Roman comagmatic province (central Italy): Evidence for subduction-related magma genesis

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ABSTRACT

Geochemical data on mafic volcanics show that important affinities exist between the Roman and the calc-alkaline rocks from the Aeolian arc (south Tyrrhenian Sea). These affinities, together with the close association of calc-alkaline and K-rich volcanics in the Aeolian arc and in the Naples area, the continuity in the variation of abundances of incompatible elements from calc-alkaline to potassic suites, and the similarity in terms of major-element geochemistry, support a genetic relationship of the Roman magmatism and the subduction processes that affected the Apennines in Tertiary time and are *still* active under the Aeolian arc.

In the genetic model presented here, both calc-alkaline and K-rich magmas were generated within a mantle heterogeneously enriched in LIL elements. Composition of the mantle was modified by addition of material, probably sediments, dragged down by the undergoing slab.

The geochemical and petrological differences displayed by the calc-alkaline and K-rich volcanics are accounted for by the different conditions of melting as well as by chemical and isotopic heterogeneities of the source.

INTRODUCTION

The genesis and geodynamic significance of the potassium-rich volcanism of central-southern Italy (the Roman comagmatic province) have been debated vigorously. Hypotheses of genesis of the volcanism range from crustal melting to anomalous mantle melting to interaction of mantle-derived melts with crustal material (see Appleton, 1972). Discussion about geodynamic significance has been focused essentially on whether this volcanism is genetically related to subduction processes (e.g., Di Girolamo, 1978) or simply to intracontinental rifting as in East Africa and the Eifel region (e.g., Cundari, 1979).

Most of the debate on geodynamic significance has been based essentially on geologic, geophysical, and petrological data, but trace-element geochemistry has been more rarely employed to support any of the hypotheses (Peccerillo et al., 1984).

Recently, extensive major- and trace-element investigations by me and my coworkers on some of the most important potassic volcanic centers of central-southern Italy have furnished new data that allow us to put constraints on magma genesis and that provide evidence indicating that important geochemical affinities exist between Roman magmatism and the Aeolian arc volcanism of the south Tyrrhenian Sea. The results of these investigations and their bearing on genetic problems will be published in fuller detail later. In this paper, I report preliminary data on some representative basic samples from different eruptive centers, and I reappraise the data available from the literature in order to discuss the possible relations between the Roman magmatism and the island-arc volcanism of the Aeolian islands. The implications of these data in regard to petrogenetic problems are also discussed briefly.

MAGMATIC OUTLINES

The Roman province consists of a series of recent (<1 m.y. old) to active volcanic centers located along the Tyrrhenian border of the Apennines from the Naples area to south Tuscany (Fig. 1). On the basis of petrological and geochemical evidence, two series of rocks have been distinguished: a potassic series (KS) and a high-potassic series (HKS) (Appleton, 1972; Civetta et al., 1981). KS is represented by saturated or slightly undersaturated rocks such as trachybasalts, latites, and trachytes, which have a lower abundance of incompatible elements and radiogenic Sr than do HKS volcanics, which consist of strongly silica-undersaturated leucitites, leucite tephrites, leucite phonolites, etc. HKS rocks crop out extensively at Vesuvius, the Alban Hills, Sabatini, Vico, and Vulture. KS rocks occur at Ischia, the Phlegrean Fields, and the Pontine Islands. At Monti Ernici, Roccamonfina, and Monti Vulsini, both KS and HKS rocks crop out extensively. In the latter three areas the KS volcanics appear younger than most, if not all, of the HKS rocks.

The northern part of the Roman province overlaps the Tuscan magmatic province (7 to <1 m.y. old). This is generally referred to as a crustal anatectic province. However, recent investigation has revealed that silicic rocks of crustal anatectic origin occur with mafic rocks (e.g., trachybasalts from Radicofani and minettes from Montecatini Val di Cecina and Orciatico) having high contents of ferromagnesian elements consistent with a mantle rather than crustal provenance, and with suites of volcanics from Monte Amiata and Monti Cimini that have geochemical and Sr isotopic characteristics indicating a genesis by combined processes of crystal fractionation and assimilation of crustal material, starting from HKS mafic magmas (Poli et al., 1984; Peccerillo, unpub. data).

