13)	0.04 (0.06)
CaO	0.95 (0.03)	1.84 (0.29)	1.56 (0.16)	1 (0.09)	2.17 (0.33)	3.15 (0.36)
Na ₂ O	6.47 (0.70)	6.27 (0.49)	4.99 (0.99)	7.81 (0.73)	3.86 (0.52)	4.38 (0.54)
K ₂ O	6.76 (0.19)	7.72 (0.54)	7.98 (0.42)	6.5 (0.28)	8.86 (0.42)	9.05 (0.24)
Age kyr	8.9	51	57.2	65	26.9	33.5

The ash layers are either numbered, or noted by their level of depth, followed by the two last numbers of the cores.

*The number of analyzed glass shards.

rocks standards (GSN and BEN) from the CRPG (Centre de Recherches Pétrographiques et Géochimiques de Nancy). Analytical precision is 10 % for Sc, Co, Zr, Cs, La, Ce, Sm, Eu, Tb, Yb, Hf, Ta, and Th; 15 % for Cr, Sb, Ba, Nd and Lu and 20 % for U.

Trace element analyses could not be performed on all marine ash layers because of the small sample sizes of some tephra or because of geochemical heterogeneity, mainly due to bioturbation [Paterne *et al.*, 1988]. Detailed analyses of the

major element composition of all ash layers are presented elsewhere [Paterne, 1985], and only major and trace element data obtained on the same tephra are given in Tables 2a, 2b and 3.

MAGMA EVOLUTION

Trace element patterns of the ash layers were compared with the compositions of pure glass shards from continental

TABLE 2a. Major and Trace Element Analyses of Marine Ash Layers Originated from Ischia Island

	Ash layer															
	5-19	70-04	142-04	C-3	C-5	35M	104	260-04	C(i)-5	C-11	C-13	460-04	C-14	C-15	C-16	C-17
N ₀ *	20	21	20	18	14			19	15	31	64	30	15	30	53	47
SiO ₂	63.60	63.36	63.09	65.20	63.43	60.72	52.6	64.86	62.22	61.6	62.05	62.04	63.02	61.35	61.63	62.97
TiO ₂	0.55	0.6	0.52	0.27	0.33	0.66	1.36	0.34	0.36	0.28	0.35	0.27	0.35	0.29	0.31	0.41
Al ₂ O ₃	17.73	18.97	19.36	17.98	19.02	19.32	18.69	18.48	19.10	19.31	19.32	19.5	18.98	19.13	19.09	18.79
FeO	2.51	2.74	2.64	2.34	2.11			2.79	2.95	2.95	2.75	2.55	2.23	3.06	2.97	2.53
MnO	0.21	-	-	-	-	0.1	0.14	-	-	-	-	-	-	-	-	-
MgO	0.60	0.11	0.2	0.00	0.42	0.84	3.25	0.05	0.00	0.13	0.13	0.16	0.08	0.13	0.14	0.05
CaO	1.26	0.95	0.99	1.38	1.3	2.51	7.52	0.91	1.92	1.79	1.63	1.68	1.28	1.95	1.84	1.5
Na ₂ O	6.36	6.47	6.59	5.83	6.07	5.13	3.61	6.5	5.94	5.67	6.12	6.19	7.56	6.52	6.27	6.86
K ₂ O	6.57	6.76	6.57	6.65	7.31	6.9	3.89	6.03	7.47	8.23	7.61	7.56	6.47	7.53	7.72	6.85
Sc	3.29	2.09	2.64	1.27	3.7	3.8	20	1.61	3.04	3.3	2.3	3	5.6	2.5	2.4	4
Cr	24.5	7	12.6	11.3	12	5	11	-	-	-	6.4	9.5	41	9	29	-
Co	3.3	1.1	2.05	2.4	62	11.4	22	12	4.1	4.2	2.6	3.3	7.5	3	3.5	7
Ni	17	-	-	-	-	-	-	26	21	-	-	-	12	-	-	-
Rb	334	399	520	454	546	240	106	503	305	286	929	427	144	315	300	298
Sr	75.5	126	407	62.3	-	294	711	-	187	282	98	110	177	135	104	207
Zr	456	446	680	816	1070	260	165	920	425	372	470	698	173	460	424	358
Sb	0.69	-	-	2.28	2.5	-	-	2.07	0.9	-	-	2.15	0.59	1.34	1.32	1.22
Cs	22.2	29.5	41.36	48.5	48.52	1.8	5	50.9	22	21.5	28.9	41.8	10.81	24.85	21.87	16.34
Ba	194	225	351	340	307	433	1350	345	284	455	277	279	335	280	-	347
La	76	98	134	128	159	58	42	145	89	78	108	146	60	104	87	70
Ce	167	188	250	260	308	95	97	279	179	159	219	288	73	208	165	157
Nd	61	50	61	71	79	63	45	69	59.5	53	70	92	25	63	56	48
Sm	10.8	10	11.7	12	12.7	8.2	8	12.5	10.4	9.2	12.8	16.3	6.7	13.2	11.6	8.9
Eu	1.3	0.88	1.76	1.16	0.7	0.9	2.8	0.82	1.55	1.5	1.6	1.25	0.7	1.7	1.6	1.8
Tb	1.1	1	1.2	1.25	1.5	0.96	0.9	1.16	1.19	0.92	1.09	1.76	0.4	1.24	1.07	1.09
Yb	4.4	4.72	8.4	5.43	8.38	0.94	2.5	6.91	3.77	3.5	4.6	6.29	1.83	4.27	3.75	3.28
Lu	0.75	0.93	1.27	0.93	1.4	0.2	0.51	1.3	0.62	0.52	0.66	1.01	0.28	0.7	0.57	0.52
Hf	11.03	13.68	20.4	18.3	25.1	5.7	3.9	22.2	9.9	8.7	13	17.4	4.7	11	9.6	8.5
Ta	5.59	5.35	6.5	6.22	7.67	3.3	1.9	6.05	4.5	4.56	5.5	8.35	1.77	5.42	4.55	3.91
Th	40.5	50.9	77.6	83.3	105.8	20.1	9.5	84.3	36.3	32.1	44.3	65.72	12.8	40.5	36.4	27.4
U	12.9	16.3	21.8	28.4	30.8	4.9	2.5	26.6	11.78	9.5	17.9	23.5	5.4	15.56	12	8.38
Age kyr	4.35	8.9	13.9	14.4	19.62	23.6	28.1	26.4	35.2	36.6	40	40.5	41.8	46.7	51	55.4
	C			C*	B1	A1	A1	D2		C2	C*	B2	A2	D3		C3

