

Comparisons of $^{18}\text{O}/^{16}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ in volcanic rocks from the Pontine Islands, M. Ernici, and Campania with other areas in Italy*

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Abstract—New $^{18}\text{O}/^{16}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ data dramatically confirm and extend the systematic regional isotopic and geographic correlations observed in Quaternary volcanic rocks from Italy: (1) The High-K Series (HKS) and Low-K Series (LKS) potassic magma source regions are isotopically distinct; the relatively rare, *primitive* (high-Ca) parent magmas of both suites have $\delta^{18}\text{O} = +5.5$ to $+7.5$, but the LKS parent has a much lower $^{87}\text{Sr}/^{86}\text{Sr}$ and slightly lower $\delta^{18}\text{O}$ than the HKS parent. (2) The more abundant *evolved* (fractionated) magmas of both suites have a wide range of $\delta^{18}\text{O}$ ($+6.0$ to $+13.0$), but in the offshore island centers (Ischia, Pontine Is., Procida) these magmas are all much lower in $\delta^{18}\text{O}$ ($< +8.0$) than those from the Italian mainland, as a result of the absence of involvement of high- ^{18}O continental crust. (3) At a given center, the ^{18}O -enrichments correlate with major-element changes (*i.e.*, CaO depletion and K_2O and SiO_2 enrichment) attributable to fractional crystallization in *crustal* magma chambers (4 to 13 km depth?); because such ^{18}O enrichments cannot be produced in a closed system, these correlations imply that AFC processes were important, particularly north of Rome where they are enhanced by an increase in the temperature of the crust (due to igneous activity associated with the 0–7 Ma Tuscan anatectic event). Thus, the high $\delta^{18}\text{O}$ values of the potassic magmas of Italy should not be used as evidence in support of genetic models invoking recent subduction of sedimentary rocks into the source regions of these magmas. (4) On $\delta^{18}\text{O}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ diagrams, the LKS and HKS magmas at each volcanic center display separate, steep positive trends indicating mixing with high- ^{18}O continental crustal material; this type of mixing had little effect on $^{87}\text{Sr}/^{86}\text{Sr}$ in these Sr-rich magmas, but it had a dramatic effect on the $\delta^{18}\text{O}$ values. (5) Two distinctly different groups of rhyolites and quartz-normative trachytes are observed in the northernmost Pontine Islands, a high- ^{18}O group similar to the anatectic Tuscan rhyolites ($\delta^{18}\text{O} > +10$) and a low- ^{18}O group similar to the rhyolites of the Aeolian Islands ($\delta^{18}\text{O} = +7$ to $+7.5$). (6) All of the magmas produced in and around Italy during the past five million years can be derived by mixing of (i) a SiO_2 -rich continental crustal end member, having $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.715$ to 0.735 and $\delta^{18}\text{O} \sim +10$ to $+20$, with three distinct mantle end members: (ii) a relatively low-K (LKS), moderate-Sr parent with $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.706$ and $\delta^{18}\text{O} \sim +6$, dominant to the south of Rome and perhaps related to an upper mantle source modified by a recent subduction event; (iii) a high-K (HKS), high-Sr parent with $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.711$ and $\delta^{18}\text{O} \sim +7$ dominant in the vicinity of Rome and farther north, and possibly related to older subcontinental mantle modified by a recent metasomatic event; and (iv) a very low-K, low-Sr Tyrrhenian Sea MORB-type parent with $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.7025$ and $\delta^{18}\text{O} \sim +5.7$.

INTRODUCTION

IN THIS PAPER, we compare $^{18}\text{O}/^{16}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ data on potassic rocks from volcanic centers south and southeast of Rome with earlier studies on the Pleistocene and Holocene potassic volcanic rocks of Italy: FORNASERI and TURI (1969), BARBIERI *et al.* (1975), TURI and TAYLOR (1976), TAYLOR and TURI (1976), TAYLOR *et al.* (1979, 1984, 1987), VOLLMER (1976), HURLEY *et al.* (1966), COX *et al.* (1976), HOLM and MUNKSGAARD (1982); CIVETTA *et al.* (1981), FERRARA *et al.* (1985, 1986), CORTINI and HERMES (1981), ROGERS *et al.* (1985), and HAWKESWORTH and VOLLMER (1979), and other references quoted in the above papers.

The new samples analyzed in the present work are mainly from M. Ernici and from the islands off the western coast of Italy—Ischia, Procida, and the Pontinian Archipelago (Fig. 1). However, a few samples were also analyzed from on-shore centers (Roccamonfina, Phlegrean Fields, and Vesuvius), as well as single samples from some more distant centers (Table 1).

REGIONAL PETROLOGICAL AND GEOLOGICAL RELATIONSHIPS

General statement

APPLETON (1972) used K_2O - SiO_2 diagrams to delineate a High-K Series (HKS) and a Low-K Series (LKS, also simply termed Potassic Series, or KS, by some workers) among the potassic volcanic rocks of Italy. HKS rocks include strongly SiO_2 -

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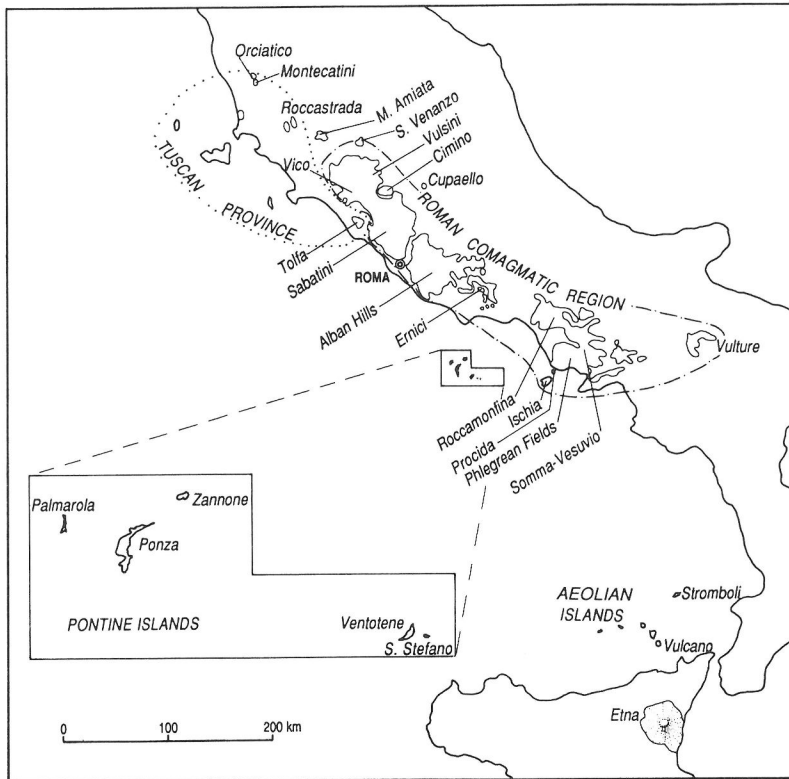


FIG. 1. Map of central Italy, showing the localities referred to in the text. The Pontine Islands are shown at a larger scale on the inset.

undersaturated leucite, leucite tephrite, and leucite phonolite, with $K_2O = 4$ to 11 wt.%, $K_2O/Na_2O = 3$ to 5, and $Al_2O_3 = 16$ to 20 wt.%. LKS rocks include trachybasalt, latite, and trachyte just slightly over- or just slightly undersaturated with respect to SiO_2 . They typically have $K_2O = 1$ to 3 wt.% and $K_2O/Na_2O = 0.5$ to 1.5.