A few alkaline leucite-bearing rocks also occur in the Aeolian arc, closely associated with the calc-alkaline and shoshonitic volcanics (Barberi et al., 1974). These are associated with deep earthquakes defining a rough Benioff plane dipping 50°–60° north-northwest (Gasparini et al., 1982). Evidence of close association between calc-alkaline and potassic alkaline volcanics has been found also in the Naples area, where calc-alkaline andesites underlying K-rich products have been found by deep drilling (Di Girolamo et al., 1976).

GEOCHEMICAL DATA

Table 1 lists analyses of representative mafic rocks of the KS and HKS from different centers, of a leucite tephrite and a calc-alkaline basalt

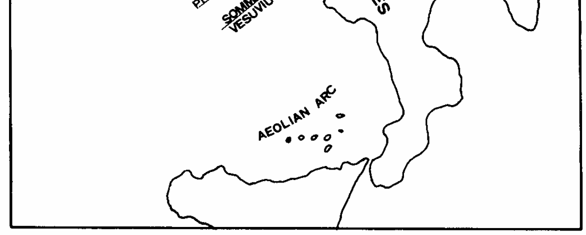

Figure 1. Schematic distribution of recent Italian volcanics; ruled area = Roman comagmatic province; black areas = Tuscan province.

TABLE 1. SELECTED MAJOR AND TRACE ELEMENT DATA ON REPRESENTATIVE BASIC VOLCANICS FROM CENTRAL-SOUTHERN ITALY

	Aeolian arc		Vesuvius	Monti Ernici		Roccamonfina	Alban Hills	Vico	Vulsini	Radicofani	Cimini
	F-12	IV-14	1944 lava	S-9	Ern-11	R-6	Alb-20	E-2	VS-6	R-4	77-16
Major elements (%)											
SiO_2	49.7	53.4	48.6	48.5	46.5	46.7	47.3	50.8	46.9	52.9	57.4
TiO_2	1.05	0.67	0.60	0.72	0.82	1.22	0.99	0.80	0.66	1.28	0.85
MgO	7.4	4.5	3.2	9.0	6.0	8.5	6.5	4.6	9.3	9.1	6.3
K_2O	1.2	5.0	7.5	2.6	6.9	1.1	7.0	8.2	5.1	4.2	5.0
P_2O_5	0.25	0.45	0.50	0.27	0.45	0.37	0.53	0.50	0.37	0.47	0.31
$Mg\text{-}v^+$	63.4	56.9	44.4	73.4	68.8	66.0	59.3	56.8	73.6	73.1	73.4
Trace elements (ppm)											
Ni	62	19	-	87	63	74	52	68	-	171	108
Cr	118	46	-	490	146	-	192	78	514	585	302
Cs	0.2	-	-	-	-	-	36	66	-	14	27
Rb	20	151	300	112	421	207	365	(550)	362	264	336
Sr	(605)	1184	1000	848	1666	983	1550	1000	895	346	688
Th	2.1	25	(21.9)	9.7	30	8	36	47.5	29	36	50
Ta	0.2	1.3	-	0.56	0.69	0.29	0.55	0.91	0.5	1.1	1.6
Nb	-	-	10	8	12	-	(5)	-	-	-	-
Hf	1.2	4.1	-	2.7	5.9	2.7	8	9.2	4.8	8.9	9.7
Zr	75	140	270	86	227	122	-	-	191	269	366
La	16.7	59	-	33	93	43	104	103	54	53	94
Ce	34	108	(93.3)	68	173	78	239	266	119	146	196
Sm	3.5	8.8	(7.43)	6.4	15.7	9.4	20	17.2	9.7	10.9	11
Tb	0.57	0.8	-	0.7	1.4	0.9	1.8	1.48	1.0	0.8	1.0
Yb	1.33	1.82	(1.57)	1.9	2.7	2.1	2.7	2.28	1.7	1.76	2.3