The ash-layers are either numbered, or noted by their level of depth, followed by the two last numbers of the cores. Alphabetic numbering of the ash layers referred to their position in the geochemical cycle. See Text.

* Number of analyzed glass shards.

deposits and with published whole rock analyses (Figure 2) [Poli *et al.*, 1987, 1989; Villemant, 1988; Crisci *et al.*, 1989]. As noted previously [Paterne *et al.*, 1988], trace element patterns of marine tephra follow similar trend as the continental ones. Thus, the marine environment has not played a significant role in the alteration of vitric particles during the time sequence considered.

Source regions of the Campanian tephra have been previously deduced from the comparison between the alkali ratios in marine and land deposits [Paterne, 1985; Paterne *et al.*, 1988]. Products that were derived from Ischia island have a lower K₂O/Na₂O ratio than products of the Phlegrean Fields, which are relatively enriched in K₂O (Tables 2 and 3). In marine ash layers, the activity of the Phlegrean Fields is represented by trachytes (Table 3), one trachybasaltic and one latitic ash layer [Paterne, 1985]. No marine tephra of phonolitic composition has been found, but continental deposits of such a composition are very scarce in this area [Armienti *et al.*, 1983]. Nevertheless, marine ash layers reflect the full range of composition [Villemant, 1988], matching the weight abundance of the different chemical groups observed in the Phlegrean Fields on land [Armienti *et al.*, 1983]. Products of Ischia island are only represented by peralkalic trachytes in marine ash layers, which is strongly consistent with field observations which showed that the full range of composition from trachybasalt to phonolite is only observed in the lava flows of the recent phase of activity [Poli *et al.*, 1987, 1989].

Processes of magma evolution have been analysed using the behavior of hygromagmaphile elements [Treuil and Varet,

1973; Allègre *et al.*, 1977; Allègre and Minster, 1978]. In Phlegrean Fields tephra, the highest enrichment factors, characterizing hygromagmaphile elements, are observed for U, Cs, Rb, Th and Ta, and in the products of Ischia island for Th, Zr, Ce, U, Hf. Correlation diagrams between some of hygromagmaphile elements and of compatible elements, using Th as a reference element because of its low mineral/liquid partition coefficient, are shown in Figure 3. In the Phlegrean Fields, magmatic evolution is clearly related to a fractional crystallization process, as demonstrated by the linear correlations between incompatible elements through a continuous and single trend crossing the origin and by the rapid decrease of the transition series elements, such as Sc and Cr, with differentiation. Magmatic evolution processes are relatively difficult to trace within the products of Ischia island because of their high degree of differentiation (two tephra-layers in the range 10 to 20 ppm of Th), and because the bulk partition coefficient varies with differentiation. Nevertheless, a fractional crystallization process may be envisaged, taking into account the trachybasalts present on the island [Poli *et al.*, 1987].