HKS and LKS volcanic rocks occur together in close association at Ernici and Roccamonfina, and in the Somma-Vesuvius-Phlegrean Fields area (Fig. 1), as well as farther north at M. Vulsini (although at Vulsini the HKS is *much* more abundant than LKS rocks). South of the Alban Hills, the LKS is predominant over the HKS, particularly in the islands of southern Italy (Pontine Islands, Stromboli, and Vulcano). LKS rocks occur only sporadically to the north of M. Ernici. For example, the Alban Hills, M. Sabatini, and most of Vico seem to be composed exclusively of HKS lavas and pyroclastics. However, LKS volcanic rocks do occur at Radicofani in southern Tuscany, situated just a few km NE of M. Vulsini, as well as at Capraia, the northernmost island of the Tuscan Archipelago; both of these centers belong to the Plio-Pleistocene

Tuscan Magmatic Province (Fig. 1; see TAYLOR *et al.*, 1991).

Pontine Islands

The Pontine Islands (Fig. 1) lie between the northern and southern basins of the Tyrrhenian Sea on the edge of a 20 to 25 km-thick continental platform that borders the western coast of the Italian peninsula. They are divided into two geologically and geographically distinct groups, a northwestern group (Ponza, Palmarola, and Zannone) and a southeastern group (Ventotene and S. Stefano).

In the southeastern Pontine Islands, volcanic activity was dominantly subaerial, producing trachybasaltic pyroclastics and lavas (at Ventotene) to phonolitic lava flows and pyroclastics (at S. Stefano). Two volcanic series are identified on Ponza: an older rhyolitic group and a younger group of SiO_2 -undersaturated trachytic rocks. The early rhyolites and rhyodacites on Ponza were emplaced in a submarine environment (CARMASSI *et al.*, 1987), but the youngest volcanics are trachytic and subaerial (*e.g.*, the M. La Guardia trachytic dome, with a K/Ar age of 1.1 to 1.2 Ma, BARBERI *et al.*, 1967).

Table 1. Oxygen isotope, strontium isotope, and chemical compositions of samples of volcanic rocks from central and southern Italy (south of Rome)

Sample ^a	Rock ^b type	$\delta^{18}\text{O}$ W.R. (meas.)	$\delta^{18}\text{O}^c$ W.R. (calc.)	$\delta^{18}\text{O}$ Mineral	$\delta^{18}\text{O}^d$ "corrected" (W.R.)	$^{87}\text{Sr}/^{86}\text{Sr}^e$ $\pm 1\sigma$ (W.R.) ($^{87}\text{Sr}/^{86}\text{Sr}_0$)	Sr (ppm)	Oxide (wt.%) ^f											
								SiO ₂	Al ₂ O ₃	CaO	K ₂ O	H ₂ O							
Ponza																			
PO-401 (=P30 ⁹)	Tr	8.05	7.03	7.33 ± 0.15 kf	7.73	0.7086 ± 6 (0.7086) ^o	527	58.01 ⁹	18.94	3.52	6.72	0.86 ⁺							
PO-402 (=P4 ⁹)	R	17.40	11.11	10.91 ± 0.12 plag	11.11	0.71098 ± 6 (0.71055) ^o	156	72.85 ⁹	14.11	1.54	4.92	4.43 ⁺							
PO-403 (=P1 ⁹)	R (dike)	10.57	10.40	10.20 ± 0.07 kf	10.08	0.7111 ± 4 (0.7106) ^o	100	75.01 ⁹	13.18	1.12	5.45	1.06 ⁺							
PO-101 (=101 ⁹)	sR (dike)	7.93	—	—	6.55	0.71010 ± 3 [age not known]	40	69.05 ⁹	13.14	0.61	4.74	2.14 ⁺							
Palmarola ¹⁷																			
PAL-1	R	7.06 ± 0.10	—	—	—	0.7146 ± 4 (0.7108) ^o	8	—	—	—	—	—							
156-A ⁹	R	7.41 ± 0.07	—	—	7.04	0.7130 ± 4 (0.7084) ^o	7	73.72 ⁹	13.77	0.62	4.97	0.95 ⁺							
Ventotene																			
VT-451	TrB	6.89 ± 0.03	—	—	6.89	0.7072 ± 3	697	49.12	17.68	10.75	2.19	0.13 ⁺							
VT-453	TrB	6.83	—	—	6.35	0.70760 ± 10	829	49.28	18.20	10.43	2.88	1.08 ⁺							
V-58 ⁹	TrB	6.66 ± 0.17	—	—	5.95	0.70782 ± 4	873	48.96 ⁹	18.52	10.64	2.95	1.34 ⁺							
S. Stefano																			
ST-533 (=76 ⁹)	P	8.02 ± 0.19	—	—	7.62	0.7102 ± 5	16	57.83 ⁹	21.47	1.37	7.49	0.94 ⁺							
Procida																			
PP-2 ¹⁰	Tr	8.84	7.80 kf	8.10 ± 0.13 kf	—	0.7069 ± 4	354	59.81 ¹⁰	18.77	2.80	8.00	0.33 ⁺							
PL-11	La	7.46 ± 0.09	7.53 px	7.08 ± 0.08 px	7.00	0.7078 ± 2	308	55.87	17.68	7.41	4.08	1.06 ⁺							
PS-9	TrB	6.49 g	7.76	7.31 ± 0.05 px	—	0.7053 ± 5	473	48.12	15.53	12.00	1.49	—							
PS-11	TrB	6.60 ± 0.10	6.21	5.76 ± 0.02 px	6.60	0.70594 ± 7	705	48.01	17.66	11.51	2.78	0.43 ⁺							
PS-12	TrB	6.12 ± 0.40	5.98	5.53 ± 0.03 px	5.75	0.70593 ± 2	738	48.50	17.32	11.72	2.65	1.10 ⁺							
Ischia																			
IS-1 (=35 y ²¹)	Tr	—	6.44	6.74 kf	—	—	—	63.60	18.32	1.24	6.37	0.55*							
IS-4 (=RE-17 ¹)	SP	6.65	6.24	6.54 ± 0.01 kf	5.85	0.70763 ± 5 ¹	30 ¹	60.26 ⁸	18.11	1.48	7.52	1.36*							
IS-5 (=Mt. S. Angelo ¹)	SP	—	6.58	6.88 ± 0.08 kf	—	0.70703 ± 6 ¹	13 ¹	63.15	18.74	0.98	5.91	1.03*							
IS-2 (=11 ²)	La	6.35 ± 0.01	6.30 kf	6.60 ± 0.09 kf	6.35	0.70638 ± 4 ⁶	551g ²	55.30	19.14	5.88	5.29	0.32*							
IS-3 (=RE-12 ¹)	TPTr	7.02	6.26 px	5.81 ± 0.06 px	7.02	0.70607 ± 3 ¹	54 ¹	62.88	18.64	1.47	6.80	0.42*							
IS-7 (=27 ²¹)	ATr	—	5.91 px	5.46 ± 0.10 px	—	—	—	62.10 ⁸	18.13	1.15	6.74	0.37##							
IS-8 (=35 La ²¹)	ATr	—	6.40	6.70 ± 0.11 kf	—	—	—	61.58 ⁸	18.62	2.29	6.36	0.50##							