Note: Sources of data: F-12 calc-alkaline basalt—Hoppemberg and Kiesl, 1975; Vesuvius 1944 lava—Savelli, 1967; Hawkesworth and Vollmer, 1979; S-9 trachybasalt and Ern-11 leucite tephrite—Civetta et al., 1981; Alb-20 leucite tephrite—Peccerillo et al., 1984; R-4 trachybasalt and 77-16 olivine latite—Poli et al., 1984; R-6 basalt and IV-14, E-2, VS-6 leucite tephrites—Peccerillo, unpub. data.

$^+$Mg-v = $Mg/(Mg+Fe^{2+})$ atomic ratio, assuming $Fe_2O_3/FeO = 0.15$. Data in parentheses are from different samples from the same flow.

from the Aeolian arc and a trachybasalt and an olivine-latite from Radicofani and Monti Cimini.

One way to achieve comparison of mafic rocks is to normalize their incompatible-element abundance on the basis of a reference composition. Figure 2 illustrates the patterns of incompatible elements, normalized in reference to a hypothetical primordial mantle composition (Wood, 1979), of the samples reported in Table 1, of a madupite from East Africa (Mitchell and Bell, 1976), and of a porphyritic gabbro from the Pietre Nere outcrop. The East Africa madupite has been chosen as a representative of typical intraplate potassic alkaline mafic rocks. The Pietre Nere gabbro is reported because this small alkaline body, intruded into the Mesozoic carbonate platform of the Apulian foreland, has been thought by some workers to be genetically related to Roman magmatism (e.g., Hawkesworth and Vollmer, 1979), despite its age (ca. 55 Ma) and tectonic position.

Figure 3 is a Th/Yb vs. Ta/Yb diagram (Pearce, 1982) where the compositional fields of volcanics from different tectonic settings are also shown. In this diagram all the available data on mafic rocks from the Aeolian arc and the Roman and Tuscan areas are plotted. The mafic terms of potassic alkaline volcanics from the Birunga–Toro Ankole region (East Africa) are also reported for comparison.

DISCUSSION

The geochemical data indicate the following:

1. The most primitive Roman rocks have high Mg value and Ni and Cr contents typical of magmas formed by mantle melting (Frey et al., 1978) that have undergone a rather small degree of fractionation during their rise to the surface. The aphyric or poorly porphyritic texture of some samples (e.g., Ern-11 and VS-6) excludes the possibility that such values are produced by mafic mineral accumulation. This not only supports a mantle provenance for the parental magmas of the potassic suites but also limits the role of the continental crust in determining the geochemical characteristics of these liquids.

2. The KS rocks have lower incompatible-element contents than the HKS rocks but display a similar distribution pattern of incompatible elements with a high ratio of large ion lithophile (LIL) elements vs. high field strength (HFS) elements and strong negative anomalies of Ta, Nb, and Ti. A similar pattern occurs in the leucite tephrite from the Aeolian arc and in the rocks from Radicofani and Cimini. High LIL/HFS ratios and negative anomalies of Ta, Nb, and Ti are typical of all island-arc rocks (e.g., Perfit et al., 1980).

3. The madupite from East Africa displays a bell-shaped incompatible-element pattern, typical of alkaline rocks (Wood, 1979), Ta and Nb spikes, and no Ti anomaly. A similar pattern occurs in the Pietre Nere gabbro, and this is considered as additional evidence, which agrees with geochronological and geologic data, against any genetic relation with Roman magmatism.

4. The KS rocks have Th/Yb, and Ta/Yb values within or close to the field of arc basalts. The HKS values fall in the field of shoshonitic rocks in continuity with KS and Aeolian arc rocks. A continuity can be observed even on other diagrams based on discriminant elements such as Hf-Th-Ta and Ce/Yb vs. Ta/Yb. The leucite tephrite from the Aeolian arc plots in the same field of the HKS rocks. The East African rocks plot within the field of intraplate volcanics, far away from the Roman rocks.