Furthermore, marine ash layers from both the Phlegrean Fields and Ischia island show one single continuous trace element trend (Figures 2 and 3), suggesting that these magmas are derived from fractional crystallization of similar parental liquid(s). The different behavior of some elements, particularly the strong decoupling of compatible and incompatible elements in Ischia products, which is not observed in those of the Phlegrean Fields (Tables 2 and 3), indicates that magmatic

TABLE 2b. Major and Trace Element Analyses of Marine Ash Layers Originated from Ischia Island

	Ash layer														
	C(i)-6	457-11	C-18	644-04	654-04	690-04	717-04	745-04	855-04	920-04	958-04	968-04	985-04	1290-04	1410-04
N ₀ *	20	20	25	11	25	20	15	16	42	19	15	12	29	29	26
SiO ₂	64.37	62.64	62.78	64.52	62.57	62.27	62.38	63.47	62.44	63.21	62.89	62.38	62.18	63.7	64.25
TiO ₂	0.13	0.56	0.48	0.47	0.57	0.56	0.44	0.69	0.44	0.55	0.35	0.36	0.33	0.64	0.64
Al ₂ O ₃	18.55	19.28	18.56	18.13	18.79	19.05	19.37	18.73	18.99	18.45	18.92	18.71	18.66	18.67	18.44
FeO	2.39	2.54	2.59	2.58	3.09	2.68	2.54	3.03	2.61	2.71	2.87	3.02	2.97	2.61	2.54
MnO	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MgO	0.01	0.13	0.07	0.05	0.02	0.09	0.04	0	0.05	0.07	0.05	0.05	0.1	0.05	0.02
CaO	1.56	1.1	1.32	1.24	1.23	1	1.41	1.27	1.02	1.2	1.82	1.76	1.84	0.9	1
Na ₂ O	4.99	7.44	7.45	6.15	6.94	7.81	7.28	5.75	8.28	7.64	6.33	6.98	6.64	7.23	6.7
K ₂ O	7.98	6.27	6.71	6.81	6.75	6.5	6.49	7.04	6.15	6.15	6.73	6.69	7.25	6.18	6.37
Sc	2	2.41	2.5	2.91	2.3	1.87	3	2	2.08	5.4	2.75	2.32	4.1	3.3	2.7
Cr	5	16	23	7	8	-	27	-	8	29	13	14	13	25	7
Co	2	1.9	3	2	3	11.7	4	1	1.4	3	4	2.9	7	6	5
Ni	-	18	-	14	-	16	11	-	-	-	25	24	0.19	-	-
Rb	363	316	341	307	356	377	205	420	349	383	347	456	254	359	320
Sr	52	207	119	90.5	58	-	231	-	71	179	276	-	306	70	28
Zr	510	416	485	413	386	602	263	601	648	652	647	849	447	605	509
Sb	0.74	0.82	0.8	0.76	1	1.57	0.56	-	1.03	1.6	1.4	2.1	1.49	-	1
Cs	21.56	17.7	20.93	17.66	19.84	-	13.99	33.01	22.8	24.6	25.76	36.9	20.24	20.8	17.83
Ba	197	233	217	275	37	149	340	233	219	293	420	257	513	96	35
La	118	95	108	89	103	135	52	165	147	140	142	174	114	132	137
Ce	223	198	222	187	175	259	101	322	267	292	301	447	205	233	294
Nd	73	68	75	67	90	103	34	89	84	88	88.5	154	71	76	87
Sm	12.5	11	15.4	11.9	15.1	16.3	6.1	16.4	15.1	13.4	16.8	20	11.2	15.2	15.2
Eu	1	1.22	1.3	1.27	1.2	1.01	1.1	1	1.1	1.2	2.2	2.2	1.6	1.2	1.3
Tb	1.62	1.27	1.44	1.06	1.57	1.49	0.63	2.06	1.68	1.69	1.7	2.27	1.21	1.33	1.47
Yb	5.22	4.49	4.67	4.1	5.21	6.3	2.63	7.7	6.28	6.23	5.92	7.4	4.33	5.47	5.77
Lu	1.13	0.73	0.8	0.66	0.78	1.11	0.38	1.22	1.01	1.07	0.82	1.45	0.74	0.81	0.93
Hf	13	10.8	11.8	10.4	11.9	15.5	6.25	19.7	16.5	17.7	13.5	19.3	9.8	14.3	12.7
Ta	5.01	4.54	5.08	4.35	5.51	6.92	2.31	7.18	5.91	5.62	5.72	8.14	3.75	4.49	4.15
Th	37.8	32.1	35.7	32.5	29.7	52.2	19.5	64.3	52.7	59.4	54.2	77.3	37.5	62.3	52.9
U	11.5	9.45	10.86	10.6	8.41	16.8	6.9	16.3	16	16.8	16.3	19.5	13.45	14.8	14.1
Age kyr	57.2	58.9	60.3	60.7	62.2	65	68.5	76.5	93.7	100.6	104.5	105.8	107.3	155.1	186.6
					C*	B3	A3	D4	C4		C*	B4	A4		

The ash-layers are either numbered, or noted by their level of depth, followed by the two last numbers of the cores. Alphabetic numbering of the ash layers referred to their position in the geochemical cycle. See Text.

