

Petrology and isotope-geochemistry of San Vincenzo rhyolites (Tuscany, Italy)

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Abstract. Two groups of rhyolites have been recognized at San Vincenzo (Tuscany, Italy). Group A rhyolites are characterized by plagioclase, quartz, biotite, sanidine and cordierite mineral assemblages. They show constant MgO and variable CaO and Na₂O contents. Initial ⁸⁷Sr/⁸⁶Sr ratios in group A samples range between 0.71950 and 0.72535, whereas the Nd isotopic compositions are relatively constant (0.51215–0.51222). Group B rhyolites are characterized by orthopyroxene and clinopyroxene as additional minerals, and show textural, mineralogical and chemical evidence of interaction with more mafic magmas. The Sr and Nd isotopic ratios range between 0.71283–0.71542 and 0.51224–0.51227 respectively. Magmatic inclusions of variable size (1 mm to 10 cm) were found in groups B rhyolites. These inclusions consist mainly of diopsidic clinopyroxene and minor olivine and biotite. They are latitic in composition and represent blobs of hybrid intermediate magmas entrained in the rhyolitic melts. These magmatic inclusions have relatively high Sr contents (996–1529 ppm) and Sr and Nd isotope-ratios of 0.70807–0.70830 and 0.51245–0.51252 respectively. ⁸⁷Sr/⁸⁶Sr data on minerals separated from both group A and B rhyolites and magmatic inclusions reveal strong isotopic disequilibria due to the presence of both restitic and newly crystallized phases in group A rhyolites and due to interaction of rhyolites with a mantle-derived magma in group B rhyolites. Isotopic data on whole rocks and minerals allow us to interpret the group A rhyolites as representative of different degrees of melting of an isotopically fairly homogeneous pelitic source; conversely, group B rhyolites underwent interactions with a mantle-derived magma. The crustal source as inferred

from isotopic systematics would be characterized by ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios close to 0.7194 and 0.51216 respectively. The sub-crustal magma would have Sr isotopic composition close to 0.7077 and a ¹⁴³Nd/¹⁴⁴Nd ratio greater than or equal to 0.51252. These isotopic features are different from those reported for the parental magmas postulated for Vulsini and Alban Hills in the nearby Roman Magmatic Province, and are similar to those of the Vesuvius and Ischia magmas.

Previous work and geological outlines

The Tuscan Province is mainly composed of granitic to granodioritic intrusions and acid volcanic complexes. The anatectic origin of the magmas of this province has been demonstrated by isotopic (Ferrara 1969; Taylor and Turi 1976; Vollmer 1976, 1977) and trace element studies (Dupuy and Allegre 1972; Giraud et al. 1986) as well as by petrographic evidence (Marinelli 1971; Barberi et al. 1967). The San Vincenzo volcanites have been considered relatively chemically and mineralogically homogeneous (Marinelli 1961; Barberi et al. 1967; Pinarelli and Poli 1985). The large range in ⁸⁷Sr/⁸⁶Sr found by Hawkesworth and Vollmer (1979) was not discussed in detail, perhaps because the variation of Nd, Pb and O isotopes was very small (Taylor and Turi 1976; Vollmer 1976, 1977). Ferrara (1983) pointed out that the marked Sr isotopic disequilibria between glass-sanidine and plagioclase-cordierite-biotite in a San Vincenzo rhyolite was due to disequilibrium crustal anatexis with plagioclase, cordierite and biotite being in part restitic.

Both sedimentary and magmatic inclusions are found sporadically in the volcanic complex

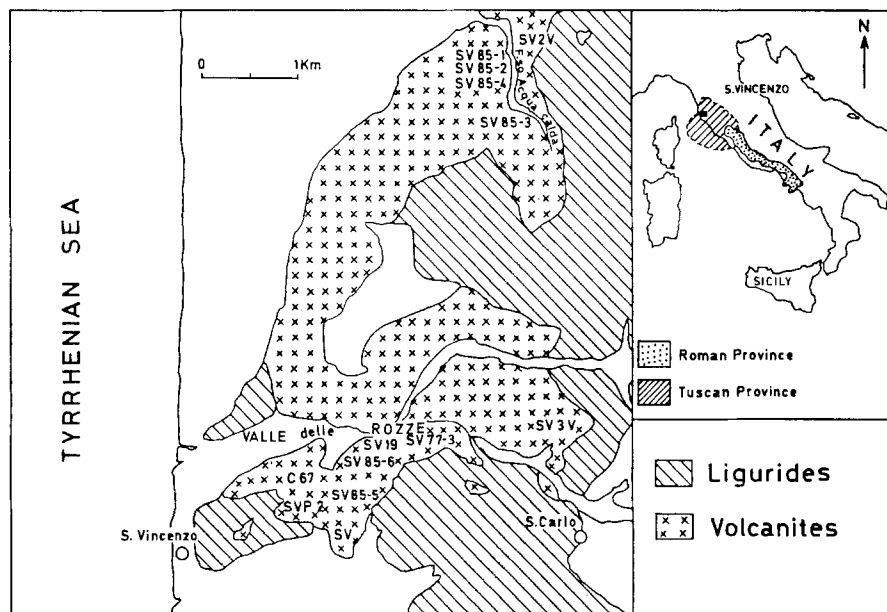


Fig. 1. Geological sketch-map of the San Vincenzo area, including sample locations