The summarized evidence indicates that the Roman rocks have significant geochemical island-arc signatures and quite similar patterns of incompatible-element distribution—e.g., the leucite tephrite from the Aeolian arc, where leucite-bearing volcanics are unambiguously associated with an active subduction process. This evidence, together with the

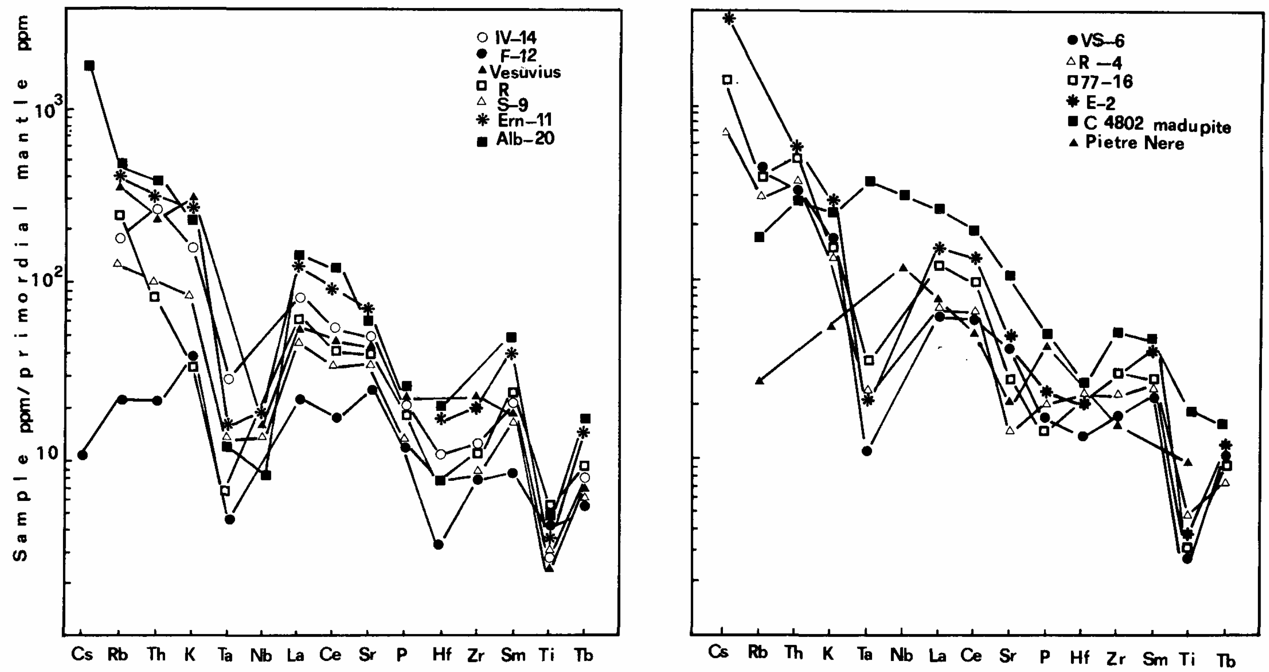

Figure 2. Patterns of incompatible elements normalized to estimated primordial mantle composition (Wood, 1979) for samples reported in Table 1 and for a Pietre Nere gabbro and madupite from East Africa.