Sample ^a	Rock ^b type	$\delta^{18}\text{O}$ W.R. (meas.)	$\delta^{18}\text{O}^c$ W.R. (calc.)	$\delta^{18}\text{O}$ Mineral	$\delta^{18}\text{O}$ "corrected" (W.R.)	$^{87}\text{Sr}/^{86}\text{Sr}^d$ $\pm 1\sigma$ (W.R.) ($^{87}\text{Sr}/^{86}\text{Sr}_0$)	Sr (ppm)	Oxide (wt.%) ^f				
								SiO ₂	Al ₂ O ₃	CaO	K ₂ O	H ₂ O
IS-6 (=1146 ²¹)	ATr (tuff)	13.10 ± 0.06	7.45	7.75 ± 0.13 kf	—	—	—	62.92	18.00	0.82	7.78	7.15*
I-109 ¹	TrB	6.14	—	—	5.28	0.70617 ± 4 ¹	600 ¹	54.54	18.50	8.42	2.98	1.52 ⁺
Re-9 ^{1,7} (Arso flow)	Tr	6.86 ± 0.03	—	—	6.86	0.70661 ± 3 ¹	533 ¹	53.18 ⁷	18.38	6.86	4.33	0.44 ⁺
5103e ³	Tr	6.74 ± 0.25	—	—	—	0.70683 ⁷	77 ³	—	—	—	—	—
Phlegrean Fields												
CF-1 ¹⁰	ATr	—	8.06	8.36 kf	—	—	—	58.64 ¹⁰	19.09	3.90	8.18	0.23 ⁺
CF-3 ¹⁰	SP	—	8.08	8.38 ± 0.09 kf	—	0.70769 ± 3 ¹	12 ¹	59.48 ¹⁰	19.30	2.00	6.61	0.33 ⁺
CF-231	TrB	—	7.90	7.45 ± 0.16 px	—	—	—	52.36	16.74	10.44	3.16	1.01 ⁺
5106 ³	Tr	7.09 ± 0.12	—	—	—	0.70773 ³	700 ³	—	—	—	—	—
5107 ³	Tr	7.68 ± 0.03	—	—	6.97	0.70823 ³	1114 ³	59.73 ¹¹	20.24	1.74	6.86	1.36*
Parete#												
PAR-2 (-1800m)	BAnd	9.26 ± 0.24	—	—	—	0.70776 ± 3 ⁴	587 ⁴	54.13 ⁴	18.20	10.01	2.26	1.00 ⁺
PAR-2 (-1203m)	BAnd	—	—	9.73 plag	—	—	579 ⁴	51.53	19.64	11.25	1.67	3.06 ⁺
Somma												
Cast. di Cisterna ¹	PLT	7.33	—	—	—	0.70761 ± 4 ¹	737 ¹	50.55 ¹	—	—	5.76	—
PFSV-16 ¹	Tr (block)	8.77	—	—	6.98	0.70734 ± 4 ¹	—	59.94 ¹²	20.56	2.66	8.96	2.72*
Vesuvius**												
02717 (1858 flow) ¹	PLT	9.17 ± 0.02	—	—	9.17	0.70740 ± 3 ¹	977 ¹	47.67 ¹	—	—	8.00	0.28*
02718 (1872 flow) ¹	L	7.72	—	—	7.72	0.70722 ± 3 ¹	1031 ¹	48.11 ¹	—	—	7.98	0.41*
PFSV-36 (1906 flow) ¹	LT	7.89	—	—	7.87	0.70737 ± 2 ¹	1066 ¹	47.77 ¹²	19.66	8.04	7.89	0.54*
VES-3	—	7.22 ± 0.13	—	—	—	—	—	—	—	—	—	—
5098 ³	—	7.10 ± 0.20	—	—	—	0.70963 ³	977 ³	—	—	—	—	—
5099 (1861 flow?) ³	LT	7.68 ± 0.01	—	—	—	0.70793 ³	905 ³	—	—	—	—	—
5100 (1804 flow?) ³	LT	8.13 ± 0.16	—	—	—	0.70983 ³	974 ³	—	—	—	—	—
VES-1 (1858 flow)	L	7.72 ± 0.16	—	—	—	0.70739 ± 3 ¹	1033 ¹	47.38	18.40	9.10	8.28	—
VES-2 (1944 flow)	LT	8.02	8.13	7.93 ± 0.15 leucite	—	0.70721 ± 3 ¹	—	48.6	18.90	8.60	7.50	—
Roccamonfina												
36R (>1.0 Ma)	LBs	6.69 ± 0.11	—	—	6.69	0.70799 ± 3	1116	46.39	17.32	13.64	1.92	0.25*
41R (.616 Ma)	LP	8.68 ± 0.15	—	—	8.68	0.70947 ± 2	146	60.09	20.68	1.75	9.60	0.47*
46R (.695 Ma)	LT	7.28 ± 0.06	—	—	7.08	0.70947 ± 5	2027	50.36	19.02	8.58	7.51	0.83*
53R (.053 Ma)	MgL	6.46 ± 0.05	—	—	6.20	0.70989 ± 4	1858	46.12	15.95	12.27	6.98	0.93*
56R (.656 Ma)	ShB	10.96 ± 0.04	—	—	10.96	0.70850 ± 4	656	—	—	—	—	0.27*
58R (.096 Ma)	LaTr	7.93 ± 0.06	—	—	—	0.70712 ± 2	—	—	—	—	—	—
M. Ercici												
M-1	PL	6.69 ± 0.02	—	—	5.80	0.71121 ± 3 ⁵	1815 ⁵	46.99	17.24	9.85	9.01	1.83* ⁵
Em-1N (=ERN5 ⁵)	TL	7.98 ± 0.10	—	—	7.80	0.70967 ± 7 ⁵	1538 ⁵	47.68 ⁶	17.21	10.96	8.13	0.77 ⁺
Em-1B (=ERN5 ⁵)	TL	8.38 ± 0.23	—	—	8.16	0.70967 ± 7 ⁵	1538 ⁵	47.52	17.37	11.12	6.80	0.84 ⁺
Em-3	TL	8.63 ± 0.21	—	—	8.10	0.70928 ± 4	1397	47.88	17.14	10.90	7.14	1.35 ⁺
Em-4	PL	8.85 ± 0.11	—	—	8.45	0.71078 ± 2	1419	46.85	17.40	9.93	9.79	1.09 ⁺
Em-5	TL	8.18 ± 0.11	—	—	7.80	0.70989 ± 2	1505	46.92	17.11	11.30	7.23	1.06 ⁺
VL-6A	—	8.15	—	—	—	0.70951 ± 4	1515	47.48	18.25	10.23	7.27	—
VL-65 (=S8 ⁵)	TrB	7.15 ± 0.04	—	—	6.36	0.70639 ± 3	822	48.77	17.69	11.93	2.90	1.68* ⁵