* Number of analyzed glass shards.

evolution in both areas has taken place within different reservoir systems.

GEOCHEMICAL FLUCTUATIONS THROUGH TIME

Magma evolution trends through time, as recorded by the marine tephra, are first compared with continental volcanic records, and then with fluctuations in the frequency of eruptions. Variations in thorium concentrations with time are thus reported for tephra originating from Ischia island in Figure 4, since this element is highly hygromagmaphile and is relatively insensitive to alteration. Because of the small number of trace element data obtained on glass shards in marine tephra from the Phlegrean Fields, we report the SiO₂ values through time (Figure 5d), as SiO₂ has a similar behavior to that of thorium.

Comparison of the volcanic records in Ischia island shows that the amplitude of the thorium variations is similar, with the exception of one event at 108 ppm in the marine record, but thorium concentrations are slightly higher in marine ash layers than in land samples [Poli *et al.*, 1987; 1989]. This may be due to crystal abundance in the analysed land samples, including lavas, which tends to decrease thorium

concentrations. Nevertheless, the main features of magma evolution are preserved throughout time. The time span, ranging from 110 kyr to nearly 60 kyr, is much better documented in marine ash layers than on land. During the past 20 kyr, both marine and land data are strongly consistent, defining a decrease of thorium concentration. Counterpart of the lava flows, which show depleted thorium concentrations in the land record at around 25 kyr, have not been found in marine ash layers because this type of activity cannot be recorded in the marine sediments. Therefore, the sharp Th increase, which occurred between 35 kyr to 20 kyr in the marine ash layers, is constrained by land data to occur between 25 kyr and 20 kyr [Poli *et al.*, 1987, 1989]. The land samples of trachybasaltic composition will be further taken into account in the geochemical marine record. Finally, from 55 to 35 kyr, the marine ash layers show two repetitive oscillations, each one marked by increasing and decreasing trends from 55 to 42 kyr and from 42 to 35 kyr. Similar features may be observed in compositional variations of land samples, but, on land, the age of the maximum thorium concentration during the second oscillation from 42 to 35 kyr does not coincide with that of the marine record. However, the age of this land deposit is estimated from stratigraphical relationship between two dated

TABLE 3. Major and Trace Element Analyses of Marine Ash Layers Originated From the Phlegrean Fields

	Ash layer						
	C-1	120-18	C-2	C-4	C-7	C-10	C-9
N _a *	32	23	20	17	43	42	19
SiO ₂	59.86	60.5	61.94	52.32	63.12	60.4	66.16
TiO ₂	0.44	0.3	0.31	1.45	0.25	0.23	0.24
Al ₂ O ₃	19.78	19.23	19.63	18.44	18.53	20.0	27.82
FeO	3.46	3.72	2.99	7.86	3.03	2.69	1.98
MnO	-	-	-	-	-	-	-
MgO	0.37	0.07	0.2	4.4	0.14	0.04	0.04
CaO	2.76	3.32	1.99	8.18	2.17	3.15	2.26
Na ₂ O	3.58	3.98	4.34	4.27	3.86	4.38	3.6
K ₂ O	9.72	8.83	8.57	3.08	8.86	9.05	7.85
Sc	4.16	4.8	4.57	30.4	3.1	1.7	1.8
Cr	37	30.5	21.5	91	10	8.75	-
Co	7	5.5	4.05	34	4.2	8.7	8.3
Ni	-	25	-	-	-	-	-
Rb	258	223	237	85	675	-	359
Sr	804	659	510	714	253	601	350
Zr	271	206	278	143	298	305	364
Sb	0.76	0.56	0.37	0.38	-	0.45	-
Cs	16.7	12	14.5	3.01	17.9	21	30.48
Ba	1661	800	720	744	301	676	376
La	52	44	74	23	60	78	70
Ce	108	90	106	123	120	153	136
Nd	38	31.5	42.4	26	41	49	44
Sm	7.2	6	8.6	5.6	7.2	8.9	7.7
Eu	1.7	1.8	1.5	2	1.6	2	1.6
Tb	0.68	0.64	0.7	1.06	0.6	0.82	0.74
Yb	1.97	1.94	2.68	2.1	2.55	2.97	3.3
Lu	0.37	0.31	0.48	0.36	0.42	0.48	0.48
Hf	6.4	5.7	6.52	3.2	7.5	7.2	8.4
Ta	2.46	2.32	2.6	0.95	2.72	3.1	2.94
Th	23	18.9	23.3	6	26.6	32.2	36.8
U	7.47	7.93	8.09	1.08	8.4	10.18	13
Age kyr	9.76	11.4	12.3	19.62 Al	26.9	33.5	36