(Barberi et al. 1967). Magmatic inclusions are larger and more common in the southern sector of the volcanic complex, where the samples analyzed in this study were taken from (Fig. 1).

Analytical procedures

Major element compositions were determined by X-ray fluorescence (Franzini et al. 1975). Sr isotopic analyses on whole rock samples and separated minerals were performed after chemical matrix separation by standard chromatographic methods. The Sr isotopic analyses have been carried out on both a VARIAN MAT TH5 and a MICROMASS 54E mass-spectrometer. Nd isotopic analyses were carried out on the MICROMASS 54E, after Nd collection following slightly modified chemical procedures with respect to those of Richard et al. (1976). Data acquisition and reduction for Sr and Nd isotopic analyses on the MICROMASS 54E mass-spectrometer are those reported in Ludwig (1982). Repeated analyses of NBS 987 gave an averaged $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.71027 ± 2 ; no instrumental bias correction was applied to the measured Sr isotopic compositions. The mean Nd isotopic value of several runs of the La Jolla standard was 0.51192 ± 2 , so that the measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios presented here are adjusted to a value of 0.51186. All the reported uncertainties on isotopic ratios represent in-run statistics at 95% confidence level. Rb and Sr concentrations were determined by standard isotope-dilution methods.

Mineral separations were carried out by magnetic and gravimetric methods. Most of the collected mineral phases were purified by hand picking. They were washed repeatedly in double distilled water. The purity of mineral separates was also checked by X-ray diffractometry.

Petrography and major element chemistry

Major element analyses of San Vincenzo acid lavas and two magmatic inclusions are reported in Table 1.

All San Vincenzo rhyolites contain cordierite. The excess of Al_2O_3 that results in the appearance of corundum in the norms characterizes these samples as S-type magmas (Chappel and White 1974). The peraluminous character, being present both in whole rocks and in their glassy groundmasses, is an original feature of the magma (Barberi et al. 1967).

The rocks plot in the rhyolite field (Le Bas et al. 1986), and they are best classified as cordierite low-silica rhyolites, hereafter rhyolites, in contrast to the high-silica rhyolites of Mahood and Hildreth (1983).

All the analyzed rhyolites, apart from one devitrified sample (SV2V), have extremely well-preserved glassy groundmasses showing perlitic texture.

The San Vincenzo rhyolites can be divided into two main groups according to their MgO content: group A (samples SV 3V, SV 85-5, SV 85-6, SV 77-3, SV 19 and C67) and group B (SV 2V,

Table 1. Major element analyses of San Vincenzo rhyolites and two magmatic inclusions

	Group A						Group B						Magmatic inclusions		
	SV 77-3	SV 19	SV 85-6	C 67 ^a	SV 3V	SV 85-5	SV ^a	SV P2	SV 2V	SV 85-1	SV 85-2	SV 85-3	SV P4 I	SV P5 I	
SiO ₂	70.29	70.76	70.00	68.77	70.39	70.47	68.00	69.01	72.12	70.23	70.21	68.94	61.70	59.41	
TiO ₂	0.30	0.29	0.31	0.35	0.32	0.37	0.43	0.47	0.35	0.35	0.38	0.42	0.81	0.80	
Al ₂ O ₃	14.91	14.75	15.05	15.23	14.68	14.82	15.89	15.08	14.70	14.72	14.59	15.01	15.57	15.91	
Fe ₂ O _{3t}	2.16	2.09	2.33	2.11	2.39	2.46	2.19	2.88	1.89	2.32	2.45	2.61	6.11	5.53	
MnO	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.01	0.03	0.04	0.04	0.04	0.08	
MgO	0.57	0.55	0.61	0.60	0.56	0.58	0.61	0.93	0.75	0.78	0.82	1.12	3.15	4.55	
CaO	1.43	1.36	1.50	1.68	1.41	1.45	2.01	1.97	1.60	1.67	1.68	2.02	4.25	5.66	
Na ₂ O	3.14	3.16	3.04	3.22	2.69	2.87	2.79	2.86	3.05	2.82	2.87	2.69	2.36	2.39	
K ₂ O	4.29	4.26	4.26	4.49	4.79	4.70	4.22	4.76	4.97	4.61	4.61	4.74	4.25	3.85	
P ₂ O ₅	0.15	0.14	0.15	0.28	0.24	0.22	0.50	0.21	0.16	0.17	0.17	0.20	0.26	0.47	
L.O.I.	2.74	2.61	2.72	3.64	2.50	2.04	2.99	1.80	0.50	2.30	2.19	2.21	1.50	1.54	
	100.00	100.00	100.00	100.39	100.00	100.01	99.66	100.01	100.10	100.00	100.01	100.00	100.00	100.19	