Table 1. (Continued)

Sample ^a	Rock ^b type	$\delta^{18}\text{O}$ W.R. (meas.)	$\delta^{18}\text{O}^c$ W.R. (calc.)	$\delta^{18}\text{O}$ Mineral	“corrected” (W.R.)	$\delta^{18}\text{O}$ $\pm 1\sigma$ (W.R.) (⁸⁷ Sr/ ⁸⁶ Sr) ₀	Sr (ppm)	Oxide (wt.%) ^f				
								SiO ₂	Al ₂ O ₃	CaO	K ₂ O	H ₂ O
Mt. Vulture VU-342 ¹³	Hf	6.72 ± 0.14	—	—	6.00	0.70594 ± 7 ¹³	5703 ¹³	40.24 ¹⁴	18.29	13.17	4.70	1.54 ⁺
Vulcano VOL-2 (=VO24, IV14) ¹⁵ (=Vulc 72) ¹⁸	LT	6.95	—	—	—	0.7046 ¹⁸	1233	53.23 ¹⁵	16.67	7.60	4.95	0.50 ⁺
Etna (1971 lava flow) E-1 (=EC3 ¹⁶)	AB	5.96	—	—	—	0.70350 ²²	1119 ²²	46.82 ¹⁶	16.94	10.99	1.73	0.61 ⁺
E-2 (=VC11 ¹⁶)	AB	5.89 ± 0.09	—	—	—	0.70349 ²²	1150 ²²	47.56 ¹⁶	16.73	10.97	1.59	0.54 ⁺
E-3 (=VC13a ¹⁶)	AB	6.12 ± 0.01	—	—	—	0.70357 ²²	1040 ²²	48.15 ¹⁶	17.06	10.46	1.77	0.65 ⁺
P. Pietre Nere PDPN	Msy	8.57 ± 0.00	—	—	—	0.70370 ¹⁹	1102 ¹⁹	40.62 ²⁰	16.14	13.08	4.01	—

^a Sample numbers either refer to new samples collected by us (no superscript), or to the exact specimens previously collected and studied by other authors (indicated by superscript). In some cases, in parentheses, we indicate equivalent samples from the same outcrop localities from the references cited in the footnote. Exact locations of the samples are available from the authors on request.

^b LT = leucite tephrite; TL = tephritic leucite; Tr = trachyte; BAnd = basaltic andesite; ShB = shoshonitic basalt; R = rhyolite; sR = sodic rhyolite; TrB = trachybasalt; P = phonolite; La = latite; SP = sodalite phonolite; TPTr = tephritic phonolite trachyte; ATr = alkali trachyte; PLT = phonolitic leucite tephrite; L = leucite; LBs = leucite basanite; LP = leucite phonolite; MgL = magnesian leucite; LaTr = latitic trachyte; PL = phonolitic leucite; Hs = hauynophir; AB = alkali basalt.

^c The whole-rock (calc.) values are calculated from the $\delta^{18}\text{O}$ values of the phenocryst minerals, pyroxene (px) and K feldspar (kf); $\Delta(\text{W.R.}-\text{px}) = +0.45$; and $\Delta(\text{W.R.}-\text{kf}) = -0.30$, except for the rhyolites, where $\Delta(\text{W.R.}-\text{kf}) = +0.20$. The $\delta^{18}\text{O}$ values were measured by conventional mass spectrometric techniques, using the fluorine method (e.g., see TAYLOR, 1968). NBS-28 has a $\delta^{18}\text{O} = +9.60$ in our laboratories. The \pm indicates average deviation from the mean when two or more analyses were carried out.

^d The “corrected” whole-rock $\delta^{18}\text{O}$ values are calculated from the $\delta^{18}\text{O}$ (meas.)-H₂O plot shown in Fig. 3 in TURI *et al.* (1991).

^e The ⁸⁷Sr/⁸⁶Sr ratios are either from the indicated literature references, or they were obtained using a Varian MAT THS mass spectrometer (4 decimal places) or a VG Micromass 54E mass spectrometer (5 decimal places) on line with a computer for data collection and evaluation, normalized to a ⁸⁶Sr/⁸⁸Sr value of 0.1194. Determinations of Eimer and Amend SrCO₃ standard gave either ⁸⁷Sr/⁸⁶Sr = 0.7081 (1 σ) or 0.70805 ± 0.00002 (1 σ), respectively. Sr and Rb concentrations were determined by isotope dilution, spiked during dissolution with a mixed ⁸⁴Sr and ⁸⁷Rb spike.

^f SiO₂, Al₂O₃, CaO, and K₂O values recalculated on an anhydrous basis. A superscript on an SiO₂ analysis indicates that all of the major element chemical values are from the indicated reference. H₂O is given either as L.O.I., H₂O⁺, or H₂O (total). Complete chemical analyses of all samples are available from the authors on request.

Superscripts: * = L.O.I.; ## = H₂O_{tot}; + = H₂O⁺; ° = corrected for age; g = groundmass; ** GARLICK (1966) reports $\delta^{18}\text{O}$ values of leucite from the 1906 flow (+7.71) and clinopyroxene from the 1760 flow (+6.9); which would give calculated $\delta^{18}\text{O}$ whole-rock values of +7.9 and +7.35, respectively. # The Parete samples are the same specimens described in BARBIERI *et al.* (1975), ALBINI *et al.* (1980), and DI GIROLAMO *et al.* (1976); these hydrothermally altered samples were collected from PAR-2 drill hole at the indicated depths in meters. (1) CORTINI and HERMES (1981); (2) VOLLMER *et al.* (1981); (3) HURLEY *et al.* (1966); (4) BARBIERI *et al.* (1979); (5) CIVETTA *et al.* (1981); (6) DEGENNARO and FRANCO (1971); (7) GHIARA *et al.* (1975), ALBINI *et al.* (1980), and DI GIROLAMO *et al.* (1976); (8) RITTMANN, pers. comm. (1977); (9) BARBIERI *et al.* (1967); (10) DIGIROLAMO and STANZIONE (1973); (11) DIGIROLAMO *et al.* unpub. anal.; (12) Dept. of Earth Science, Univ. Pisa, unpub. anal.; (13) HAWKESWORTH and VOLLMER (1979); (14) HIEKE-MERLIN (1967); (15) Two different specimens from KELLER (1974) and PECCHERILLO and MANETTI (1985); (16) CAGNETTI *et al.* (1973); (17) Note that GALE (1981) made two other analyses of Palmarola obsidian: ⁸⁷Sr/⁸⁶Sr = 0.71317 ± 6 (Sr = 7 ppm); 0.71375 ± 11 (Sr = 6.9 ppm); (18) KLERKX *et al.* (1974); (19) VOLLMER (1976); (20) BURRI (1959); (21) VEZZOLI (1988); (22) BARBIERI and TADDEUCCI (pers. comm., 1987).