The ash-layers are either numbered, or noted by their level of depth, followed by the two last numbers of the cores. Alphabetic numbering of the ash layers referred to their position in the geochemical cycle. See Text.

* Number of analyzed glass shards.

marker deposits [Poli *et al.*, 1989]. Thus an age closer to 40 kyr for this event is not incompatible taking into account the stratigraphical relationships and dating of those products. Thus land and marine compositional records do not show incompatible features, and the good consistency of the different compositional trends through time both in continental and marine volcanic sequences exclude any sampling artefact in the marine environment.

In the Phlegrean Fields, the compositional variations indicate a trachytic to trachybasaltic trend for the past 10 kyr [Armienti *et al.*, 1983] that is consistent with the magma evolution observed from the marine tephra data (Figure 5d). The similar trend from 37 to 20 kyr, as recorded by marine tephra, has not been observed on land, as products erupted during this time span are not exposed because of caldera collapse [Armienti *et al.*, 1983; Barberi *et al.*, 1978; Rosi *et al.*, 1983].

Statistical analysis of the timing of the eruptions in the Campanian area provided eruptive cycles of a nearly 23 kyr periodicity for the past 190 kyr [Paterne *et al.*, 1990]. Variations of the frequency of eruptions of the Phlegrean Fields and on Ischia island have been obtained using a sliding window 8 kyr wide, and have been separated in order to compare geochemical and eruptive fluctuations in each area through time (Figures 5a and 5c). Each eruptive cycle is defined by an increase in the number of eruptions followed by a period of relatively quieter activity. Transitions between active and

quiet periods are marked by low Th and SiO₂ eruptions (A). Each volcanic pulse is then underlined by a period of increasing concentrations, followed by a decreasing one, respectively limited by points B and C. Finally, during each period of quiet activity, concentrations increase until point D and return to A along the decreasing compositional trend DA. Thus, rates of eruption and changes of their composition do not seem to be related since both quiet and active periods show similar geochemical fluctuations. However, during each eruptive cycle, compatible elements such as Sc, Co, Cr have a different behavior along the similarly decreasing Th concentrations in Ischia island, since their concentration increases during the DA path while it remains nearly constant during BC (Tables 2 and 3). Furthermore, the enrichment rates, expressed as the ratio of the concentrations of thorium and of SiO₂ from one eruption to the preceeding event (Table 4), are negatively correlated with the time span between eruptions as they are higher after a smaller time span (step AB) than after a larger one (step CD). Thus, although similar geochemical trends are observed with both quiet and active periods during each eruptive cycle, they cannot be explained by the same geophysical cause as they are marked by a different behavior of the elements.

Repetition of similar fluctuations of the compositional gradients through time within each eruptive cycle in both areas strengthens the reliability of the data obtained on the marine ash layers, since only a very selective sampling could give such a scheme of geochemical changes. Moreover, such fluctuations through time cannot be explained by a simple fractional crystallisation evolution, and mixing processes must be further envisaged.

TRACING MAGMA INFLUX FROM DEPTH

Mixing of an incoming undifferentiated liquid from depth with more evolved residual liquids of a magma chamber will result in a negative compositional gradient in volcanic time sequences. But such gradients have been commonly observed within pyroclastic deposits, their temporal composition varying from highly differentiated to more mafic magmas (negative concentration gradient), which reproduces the zonation within the reservoir (for reviews see: Hildreth [1981], Fischer and Schmincke [1984], and McBirney [1985]). Such compositional variations, ranging typically from 2% to 5% for SiO₂ for a single eruption [Hildreth, 1981; Baker and McBirney, 1985] may occur within Campanian events, but cannot be detected in the marine record according to the standard deviation obtained on the mean composition of the glass shards. In the Campanian time series, negative compositional gradients may only be observed if magma discharge increases leading to the mixing of highly differentiated upper levels with less evolved bottom levels of the zoned magma chamber [Spera *et al.*, 1989; Blake and Fink, 1987; Carrigan and Eichelberger, 1990; Sigurdsson *et al.*, 1990] because of the time spans between eruptions during which fractional crystallisation continuously proceeds.