^a Analyses from Barberi et al. 1967

SV P2, SV 85-1, SV 85-2, SV 85-4, SV 85-3). Mineralogically, group A is characterized by plagioclase, quartz, biotite, sanidine, cordierite, apatite, zircon and Fe-Ti oxides, while group B is characterized by opx and cpx as additional xenocrysts.

Some of group B rhyolites are characterized by magmatic inclusions which represent chilled blobs of intermediate magmas. Some of the group A rhyolites contain fragmented and fractured inclusions of pre-existing altered lavas. The two analyzed inclusions from group B rhyolites represent K-rich intermediates magmas that are best classified as latites (Table 1).

Isotopic data

Whole rocks

The Sr-Nd isotopic compositions and Rb and Sr contents of San Vincenzo rhyolites and magmatic inclusions are listed in Table 2. The measured ⁸⁷Sr/⁸⁶Sr ratios have been computed back to 4.7 Ma (see Table 4). The initial ⁸⁷Sr/⁸⁶Sr ratio ranges between 0.71263–0.72478 and 0.70806–0.70828 respectively in rhyolites and latitic inclusions. The ¹⁴³Nd/¹⁴⁴Nd ratios measured on six rhyolites are in the range 0.51215–0.51227. Three magmatic inclusions gave ¹⁴³Nd/¹⁴⁴Nd ratios ranging between 0.51245–0.51252.

The San Vincenzo rhyolites show a relatively small variation in Rb content (294–344 ppm), while the Sr abundances are more variable (103–296 ppm).

The four analyzed magmatic inclusions are characterized by Rb and Sr content between 102–169 ppm and 996–1529 ppm respectively. In Fig. 2 the initial Sr isotope-ratios of San Vincenzo volcanites have been plotted against their MgO and Na₂O content. It is evident from these diagrams that the group A rhyolites show a significant ⁸⁷Sr/⁸⁶Sr variation (0.72478–0.71904) at almost constant MgO (Fig. 2a). Group B rhyolites are displaced towards the magmatic inclusions (Fig. 2a, b): the spread in the ⁸⁷Sr/⁸⁶Sr ratio rules out the possibility that group B samples and inclusions are related by simple crystal fractionation processes. San Vincenzo rhyolites and magmatic inclusions have been plotted in the ⁸⁷Sr/⁸⁶Sr vs 1/Sr diagram (Fig. 3): at a first-order approximation, samples from group A, B and inclusions lie on a straight mixing line. Nevertheless, group A and B magmas evolved in different ways and the interaction between crustal and sub-crustal magmas was

Table 2. Sr-Nd isotopic compositions of San Vincenzo rhyolites and magmatic inclusions

	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_i$	$^{143}\text{Nd}/^{144}\text{Nd}$
Rhyolites						
Group A						
SV 77-3	306	104	8.55	0.72535 ± 2	0.72478	0.51216 ± 4
SV 19	295	103	8.28	0.72510 ± 6	0.72455	0.51217 ± 1
C 67	295	104	8.22	0.72513 ± 9	0.72458	
SV 85-6	294	109	7.81	0.72428 ± 2	0.72376	
SV 3V	344	117	8.54	0.72220 ± 2	0.72143	0.51222 ± 4
SV 85-5	335	137	7.06	0.72053 ± 3	0.72006	
SV	336	140	6.93	0.71950 ± 12	0.71904	0.51215 ± 2
Group B						
SV P2	304	225	3.90	0.71542 ± 4	0.71516	
SV 2V	348	211	4.77	0.71484 ± 2	0.71452	0.51224 ± 2
SV 85-1	314	213	4.26	0.71482 ± 5	0.71452	
SV 85-2	316	215	4.26	0.71482 ± 3	0.71452	
SV 85-4	306	200	4.43	0.71566 ± 3	0.71536	
SV 85-3	299	296	2.93	0.71283 ± 8	0.71263	0.51227 ± 2
Magmatic inclusions						
SV P1	—	1254	—	0.70819 ± 8	0.70817	0.51252 ± 2
SV P2 I	102	1529	0.19	0.70807 ± 5	0.70806	0.51245 ± 5
SV P4	169	996	0.49	0.70828 ± 2	0.70825	
SV P5	139	1206	0.33	0.70830 ± 2	0.70828	0.51247 ± 3