Zannone is dominantly made up of rhyolite. This is the only Pontine Island that contains metamorphic rocks ("schistes lustrés") and sedimentary rocks (ranging from Triassic dolomites and limestones to late Tertiary flysch), tentatively correlated with the basement rocks in Tuscany by PAROTTO and PRA-TURLON (1975).

Ischia

The Island of Ischia (Fig. 1) is essentially a volcano-tectonic horst made up of >150,000-year-old latitic and trachytic lavas and pyroclastics intruded by younger lava domes, which are in turn overlain by a major (about 1000 m thick) alkali-trachyte pyroclastic flow (the "Mt. Epomeo Green Tuff"); the latter was erupted subaerially about 55,000 years ago. The chemical compositions of the volcanic products at Ischia range from olivine latite to alkali trachyte, these latter being dominant (CAPALDI *et al.*, 1985; VEZZOLI, 1988). The latest eruption was in 1302 A.D. (Arso flow).

Procida

Although geographically and geologically linked to Ischia on the west and the Phlegrean Fields to the northeast by a NE-trending, deep-seated fault system (Fig. 1), the Island of Procida is petrographically distinct from these adjacent centers (see ALBINI *et al.*, 1977, 1980, and refs. therein). The dominant lavas on Procida and in the Ischia Channel are trachybasalt.

Mts. Ernici

The Mts. Ernici or Media Valle Latina district is located about 50 km ESE of the Alban Hills and 70 km NW of Roccamonfina (Fig. 1). It comprises numerous small eruptive centers spread over about 100 km². The volcanic activity was mainly explosive, producing both HKS and LKS pyroclastics and subordinate lava flows between about 700 ± 20 to 80 ± 40 Ka. The HKS products have K/Ar ages from about 700 to 200 Ka, and thus appear to be typically older than the LKS lavas, which have K/Ar ages between about 200 and 100 Ka (BASILONE and CIVETTA, 1975; CIVETTA *et al.*, 1981).

EXPERIMENTAL PROCEDURES

Measurements of strontium isotope ratios and concentrations were obtained by conventional techniques, as indicated in Table 1. Oxygen was liberated from the silicate samples by reaction with fluorine gas (TAYLOR and EPSTEIN, 1962). The ¹⁸O/¹⁶O data obtained on these samples are reported in Table 1 in the familiar δ notation; the

reference standard is Standard Mean Ocean Water (SMOW) and NBS-28 has a δ¹⁸O = +9.60 on this scale. The mineral separates were obtained by conventional techniques, and their purity, checked by XRD, was found to be generally better than 95%.

Essentially all measured whole-rock δ¹⁸O values of old volcanic rocks on Earth have been increased by hydration and water/rock exchange during low-temperature weathering and diagenesis (even in some rocks only a couple of thousand years old). The ¹⁸O/¹⁶O ratios of all such rocks are therefore suspect and cannot be assumed to reflect the δ¹⁸O of the original magmas (TAYLOR, 1968; TAYLOR *et al.*, 1984). This particularly applies to tuffs, pyroclastics, and ignimbrites, but it is also true of lavas. Therefore, except for such recently erupted lavas as those from Vesuvius and Etna, which are very fresh, we have followed two different procedures used previously by us and by other workers (*e.g.*, FERRARA *et al.*, 1985, 1986; MUEHLENBACHS and BYERLY, 1982; MUEHLENBACHS and CLAYTON, 1972) to calculate the primary δ¹⁸O values of the lavas: (1) calculation of whole-rock δ¹⁸O by measuring the δ¹⁸O of coexisting phenocrysts, and then assuming an appropriate equilibrium ¹⁸O/¹⁶O fractionation between mineral and melt (Table 1); (2) "correcting" the whole-rock δ¹⁸O in a crude way simply from the correlation between the measured H₂O content (or L.O.I.) and the ¹⁸O increase due to hydration.

The "correction" procedure in this paper follows that utilized by FERRARA *et al.* (1985, 1986) for similar rock types from the Alban Hills and M. Vulsini (see TURI *et al.*, 1991). For two extremely hydrated samples from Ischia and Ponza (IS-6 and PO-402), we made direct measurements of phenocrysts and hydrated lava; the "correction" lines determined in this way for IS-6 and particularly for PO-402 are even steeper than the one obtained for the Alban Hills lavas by FERRARA *et al.* (1985). Therefore, we have conservatively utilized the original Alban Hills trend-line for all the samples from the Italian mainland and used the slightly steeper Ischia (IS-6) trend line only for samples from the offshore islands and the directly adjacent localities of Somma-Vesuvius and the Phlegrean Fields. In all cases, the lowering of the measured δ¹⁸O value is less than 0.8 per mil, with the exception of one sample from Somma (PFSV-16), one from Ponza (PO-101), and the aforementioned samples PO-402 and IS-6; in most cases the "corrections" are only 0.0 to 0.4 per mil (Table 1; also see TURI *et al.*, 1991). Even though these corrections are small, they *must be made*, otherwise, the ¹⁸O/¹⁶O data cannot be plotted in graphs or discussed as if they represented true magmatic values. Fortunately for comparative purposes, these hydration corrections are always unidirectional (*i.e.*, they always give results that are *lower* than the measured δ¹⁸O value).

CORRELATIONS BETWEEN CHEMICAL AND ISOTOPIC COMPOSITIONS

K₂O vs. SiO₂

Our new data from Table 1 are plotted on Fig. 2, where they are compared with samples from other volcanic centers south of Rome (Alban Hills—FERRARA *et al.*, 1985; Roccamonfina—TAYLOR *et al.*, 1979; HAWKESWORTH and VOLLMER, 1979). Linear trends upward and to the right on such dia-