Erupted volumes have not been directly investigated from field studies, except for the two very large eruptions of the Neapolitan Yellow tuff and the Campanian Ignimbrite which occurred in the Phlegrean Fields, with volumes of 10 km³ and 80 km³, respectively [Barberi *et al.*, 1978; Armienti *et al.*, 1983]. Although large masses of volcanic particles may be

Fig. 2. Comparison of the geochemical composition of marine tephra (crosses) and of the Phlegrean Fields (triangles) and Ischia island (squares) subaerial volcanics. Concentrations are expressed in ppm.

dispersed by the winds over broad areas [Sparks and Walker, 1977], eruption volumes cannot be directly estimated from marine ash layers since the main parts of the deposits are continental. The aerial dispersal of the volcanic particles is controlled by the column height, and the higher the eruption column height, the larger the mass output [Carey and Sigurdsson, 1989]. Thus, considering a similar wind strength for all the eruptions, the larger the erupted mass, the larger the observed one in the same site situated on the dispersal axis of the eruption, at a constant distance from the source area. We have estimated the relative masses of erupted products by weighing the total dried sediment and sieving it at 40 μ in all the cores, except core KET 8019. Then the weight of the coarser volcanic fraction for each eruption has been obtained after decalcification, and expressed in g of the coarser fraction per 1 g of sediment. Such masses have been integrated over the

total thickness of the ash layers, which can range from some millimeters to some tens of centimeters. As the larger weights are generally found in core KET 8004 (Figures 6a and 6b), this site has been considered as the reference situated at a distance of about 150 Km from the source area (Figure 1). However, for some eruptions, larger masses of volcanic material are observed in the most distant core KET 8011 suggesting that this core is nearest to, or is situated on the dispersal axis of the volcanic cloud. In those cases, rough mass calculations have been made in order to compare the detrital fraction which would be observed at the same distance as KET 8004. Considering that the detrital fraction increases linearly from site KET 8003 to site KET 8011, we have used a similar coefficient from site KET 8004 to this dispersal axis. The obtained relative masses M are shown as a function of time on Figures 6a and 6b. They are generally very small, except for the ash layers previously

Fig. 3. Correlation diagram between some compatible and incompatible elements in marine ash layers from the Phlegrean Fields (triangles) and from Ischia Island (diamonds). Concentrations are expressed in ppm. Trachybasaltic lavas from Ischia island dated by the K/Ar method [Poli *et al.*, 1987] are indicated as solid diamonds.

related to the Campanian Ignimbrite and the Neapolitan Yellow Tuff [Paterne *et al.*, 1986], which are considered as the largest eruptions in the Phlegrean Fields [Barberi *et al.*, 1978; Armienti *et al.*, 1983]. Relative mass estimates, obtained on marine tephra from Ischia island, demonstrate that the largest eruptions are related the Green tuff of Mount Epomeo and the Citara formation (Figure 6b), as it has been observed from field investigations [Forcella *et al.*, 1983; Poli *et al.*, 1987, 1989]. In the Ischia area, some other eruptions have apparent masses above the background, occurring at 14.4 kyr, 62.3 kyr and 93.7 kyr, which have not been related to continental deposits.

In both the Phlegrean Fields and Ischia island, the larger volume events preferentially occur during the negative compositional gradient BC (Figures 6a, 6b), either at C* immediately after eruption B and/or at C at the end of this

trend. The relative mass, erupted during the event B is lower than that produced during the following eruption C*, which underlines the decrease of thorium concentrations. Thus, the depleted concentrations observed at C* may be explained by an increase in magma discharge with respect to B, allowing the mixing of upper and lower layers of highly to less differentiated products within continuously crystallising zoned reservoirs. Furthermore, caldera formation, as observed in the Phlegrean Fields consecutively to the huge eruption of the Campanian Ignimbrite at 33.5 kyr (point C in Figure 6b), does not favor the hypothesis of large refilling of the reservoir at this time. A similar mechanism cannot be envisaged for the DA depletion since the erupted masses in A are very small (Figures 6a and 6b), the related trachybasalts being lava flows or pyroclastic deposits of small extent and volume both in the

Fig. 4. Fluctuations of thorium concentrations of the volcanic products from Ischia island versus time, as recorded by land deposits, either directly dated (squares) or stratigraphically estimated (diamonds) [Poli *et al.*, 1987; 1989] and by marine tephra.