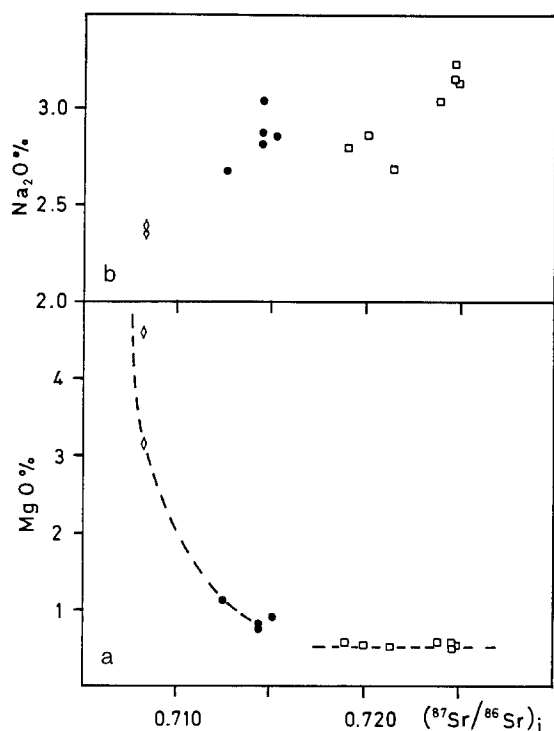


Fig. 2. a $(^{87}\text{Sr}/^{86}\text{Sr})_i$ vs. MgO; b $(^{87}\text{Sr}/^{86}\text{Sr})_i$ vs. Na_2O diagrams. Symbols: *open squares*, group A rhyolites; *filled circles*, group B rhyolites; *diamonds*, magmatic inclusions. Group A rhyolites show variable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and relatively constant MgO contents. Group B rhyolites are shifted towards the magmatic inclusions

important only for group B rhyolites (see further on).

In a $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$ plot (Fig. 4) San Vincenzo rhyolites and inclusions show an hyperbolic correlation in agreement with the mixing hypothesis (Langmuir et al. 1977). Most samples from group A rhyolites have an identical Nd isotopic composition (within the experimental errors) despite the large variation in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Group B rhyolites have a Nd isotope-ratio (average $^{143}\text{Nd}/^{144}\text{Nd} = 0.51226$) higher than group A samples (average $^{143}\text{Nd}/^{144}\text{Nd} = 0.51218$), due to the interaction with the magmatic inclusions (average $^{143}\text{Nd}/^{144}\text{Nd} = 0.51248$). The low variability of the MgO content and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios in group A samples suggest that group A magmas did not interact significantly with sub-crustal magmas.

Minerals

Detailed Sr isotopic analyses have been carried out on minerals separated from group A and B rhyolites and magmatic inclusions (Table 3).

Group A rhyolites. Minerals and glassy groundmasses have been separated from samples SV 77-3

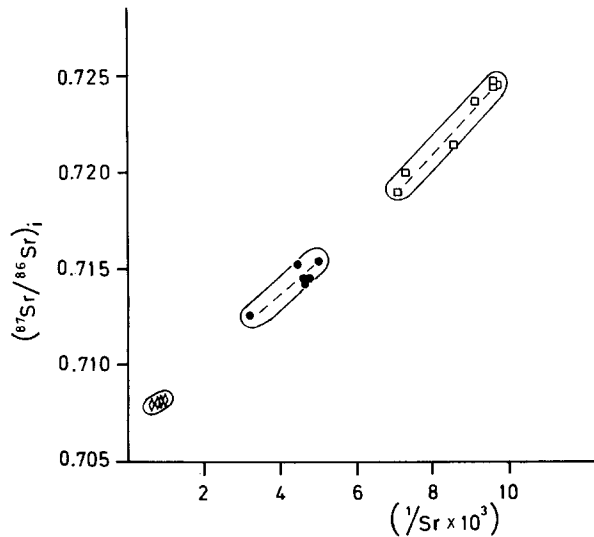


Fig. 3. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ vs $1/\text{Sr}$ correlation diagram. Group A and B rhyolites define linear trends with slightly different slopes. Group B rhyolites lie on a possible mixing line with a magma represented by the magmatic inclusions. Symbols as in the previous figure

and SV 85-6. Glass from SV 77-3 has a higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.7251) if compared with the glass of SV 85-6 (0.7243); this could be due to the different degree of melting of the crustal source. K-feldspar from SV 77-3 is in isotopic equilibrium (0.7252) with the corresponding glass (0.7251). Plagioclases from SV 85-6 (which represents a