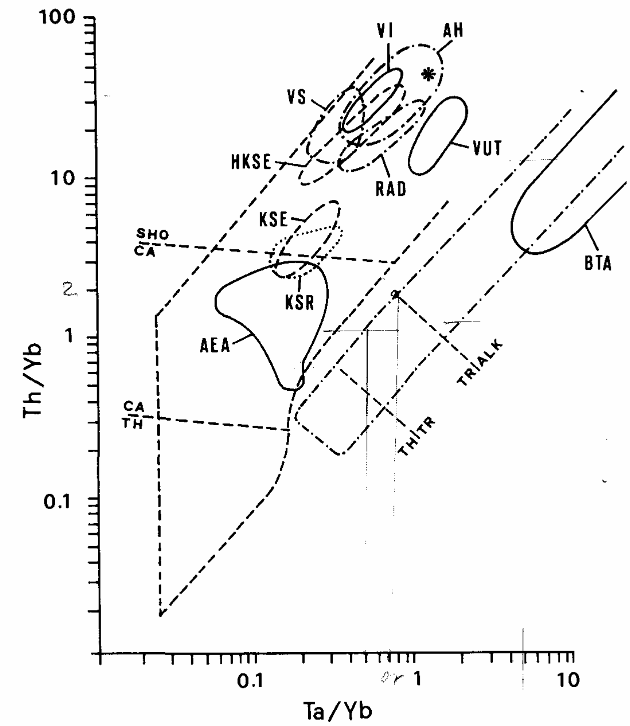

Figure 3. Th/Yb vs. Ta/Yb discriminant diagram (Pearce, 1982). BTA = Birunga, Toro-Ankole regions; RAD = Radicofani; VS = Vulsini HK-series; VI = Vico; AH = Alban Hills; VUT = Vulture; KSR = Roccamonfina K-series; KSE = Ernici K-series; HKSE = Ernici HK-series; star = Vulcanello leucite tephrite. Dashed line = field of island-arc tholeiites (TH), calc-alkaline (CA), and shoshonitic (SHO) basalts. Dot-dash line = field of intraplate tholeiitic (TH), transitional (TR), and alkaline (ALK) basalts. AEA = Aeolian arc.

association of leucite-bearing rocks and calc-alkaline volcanics even in the Naples area and the affinities in terms of major-element chemistry between arc volcanics and the Roman rocks (Di Girolamo, 1978), suggests that it is unlikely that the Roman comagmatic province is a typical example of association between K-rich volcanics and a continental rifting area, such as East Africa. Instead, the hypothesis of a subduction-related magma genesis for Roman magmatism is strongly supported.

If this conclusion is accepted, it is obvious that any petrogenetic model for Roman magmatism should be framed within the general context of all the recent Italian volcanism occurring in the eastern Tyrrhenian Sea from South Tuscany to the Aeolian islands.

PETROGENETIC CONSTRAINTS

It has been demonstrated that if one accepts a mantle provenance for potassic alkaline rocks, a variable but generally high enrichment of incompatible elements of the source must be invoked in order to explain the extreme concentration of incompatible elements in these rocks. Elemental enrichment in the mantle is believed to be produced by metasomatic processes generated by hydrous fluids coming from the deep mantle (Bailey, 1980). In the zones of plate convergence, within the mantle wedge overlying the Benioff planes, chemical changes in the peridotite can be caused by fluids coming from dehydration of the slab and/or by addition of acidic liquids generated by slab melting, and/or by addition of crustal components such as sedimentary material dragged down during subduction. It seems plausible that as a response to the difference in the enrichment mechanism, the chemical anomalies that develop within the mantle wedge overlying the Benioff zones are different from those formed in the metasomatized sections underlying cratonic areas. Consequently, the magmas formed in the two tectonic environments will have some distinct geochemical characteristics that reflect differences of the sources. Hole et al. (1984) suggested that the negative anomalies of Ti, Ta, and Nb and the high ratio of LIL/HFS elements of arc rocks are the result of addition to the upper mantle of pelagic sediments that are deficient in Ta, Nb, and Ti and rich in LIL elements.

For the Roman region, it has been suggested that the Apennine area has been affected during the Tertiary by subduction processes (Boccaletti and Guazzone, 1974; Civetta et al., 1978) that, with the rotation of Corsica-Sardinia and of the Apennine chain, progressively shifted eastward and are still active in the south Tyrrhenian Sea (Gasparini et al., 1982). The immersion of the lithospheric slab into the mantle could have caused, via fluid, sediment, or acidic melt addition, a selective enrichment of the mantle overlying the Benioff plane, which became "fertile" and ready for generation of calc-alkaline to potassic magmatism. If so, the geochemical affinities displayed by the Roman and Aeolian and some Tuscan mafic rocks could be explained by the common history of chemical changes experienced by the whole sub-Apennine upper mantle.