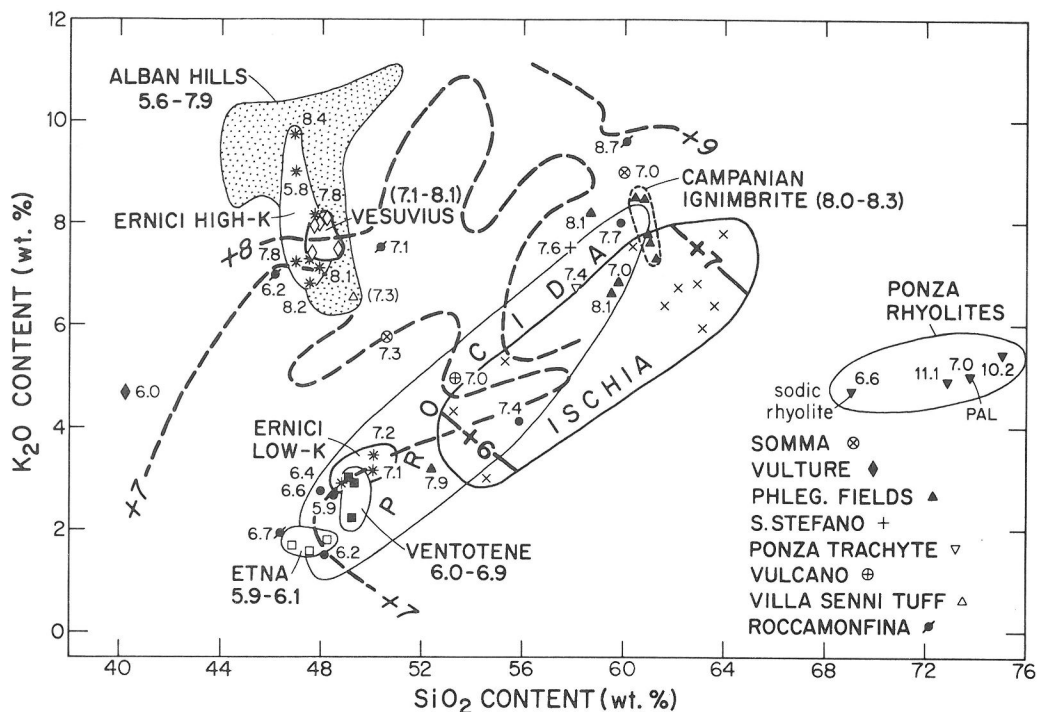


FIG. 2. Plot of K_2O vs. SiO_2 for the samples studied in this work, showing that the $\delta^{18}\text{O}$ values are related to the major-element chemistry. The positions of the Alban Hills and Roccamonfina volcanic rocks are also indicated (see text).

grams were interpreted by APPLETON (1972) to represent fractional crystallization of alkali-rich, mantle-derived primary magmas with SiO_2 contents of about 44–47 wt.% and variable K_2O contents (as low as 1–2 wt.% in the LKS lavas and as high as 8–10 wt.% K_2O for the HKS). These trends were later ascribed to processes of combined assimilation-fractional crystallization (AFC) in crustal magma chambers (TAYLOR *et al.*, 1979; TAYLOR, 1980).

Our new data plot in three well-defined K_2O - SiO_2 groupings on Fig. 2, two of which show a clear correspondence with the HKS and LKS trends of APPLETON (1972); the third corresponds closely with the high- ^{18}O rhyolites of the Tuscan Province (Ponza and Palmarola rhyolites). The Ischia, Procida, Ventotene, S. Stefano, Vulcano, and Phlegrean Fields samples, as well as the Ponza trachyte, all fit well with the trend of Appleton's Low-K Series. The strongly differentiated Campanian Ignimbrite (Campanian Grey Tuff), erupted from the northern part of the Phlegrean Fields 33,000 years ago, also belongs to the LKS. The only new lavas studied in this work that belong to the High-K Series are the three samples from Roccamonfina, the Ernici HKS, and the Somma-Vesuvius samples.

The $^{18}\text{O}/^{16}\text{O}$ variations on Fig. 2 are indicated in

different ways, either with the $\delta^{18}\text{O}$ value lettered alongside a single data point, or giving the range of $\delta^{18}\text{O}$ for an entire group of samples. In addition, the dashed contours at $\delta^{18}\text{O} = +7$, $+8$, and $+9$ show how the $\delta^{18}\text{O}$ values of the Roccamonfina samples change with chemical composition (it is satisfying to note that the plotting of our new samples did not require any modification of the systematic $\delta^{18}\text{O}$ - K_2O - SiO_2 patterns originally delineated by TAYLOR *et al.*, 1979). Note that the lowest- ^{18}O Roccamonfina sample (53R) is among the *youngest* of the products of this volcano (only 53,000 years old; RADICATI DI BROZOLO *et al.*, 1988).

Trachybasalts with $\text{SiO}_2 < 50$ wt.% are the most primitive LKS lavas analyzed in this study, and together with the Mt. Etna alkali basalts, these samples plot at the low- SiO_2 , low- K_2O end of the Roccamonfina LKS field (Fig. 2). This grouping includes three Procida samples, one Ernici sample, and all three Ventotene rocks; *all* of these samples are very low in $\delta^{18}\text{O}$ (+5.9 to +6.9), in keeping with their other primitive chemical characteristics. Moving upward and to the right on the K_2O - SiO_2 plot, the $\delta^{18}\text{O}$ values increase slightly to +7.1 to +7.2 for the Ernici trachybasalts with $\text{SiO}_2 > 50$ wt.%, and to +7.4 and +7.7 for the Procida latite and trachyte.

The S. Stefano phonolite ($\delta^{18}\text{O} = +7.6$) is geographically related to the Ventotene volcanic center (Fig. 1), and together the Ventotene and S. Stefano samples also define a trend of slight ^{18}O -enrichment with increasing K_2O and SiO_2 .

The Ischia samples overlap the trends described above, but they are overall shifted downward and to the right on Fig. 2 (note that this shift is not because they are less rich in *total alkalis*; the lower K_2O concentrations of the Ischia rocks at a given SiO_2 content go hand-in-hand with the fact that their Na/K ratios are considerably higher than those of equivalent lavas on the Italian mainland). Like the Procida and Roccamonfina samples, the $\delta^{18}\text{O}$ values at Ischia also show a slight increase upward and to the right on Fig. 2, but the most important feature of the data is that, compared with other samples having similarly high SiO_2 contents (54–64 wt.%), these Ischia samples have the lowest $\delta^{18}\text{O}$ values of *any* Quaternary volcanic rocks so far analyzed from Italy.

The four Ponza samples and the geographically closely associated rocks from Palmarola are chemically and isotopically heterogeneous; however, the Ponza group can be subdivided into (1) a couple of very high- SiO_2 rhyolites (73–75 wt.% SiO_2) that have very high $\delta^{18}\text{O}$ values (+10.2 to +11.1), and (2) a couple of lower- ^{18}O , lower- SiO_2 , alkalic rocks (a trachyte and a sodic rhyolite dike with $\delta^{18}\text{O} = +7.0$ to +7.4). The high- ^{18}O sub-group is analogous to the anatectic rhyolites of the Tuscan Magmatic Province on the mainland, compatible with the nearby occurrence of Tuscan metamorphic basement rocks on the island of Zannone. The adjacent Palmarola rhyolites are isotopically very similar to the second, or low- ^{18}O sub-group of Ponza samples. It is remarkable that rhyolitic rocks from such a small geographic area (Fig. 1) display such a large range in $\delta^{18}\text{O}$. The only other localities in Italy where such low- ^{18}O Quaternary rhyolites are known are in the Aeolian Islands (M. JAVOY, pers. comm.).