light separated fraction) have a lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.7236) than SV 85-6 glass (0.7243); these minerals are predominantly crystallized from the anatectic melt, but some resorbed nuclei of restitic nature are present. Plagioclases which represent heavy separated fractions from SV 77-3, mainly constituted by restitic resorbed nuclei, show much lower Sr isotopic composition (0.7197) than SV 77-3 glass (0.7251). Biotites from both SV 77-3 and SV 85-6 have relatively similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratio values (0.7205 and 0.7199 respectively): although biotites are likely to be a mixture of newly crystallized and restitic minerals the strong isotopic disequilibrium with glasses indicates that restitic biotite is dominant, at least in the analyzed samples. Cordierite from SV 77-3 has among the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.7183) so far measured on minerals from group A rhyolites. Glass and K-feldspar from samples SV 3V and SV 85-5 are nearly in isotopic equilibrium while plagioclases from both SV 3V and SV 85-5 have a lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.7196, 0.7193). As proposed for samples SV 77-3 and SV 85-6, this could be due to a mixture of plagioclases crystallized in the anatectic melt and restites. However, it should be noted that samples SV 3V and SV 85-5 show less pronounced glass-minerals isotopic disequilibria if compared with SV 77-3 and SV 85-6: the isotopic heterogeneities observed in glasses and minerals from group A samples are mainly inherited from the anatectic process itself, and glasses always show higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than restitic minerals.

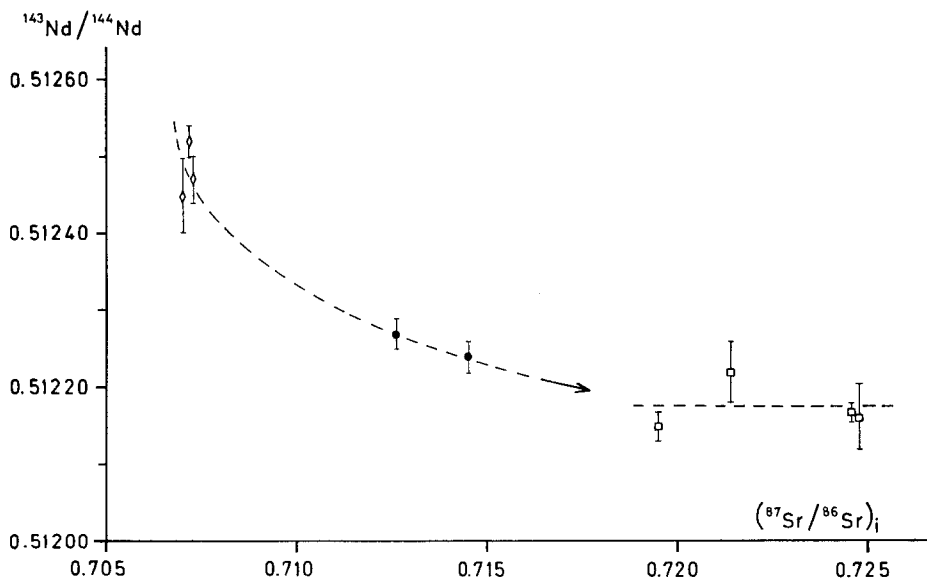


Fig. 4. $^{143}\text{Nd}/^{144}\text{Nd}$ vs $(^{87}\text{Sr}/^{86}\text{Sr})_i$ correlation diagram. Group A rhyolites show relatively constant Nd isotope-ratios and variable Sr isotopic composition. Group B rhyolites are characterized by higher $^{143}\text{Nd}/^{144}\text{Nd}$ ratios, and they lie on a possible mixing trend between magmatic inclusions and a crustal magma as represented by group A rhyolites

Table 3. Sr isotopic compositions and Rb, Sr concentration in minerals separated from San Vincenzo rhyolites and two magmatic inclusions