Phlegrean Fields and on Ischia island [Barberi *et al.*, 1978; Forcella *et al.*, 1983; Poli *et al.*, 1987, 1989]. Thus, eruption A is explained by the opening of the reservoirs, its geochemical composition resulting from the mixing of residual liquid with an incoming undifferentiated liquid from depth. Inflow of deep magma into the reservoir during the DA path would allow the increase of the highly compatible elements such as Ni, Cr, Co and Sc while the mixing of differentiated layers of a stratified magma chamber along the BC path would have little effect on compatible elements as it can be deduced from the relation of Sc or Cr versus Th (Figure 3). Then geochemical fluctuations may be explained by changes of rates of magma discharge in a stratified magma reservoir while fractional crystallisation proceeds until a new refilling and a new geochemical cycle occur.

The behavior of elements in such a model, in which outflow of the most depleted liquids occurs prior to fractionation, has been theoretically analysed [Albarede, 1985] and very strong enrichments of incompatible elements with moderate depletions of compatible elements are predicted in such open

reservoirs with respect to closed systems, taking into account small sizes of crystallised fraction and of erupted liquids. Considering a liquid of homogeneous composition A and using the equation developed by Albarede [1985], the 2 to 11 enrichment rates of thorium observed along step AB in Ischia tephra (Table 4) would correspond to either erupted volumes (Y) of 1% to 0.1% respectively of the magma chamber with 1% fractionation (X), or to 10% to 1% of fraction Y with 10 % fractionation. Such fractionation rates are more compatible with the abundance of crystals in the pyroclastic deposits, as observed either on Ischia island or in the Phlegrean Fields [Armienti *et al.*, 1983] than the required crystallisation rates for the same enrichments in a closed system, ranging from 50% to more than 80%. Such small crystallisation rates and predicted volumes of erupted products will have little effect on the concentrations of major elements [O'Hara and Matthews, 1977; 1981; Albarede, 1985], as observed in Ischia deposits. Such a decoupling is not observed within the deposits of the Phlegrean Fields (Table 3), likely because of the huge volumes of expelled pyroclastic deposits, such as the Campanian

Fig. 5. Variations of the frequency of eruptions as a function of time, as recorded by marine tephra (a) from Ischia island and (c) from the Phlegrean Fields, using a 8 kyr width sliding window. Fluctuations (b) of thorium concentrations in Ischia island products and (d) of SiO₂ composition in Phlegrean Fields deposits. Points on the X axis refer to marine ash-layers of unanalysed trace element composition. Circled numbers refer the numbers of the eruptive cycles.

TABLE 4. Enrichment/Depletion Rates During the Positive and Negative Compositional Paths for Each Eruptive Cycle in Ischia Island and in the Phlegrean Fields

Paths	Ischia island								Phlegrean Fields			
	Cycle 1		Cycle 2		Cycle 3		Cycle 4		Cycle 1		Cycle 2	
A-B	11.10	(5.4)	5.10	(1.3)	2.70	(3.5)	2.10	(1.5)	1.23	(6.4)	1.09	(2.7)
B-C1	0.80	(5.2)	0.70	(3.9)	0.57	(6.3)	0.70	(1.3)	0.91	(1.4)	0.91	(5.2)
C-D	-		2.60	(10.2)	1.48	(8.7)	1.22	(17.2)	-		1.05	(9.4)
D-A	-		0.11	(1.4)	0.32	(4.9)	-		-		0.82	(4.5)

The duration of each trend is given in kyr in the parentheses.

Fig. 6. Comparison of the relative mass abundance (M) (solid diamonds) on the left axis through time of the ash layers originated (a) from Ischia island and (b) from the Phlegrean Fields with the thorium and SiO₂ concentrations (squares) on the right axis. Event C* is indicated as (open diamonds). (see text for explanation).

Ignimbrite (80 km³), after which a large caldera collapse occurred, or such as the Neapolitan Yellow tuff (10.5 km³) [Barberi *et al.*, 1978; Armienti *et al.*, 1983].

Since major and trace element analyses were performed on pure glass shards, which reflect liquid composition, geochemical behavior of the source of deep magma has been traced through time by the analysis of ratios of incompatible elements which would be constant as crystal fractionation proceeds with liquids of similar origin. On Ischia island, the La, Ta or Zr versus Th ratios are constant from the past until about 26 kyr (Figure 7), suggesting that processes of crystallisation and refilling of magma chamber by a magma inflow of similar origin dominate along this time span. Then, they change during the most recent phase of activity, suggesting the arrival from depth of a geochemically distinct magma in the reservoir. Sr and Nd isotope measurements, performed on continental deposits [Civetta *et al.*, 1991], show similar features. At around 28 kyr, Sr isotope values show a sharp change from 0.7068 to 0.70608, related to arrival of a new geochemically distinct magma. From around 10 kyr to Recent, related to the BC path in the marine tephra record (Figure 5), Sr isotope values decrease to 0.7058 and then progressively increase to 0.70626, that has been interpreted as a new refilling with a distinct magma at 10 kyr and then as a progressive tapping of an isotopically stratified magma chamber [Civetta *et al.*, 1991]. However, the considered refilling of the magma chamber at 10 kyr does not coincide with a decrease of incompatible elements such as Th, Zr and La, as it is the case at 28 kyr [Civetta *et al.*, 1991]. So that, we suggest that one geochemical cycle occurs from 28 kyr to Recent, starting by the refilling of the reservoir with a distinct magma, and then that the augmentation of expelled masses at around 10 kyr with respect to the preceding eruptions, as

observed in marine tephra, would facilitate the mixing and the outflow of isotopically different magmas.