The M. Ernici HKS samples are coincident with the Alban Hills field on Fig. 2, and both geochemically and geographically, these are also the lavas closest to the Alban Hills volcanic rocks (Fig. 1). They also display a similar range of $\delta^{18}\text{O}$ (+5.8 to +8.5 at Ernici vs. +5.6 to +7.9 at the Alban Hills). Much of the general discussion and interpretation by FERRARA *et al.* (1985) concerning the origin and evolution of the Alban Hills volcanic rocks thus probably applies to the Ernici HKS lavas, as well.

CaO vs. $\delta^{18}\text{O}$

On Fig. 3 we present a schematic diagram that shows the kinds of changes expected in CaO and

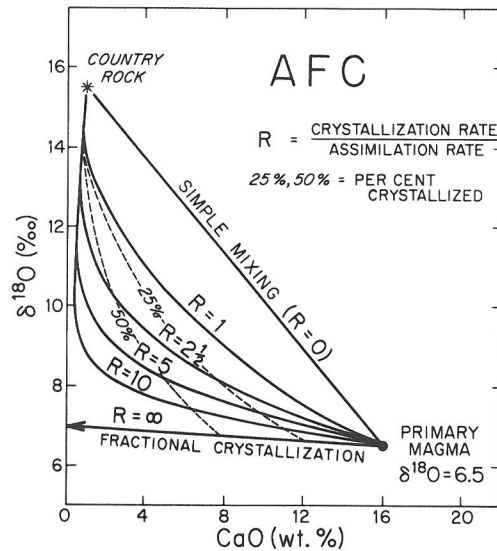


FIG. 3. Plot of CaO vs. $\delta^{18}\text{O}$, showing schematically how these parameters change during closed-system differentiation, simple mixing, and combined assimilation-fractional crystallization.

$\delta^{18}\text{O}$ during closed-system fractional crystallization, combined assimilation-fractional crystallization (AFC), and simple mixing. APPLETON (1972) and most subsequent workers (*e.g.*, HOLM and MUNKSGAARD, 1982; FERRARA *et al.*, 1986) attributed great importance to the most Ca-rich and SiO_2 -depleted lavas in the volcanic series of Italy, because these are the best candidates for primary magmas. Contrary to the opinions of VOLLMER (1989), essentially all other studies of the petrology of the potassic Roman Province have concluded that if there are *any* primitive, uncontaminated magmas represented among the eruptive products of these volcanic centers, *they must be these Ca-rich lavas*. Although fractional crystallization of olivine and clinopyroxene will drive such magmas toward higher SiO_2 and K_2O (APPLETON, 1972), thereby explaining much of the major-element variation in these K-rich lavas (Fig. 2), this process cannot account for the $^{18}\text{O}/^{16}\text{O}$ variations (TAYLOR *et al.*, 1979; FERRARA *et al.*, 1985, 1986).

On a CaO- $\delta^{18}\text{O}$ plot (Fig. 3), the above-described fractional crystallization process drives the evolved magmas horizontally to the left toward lower CaO contents. As shown by GARLICK (1966), TAYLOR (1968), MATSUHISA (1979), MUEHLENBACHS and BYERLY (1982), CHIVAS *et al.* (1982), SHEPPARD and HARRIS (1985), and TAYLOR and SHEPPARD (1986), there is probably a slight enrichment of $\delta^{18}\text{O}$ during such a closed-system process, but it will be

very small for such high-temperature magmas, certainly no more than one per mil. Thus, a diagram like Fig. 3 can provide a sensitive test of closed-system fractional crystallization (HOLM and MUNKSGAARD, 1982; FERRARA *et al.*, 1986).

Simple mixing curves are nearly straight lines on diagrams like Fig. 3 because the oxygen contents of most rocks and magmas are similar. For a specific pair of end members, processes of combined assimilation-fractional crystallization (AFC, see TAYLOR, 1980) also start off as approximately straight lines at a given R value (ratio of cumulates to assimilated rock, see TAYLOR and SHEPPARD, 1986), before beginning to curve sharply as the assimilation process starts to dominate. The various AFC curves thus lie at intermediate positions between a closed-system fractional crystallization "line" and a simple mixing line. Even for relatively low degrees of fractional crystallization (25 to 50%), the ^{18}O enrichments of the magmas should be apparent, especially if the R values are as low as two to five (Fig. 3).

On Fig. 4 we show how the $\delta^{18}\text{O}$ values of lavas from previously studied potassic volcanic centers on the Italian mainland change with CaO concentration. The two best-studied volcanic centers that also have erupted significant quantities of lavas with "primitive" CaO contents are M. Vulsini and Roccamonfina (FERRARA *et al.*, 1986; ROGERS *et al.*, 1985; HOLM and MUNKSGAARD, 1982; TAYLOR *et al.*, 1979; APPLETON, 1972). The most Ca-rich samples from both Roccamonfina and Vulsini have relatively low $\delta^{18}\text{O}$; however, with decreasing CaO the lavas of both volcanoes, but particularly those from M. Vulsini, display a sharp $\delta^{18}\text{O}$ increase. The only way these $^{18}\text{O}/^{16}\text{O}$ data can be reconciled with the strong consensus that the trend of decreasing CaO is a result of low-pressure fractional crystallization is to combine that process with a simultaneous and concurrent enrichment in ^{18}O due to assimilation of high- ^{18}O country rocks (*i.e.*, AFC).

There are significant geographic differences in Italy in the magnitudes of the $^{18}\text{O}/^{16}\text{O}$ effects attributable to AFC processes. For example, although the most Ca-rich lavas at both Vulsini and Roccamonfina display low $\delta^{18}\text{O}$ values, the more evolved Ca-poor magmas are *much* richer in ^{18}O at Vulsini (Fig. 4). Therefore, the AFC processes at Vulsini for some reason produced much greater ^{18}O enrichments. TURI and TAYLOR (1976) and TAYLOR and TURI (1976) explained these geographic differences in Italy as resulting from the fact that the M. Vulsini volcano erupted upward through a thick section of continental crust that had been heated on a regional scale during the previous million or so years; this event was sufficiently intense

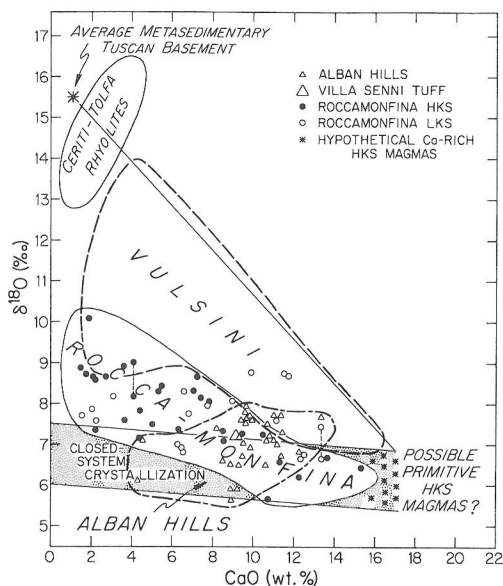


FIG. 4. Plot of CaO vs. $\delta^{18}\text{O}$ for volcanic rocks from various localities referred to in the text. For Vulsini, only the generalized data envelope is shown. Note that the Villa Senni Tuff represents the most voluminous eruption at the Alban Hills, and that the Ceriti-Tolfa rhyolites are anatectic magmas from the southern part of the Tuscan Province (see Fig. 1).