	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$(^{87}\text{Sr}/^{86}\text{Sr})_i$
Rhyolites					
Group A					
SV 77-3					
Glass	295	55.4	15.4	0.72610 ± 30	0.72507
K-feld (SAN)	153	277	1.6	0.72531 ± 12	0.72520
Pl	4.8	609	0.002	0.71972 ± 9	0.71972
Cord.	51.4	3.5	42.6	0.72115 ± 36	0.71831
Biot.	687	8.1	247	0.73699 ± 12	0.72051
SV 85-6					
Glass	333	70	13.8	0.72522 ± 6	0.72430
Pl	3.2	331	0.03	0.72362 ± 6	0.72362
Biot.	646	9.3	202	0.73341 ± 12	0.71993
SV 3V					
Glass	413	57.6	20.8	0.72245 ± 9	0.72107
K-feld (SAN)	218	296	2.13	0.72089 ± 6	0.72075
Pl	7.9	342	0.07	0.71962 ± 9	0.71962
Biot.	753	5.8	378	0.74570 ± 31	0.72047
SV 85-5					
K-feld (SAN)	319	327	2.82	0.72089 ± 6	0.72070
Pl	33	221	0.43	0.71934 ± 3	0.71932
Biot.	755	6.9	318	0.73930 ± 14	0.71808
Group B					
SV P2					
Glass	420	63	19.2	0.71667 ± 4	0.71654
Pl	51.5	269	0.55	0.71824 ± 2	0.71820
Biot.	660	12.9	148	0.72599 ± 4	0.71611
SV 85-1					
K-feld (SAN)	331	303	3.16	0.71831 ± 3	0.71810
Pl	16.2	201	0.23	0.71752 ± 6	0.71750
Biot.	854	17.8	139	0.72021 ± 17	0.71093
SV 2V					
Groundmass	430	135	9.23	0.71341 ± 6	0.71279
K-feld (SAN)	360	340	3.1	0.71759 ± 9	0.71738
Pl	10.8	196	0.16	0.71742 ± 6	0.71741
Biot.	884	13.8	185	0.72210 ± 7	0.70975
SV 85-3					
Biot.	777	11.3	198	0.72617 ± 2	0.71295
Magmatic inclusions					
SV P4					
Pl	5.6	426	0.098	0.71490 ± 2	0.71490
Cpx	1.68	177	0.027	0.70776 ± 5	0.70776
Biot.	643	39.5	47.04	0.71303 ± 3	0.70989
SV P5					
Groundmass	168	1774	0.27	0.70799 ± 3	0.70797
Pl	30.8	514	0.17	0.71426 ± 5	0.71425
Cpx	2.5	192	0.037	0.70772 ± 2	0.70772
Biot.	573	46.4	35.73	0.71212 ± 2	0.70974

Group B rhyolites. Minerals and glasses separated from group B rhyolites show a more complex variation of Sr isotopic composition with respect to group A samples.

In sample SV 2V K-feldspar and plagioclase are in isotopic equilibrium (0.7174–0.7174), while in SV 85-1 plagioclase has a slightly lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio than K-feldspar (0.7175–0.7181). Fur-

thermore, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of K-feldspar and plagioclase of group B samples are lower than the corresponding ones of group A. In SV 2P and SV 2V, glass and devitrified groundmass have a lower Sr isotopic composition (0.7165–0.7128) than the plagioclase or the K-feldspar-plagioclase pair (0.7182 vs 0.7165 and 0.7174 vs 0.7128). This suggests that the contamination with melts characterized by a lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio continued after most of the K-feldspar and plagioclase crystallized.

Biotites of group B rhyolites show a wide variation of Sr isotopic composition, from 0.7098 (biotite from SV 2V) to 0.7161 (biotite from SV P2). In sample SV P2 and especially in SV 2V, biotite has a lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratio than glass: as will be shown further on, the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of biotites belonging to group B rhyolites are similar to those measured on biotites from magmatic inclusions. In terms of $^{87}\text{Sr}/^{86}\text{Sr}$ isotopes, a possible interpretation is that some of the biotites found in group B rocks were already crystallized in the magmas represented by the inclusions.

Minerals and glasses from group B rocks testify to an important interaction between the anatectic melt and sub-crustal magmas.

Magmatic inclusions. Minerals and groundmass were separated from two magmatic inclusions (SV P4 and SV P5). Clinopyroxene from both SV P4 and SV P5 has the same $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.70772–0.70776), lower than groundmass from SV P5 (0.70797); probably clinopyroxene crystallization ended before the interaction with the more acid magmas, which on the contrary affected the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the SV P5 groundmass.

Plagioclase megacrysts from SV P4 and SV P5 have a Sr content (426–514 ppm) and isotopic composition (0.7149–0.7143) which rule out the possibility that most of them crystallized in the pristine sub-crustal magma, but probably they have been inherited partly from a more acid magma.

Biotites from SV P4 and SV P5 have an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7099 and 0.7097; hence they are not in isotopic equilibrium with either the clinopyroxene, or the groundmass.

As for the plagioclases, the variation of $^{87}\text{Sr}/^{86}\text{Sr}$ reflects the interaction between sub-crustal magmas and anatectic melts.

The above data on minerals and groundmass from magmatic inclusions indicate that they are evidently hybrid magmas due to the interaction between sub-crustal magmas with crustal-derived melts.

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of clinopyroxene probably represents at best the Sr isotopic composition of the original sub-crustal magma.

Geochronological and geochemical implications

The isotopic disequilibria among minerals of San Vincenzo rhyolites lead to important consequences for dating anatectic rocks.

Meaningless Rb/Sr ages have been obtained dating biotites occurring in San Vincenzo rhyolites (Table 4), because of the presence of non-cognetic biotites found in the rock.