OCCURRENCE OF DEEP MAGMA INFLOW THROUGH TIME

Each inflow occurs simultaneously in both magma chambers of the Phlegrean Fields and Ischia island, taking into account errors in datings (Figure 5) and it coincides uniquely to the beginning of enhanced rate of eruption. This suggests that volcanic pulses are triggered by this energy supply. Then, frequency of eruptions decreases as a function of time until a new refilling occurs, allowing the extent of the life time of volcanic areas.

Frequency of this refilling has been analysed over the best documented time span from the past 110 kyr, using the Blackman-Tukey and Maximum Entropy spectral analyses developed by Petiaux and Berger [1982; 1984], which allow a better estimates of the amplitude and a higher resolution of the frequency peaks respectively. As elemental composition changes with respect to fractional crystallisation processes and to variations of the rates of magma discharge, spectral analyses of the geochemical changes through time have been performed on the Sc/Ta ratio record in order to take into account geochemical fluctuations due to magma influx (Figure 8). Both methods show a peak of frequency corresponding to about 24 kyr, expressed at a 95% confidence level by the Blackman-Tukey method, which is similar to that of the fluctuations of the frequency of the number of eruptions through time [Paterne *et al.*, 1990]. The occurrence of such a periodicity in the marine tephra record of magma inflow though time excludes strongly sedimentary processes in the marine environment as a cause of such geochemical variations, the geochemical composition of the marine tephra being not tied to their stratigraphical position along the cores.

Fig. 7. Logarithmic variations of the Ta/Th, La/Th and Zr/Th as a function of time in kyr. Numbers are referred to eruptive cycle numbering.

Fig. 8. (a) Logarithmic variations of the Sc/Ta ratio as a function of time. Power spectra over 110 kyr of curve a following the methods described by *Petiaux and Berger* [1982, 1984], after linear detrending (b) by the Blackman-Tukey method with a 95% confidence level and (c) by Maximum Entropy.

The periodicity of inflow of magma from depth is very similar to that of the precession of Earth's orbit which leads to variations of the solar radiation budget through time and to changes in ice and water loads during Quaternary glaciations. Thus, although other hypotheses cannot be excluded aside, glacio-eustatic pressure changes, related to the lowering of sea level in the volcanic area, coupled to ice cap loading, as previously suggested [*Matthews*, 1969; *Walcott*, 1972; *Chappell*, 1975; *Rampino et al.*, 1979] may have facilitated magma ascent into the shallow reservoirs.

SUMMARY AND CONCLUSIONS

A detailed time series of the geochemical changes of the Campanian events has been developed by marine tephrochronology. Such a reconstruction is strongly consistent with previous field studies of the temporal geochemical fluctuations [*Poli et al.*, 1987, 1989; *Civetta et*

al., 1991] and is better documented for the most ancient volcanic activity.

Geochemical fluctuations in marine ash layers through time, as well as in the Phlegrean Fields and on Ischia Island, show repetitive changes in compositional gradients, related to eruptive cycles. Each geochemical cycle starts with an injection of hotter magma from a deeper source, the composition of which may vary, which triggers an eruptive period, as defined by increase of the number of eruptions. The frequency of the eruptions then decreases until a new refilling occurs which contributes to extend the life time of a volcanic area. During each eruptive and geochemical cycle, the geochemical trends may be explained by changes in the rate of magma discharge in a compositionally zoned reservoir which is continuously crystallising and periodically refilled.

Refillings of the shallow reservoirs occur with a periodicity of about 24 kyr, similar to that of the frequency of the number of eruptions through time [*Paterne et al.*, 1989]. Because the

geochemical composition of the marine tephra are not tied to their chronostratigraphical position in deep-sea sediments, the occurrence of a periodicity in both records of the geochemical and eruptive fluctuations through time strongly excludes that they are linked to sedimentary processes.

Although several hypotheses may be envisaged, the periodicity of magma influx into shallow reservoirs of about 24 kyr, similar to that of the precession of Earth's orbit, suggests that changes in glacio-eustatic pressure through time may be considered as a mechanism for controlling fluctuations in volcanic activity.

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