However, if we accept the conclusion that the Aeolian and Roman volcanics are genetically related and that both have been generated in a subduction-modified upper mantle, the next step would be to work out a genetic model that also explains the geochemical and petrological differences between Aeolian and Roman rocks. These include (1) the distinct degree of silica saturation from the oversaturated calc-alkaline basalts to the strongly undersaturated HKS rocks, (2) the variation of the degree of enrichment in incompatible elements and radiogenic Sr from calc-alkaline to KS and HKS volcanics, (3) the increase of Sr isotopic ratio from the Aeolian arc ($^{87}Sr/^{86}Sr$ = 0.704–0.707; Barberi et al., 1974) to the Roman province ($^{87}Sr/^{86}Sr$ = ca. 0.706–0.711; Hawkesworth and Vollmer, 1979) and within the Roman province itself, going from Vesuvius and Vulture (0.7059–0.7076) to the Vulsinian district (ca. 0.710–0.711; Holm and Munksgaard, 1982), (4) the variation of $\delta^{18}O$ and Nd-isotope composition from Vesuvius and Vulture to Monti Vulsini (Turi and Taylor, 1976; Hawkesworth and Vollmer, 1979).

It is beyond the scope of this paper to discuss in detail such a large spectrum of problems. However, at least some comments are needed. The large variation of petrological characteristics from the calc-alkaline to the HKS volcanics can be accounted for by the variable conditions of melt formation, in terms of degree of partial melting, depth of magma genesis, activity of the volatile phase, and composition of the volatile phase present. Wendlandt and Eggler (1980) suggested that small degrees of partial melting over a wide pressure range of H_2O-poor or K_2O-rich or CO_2-rich peridotite can generate potassic liquids whose degree of silica undersaturation increases with increasing depth of melting. Instead, in H_2O-rich conditions potassic liquids are not formed. In fact, for water-saturated conditions, phlogopite, which is a subsolidus phase, has a melting curve about 200° higher than the solidus curve of peridotite. The liquids formed in the temperature interval between the peridotite solidus and the phlogopite melting curve are quartz-normative, approximately calc-alkaline in composition up to pressure of at least 20 kbar (Mysen and Boettcher, 1975), and relatively poor in potassium, which is retained in the phlogopite.

The different enrichment of incompatible elements from calc-alkaline, KS, and HKS magmas can be ascribed to differences in degree of melting and possibly to heterogeneities of the enrichment of the source.

The isotopic variations from the Aeolian arc to Vesuvius and Vulture and up to Monti Vulsini can be ascribed to several processes. One possibility is that the northward increase of Sr-isotope composition and $\delta^{18}O$ and the decrease of Nd-isotope ratio are the result of increasing crustal contamination affecting the magmas during their rise through a continental crust progressively thickening northward. However, this possibility seems unlikely. In fact, the large increase in Sr-isotope ratio—e.g., from Vesuvius and Vulture to the Vulsinian district—would require for the latter a much more significant interaction with crustal material. If so, one would expect consistent variations of other chemical parameters, such as a decrease of ferromagnesian-element content and the degree of silica undersaturation. Such features are not observed in the Roman province. The most primitive of the Vulsinian HKS rocks have comparable or higher ferromagnesian-element abundance and degree of silica undersaturation relative to the primitive rocks of other Roman centers (Table 1).

Thus, I believe that it is more likely that the isotopic variations of the recent Italian volcanics reflect heterogeneities of the mantle. These can be generated, within the frame of the proposed model, by several mechanisms: (1) addition to the mantle of varying quantities of sedimentary material along different sectors of the subduction zone, possibly as a result of the different stress regimes acting along distinct sectors of the arc (see Uyeda, 1983); (2) differences in the isotopic signature of the sedimentary material being added to the mantle; and (3) differences in the type of crust being subducted along different sectors of the Apennine subduction zone.

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