The observed isotopic disequilibria among minerals in the San Vincenzo rhyolites place restrictions also on the meaning of the partition coefficients for trace elements, determined on anatectic volcanic rocks on which solid/liquid equilibrium relationships are not fully investigated.

Source of magmas

The isotopic data on whole rocks, minerals and glasses of San Vincenzo rhyolites and magmatic inclusions allow to constrain the isotopic features of the crustal and sub-crustal sources.

Crustal sources

Mineralogical and chemical data indicate that the crustal source was probably pelitic. The San Vincenzo rhyolites (group A) are among the few volcanic rocks which show all the mineralogical (cor-

Table 4. Rb/Sr, K/Ar and fission tracks ages on San Vincenzo samples

	Rb/Sr (WR-Biot. ages)	K/Ar (Biot. ages)	Fission track (glass)
SV 77-3	3.44 ± 0.11		
SV 85-6	3.31 ± 0.11		
SV 3 V	4.48 ± 0.15		
SV 85-5	4.25 ± 0.13		
SV P 2	5.17 ± 0.16		
SV 2 V	2.84 ± 0.09	4.64 ± 0.1 ^a	
SV 85-1	2.82 ± 0.12	4.78 ± 0.1 ^a	
SV 85-3	4.82 ± 0.15		
SV P 4	7.19 ± 0.22		
SV P 5	7.60 ± 0.23		
SV Rhy		4.70 ± 0.14 ^b	4.96 ± 0.37 ^c

^a Istituto di Geocronologia, unpublished data; ^b Borsi et al. (1967); ^c Arias et al. 1981)

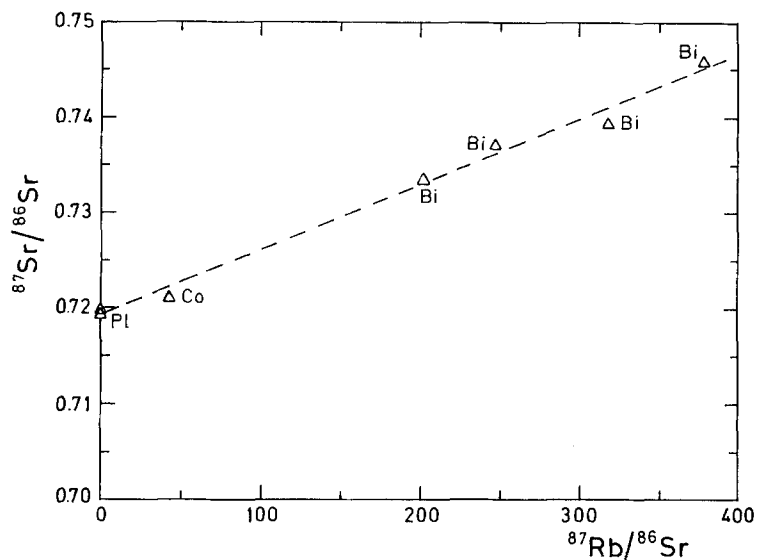


Fig. 5. $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{87}\text{Rb}/^{86}\text{Sr}$ diagram. Plagioclases (*Pl*), cordierite (*Co*) and biotites (*Bi*) from group A samples define a linear correlation ($r=0.9967$) with an intercept value of 0.71937 ± 0.00022 and a slope with a corresponding "age" of 4.8 ± 0.4 Ma (see text)

dierite + sillimanite \pm garnet), chemical (low Ca and Sr contents) and isotopic (high Sr and low Nd isotopic ratio; $\delta^{18}\text{O}$ values which range between 14.00 to 14.33; Taylor and Turi 1976) criteria for a pelitic source (Miller and Calvin 1985). The $^{87}\text{Sr}/^{86}\text{Sr}$ feature of the crustal source of the San Vincenzo rhyolites can be inferred by the Sr isotopic composition of their prevalently restitic minerals: plagioclases, biotites and a cordierite show a linear correlation in a $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{87}\text{Rb}/^{86}\text{Sr}$ diagram (Fig. 5); the slope of the linear regression would correspond to an age of 4.8 ± 0.4 Ma,

in agreement with those previously obtained (see Table 4). The calculated intercept is 0.71937 ± 0.00022 ; this implies that 4.8 Ma ago these minerals were characterized by very similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, regardless of their variability in Rb and Sr contents. This is interpreted as due to radiogenic ^{87}Sr loss and isotopic homogenization during anatexis, hence the value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.71937$ would be close to that representative of the crustal source of the San Vincenzo group A magmas. Group A glasses and K-feldspars show variable but always higher initial Sr

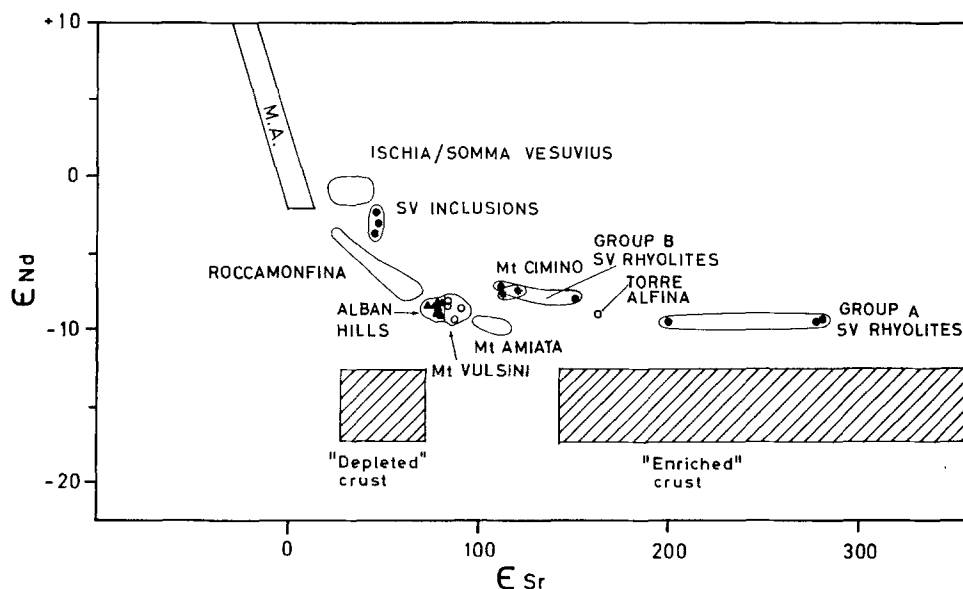


Fig. 6. Generalized ϵ_{Sr} vs ϵ_{Nd} correlation diagram. The "mantle array" distribution (M.A.) and averaged compositions for the continental crust are reported (from De Paolo and Wasserburg 1979). Sources of data: Mt Amiata (Hawkesworth and Vollmer 1979); Alban Hills (filled triangles), Mt Cimino (asterisks), Mt Vulsini (open circles) and Torre Alfina (Ferrara et al. 1985). Bulk Earth Sr and Nd isotopic compositions used for calculations are 0.7048 and 0.51264 respectively

isotopic compositions than that inferred for the crustal source (Table 3), due to the preferential radiogenic Sr migration into the liquids during incipient disequilibrium melting. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio seems to be not significantly affected by different degrees of melting of the pelitic source: hence its pristine Nd isotopic composition may be directly inferred from those of group A samples, for which the interaction with the sub-crustal magma was negligible. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the crustal source of San Vincenzo anatectic melts would be in the range 0.51215–0.51217. These values are significantly higher than the average upper crust ($^{143}\text{Nd}/^{144}\text{Nd}=0.51117$; Fig. 6), a common feature of the crustal end members of Alpine-Appennine-Maghrebian granites and of the French Phanerozoic shales (Juteau et al. 1986).

Sub-crustal sources

The Sr-Nd isotopic composition of the sub-crustal magma cannot be unequivocally stated, since the analyzed magmatic inclusions represent magmas which to variable extents underwent interactions with the anatectic melts. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the mantle-derived magma is probably similar to that measured on clinopyroxenes (0.7078–0.7077), while the Nd isotopic composition might be equal or higher than 0.51252 (sample SV P1). Therefore the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the mantle-derived magma is significantly higher if compared with the ratios reported for sub-crustal magmas of high-K series of Vulsini and Albani (Fig. 8).

Conclusions

Magmatic inclusions of latitic composition, hybrids between sub-crustal and crustal magmas, have been found in San Vincenzo acid volcanites. Some of the San Vincenzo rhyolites represent essentially the product of different degrees of melting of an isotopically relatively homogeneous, pelitic crustal source (group A samples). Other rhyolites (group B samples) show mineralogical, chemical and isotopic evidence of different degrees of interaction between group A-type magmas and a sub-crustal magma.

The crustal source involved in melting has Sr and Nd isotope-ratios of about 0.7194 and 0.51216 respectively. The $^{143}\text{Nd}/^{144}\text{Nd}$ values are significantly higher than the estimated average value of the upper crust (0.51117).

The hypothetical mantle-derived magmas have

an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio around 0.7077 and Nd isotopic composition greater than 0.51252.

Magmas with these isotopic characteristics and a high Sr content are not found in the nearby K-alkaline-parental magmas of Vulsini and Albani hills, in the Roman Magmatic Province. Similar isotopic values have been found for Vesuvius-Ischia volcanites.

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