that widespread melting of the continental crust occurred, producing the characteristic high- ^{18}O Tuscan granites and rhyolites. The Tuscan rhyolites that are geographically closest to the Pontine Islands are also plotted on Fig. 4, namely those from the Ceriti-Tolfa center (TAYLOR *et al.*, 1991). Mixing between these crustal-anatectic Tuscan magmas and the mantle-derived Roman magmas appears to have been fairly widespread, particularly at the ^{18}O -rich, hybrid M. Cimini center that lies just southeast of, and is partially covered by, the products of the M. Vulsini center (TAYLOR and TURI, 1976; TAYLOR *et al.*, 1991; BARTON *et al.*, 1982).

Because of heat-balance considerations, the isotopic effects produced by AFC processes will be enhanced dramatically if the country-rock temperatures are raised significantly above those characteristic of a normal geothermal gradient (TAYLOR, 1980; DE PAOLO, 1981). Although R values of seven to nine might be appropriate for "cold" wall rocks, R values as low as one to three might be expected for magma chambers emplaced into country rocks that have been strongly heated. North of Rome, we know that the continental crust was strongly heated and locally partially melted during the past four million years by the Tuscan magmatic episode, and the surface rocks are locally still very hot (*e.g.*, at

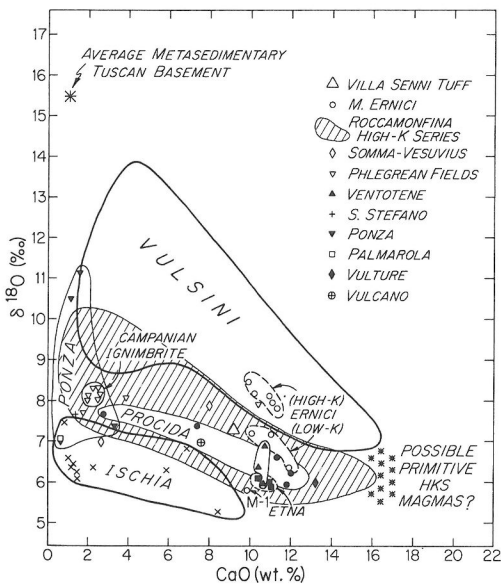


FIG. 5. Plot of CaO vs. $\delta^{18}\text{O}$ comparing new data from the offshore islands of Ischia, Procida, and the Pontine Islands with other localities referred to in the text.

M. Amiata and Larderello); however, south of Rome such heating prior to the late Quaternary potassic volcanism was minor or non-existent. On a regional scale these lateral gradients in temperature at a given depth within the Italian continental crust (*i.e.*, country-rock temperatures decreasing to the south) seem adequate to explain the observed $\delta^{18}\text{O}$ differences between the Vulsini and Roccamonfina magmas on Fig. 4 (compare with Fig. 3).

With the above discussion as background, on Fig. 5 we plot the CaO- $\delta^{18}\text{O}$ relationships observed for the other samples from the present study. This diagram elaborates on certain features in the K_2O - SiO_2 plot (Fig. 2), including the correspondence between the Procida and the Ventotene-S. Stefano trends and the fact that on a CaO- $\delta^{18}\text{O}$ plot the lavas from these islands plot between the Ischia field and the main portion of the Roccamonfina HKS field, and at much lower $\delta^{18}\text{O}$ values than the Vulsini samples. All of these trends project toward a possible primitive parent magma having a $\delta^{18}\text{O}$ somewhere in the range +5.5 to +7.5 and a CaO content of about 14 to 17 wt.%. Interestingly, the lowest ^{18}O samples that have yet been found among the highly differentiated lavas of Italy (*i.e.*, those with CaO < 2 wt.%) are *all* from the offshore islands, namely the Ischia trachytes and phonolites, *some* of the Ponza-Palmarola rhyolites, and the rhyolites from the Aeolian Islands (M. JAVOY, pers. comm.). This may be correlated with the fact that these centers are located

at the margin or outboard of the high- ^{18}O continental crust of the Italian peninsula. For example, can it be a coincidence that the sequence of increasing $\delta^{18}\text{O}$ in the Quaternary lavas erupted within a relatively small area in the vicinity of the Gulf of Naples is Ischia—Procida—Phlegrean Fields? This geochemical transition takes place over a lateral distance of only 30 km (Fig. 1) and is identical to the geographic sequence from southwest to northeast, going from low- ^{18}O oceanic crust toward high- ^{18}O continental crust.

$^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\delta^{18}\text{O}$

On Fig. 6, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the new samples from this study are plotted against $\delta^{18}\text{O}$. Also included are all available data from Roccamonfina (TAYLOR *et al.*, 1979; HAWKESWORTH and VOLLMER, 1979). Two important features are indicated on Fig. 6, both of which were previously pointed out at Roccamonfina by TAYLOR *et al.* (1979): (1) There is a steep positive correlation between $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ at each volcanic center. (2) At a given locality, the Low-K Series and High-K Series samples each form separate groupings, with the HKS exhibiting a much higher $^{87}\text{Sr}/^{86}\text{Sr}$ than the LKS.

The steep trends shown on Fig. 6 clearly require some type of mixing process between a high- ^{18}O , ^{87}Sr -rich end member(s) and a low- ^{18}O , ^{87}Sr -poor end member(s); this mixing is a local phenomenon that occurred separately beneath each volcanic center. On Fig. 7, the data from Fig. 6 are compared with data from some other Italian volcanic centers, confirming and amplifying the above conclusions.

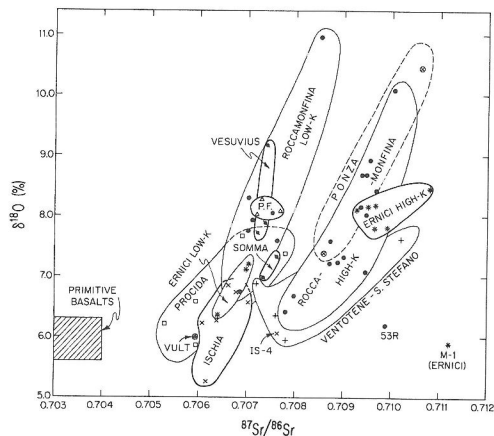


FIG. 6. Plot of $\delta^{18}\text{O}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ for various localities referred to in the text (see Fig. 1). P.F. indicates Phlegrean Fields.

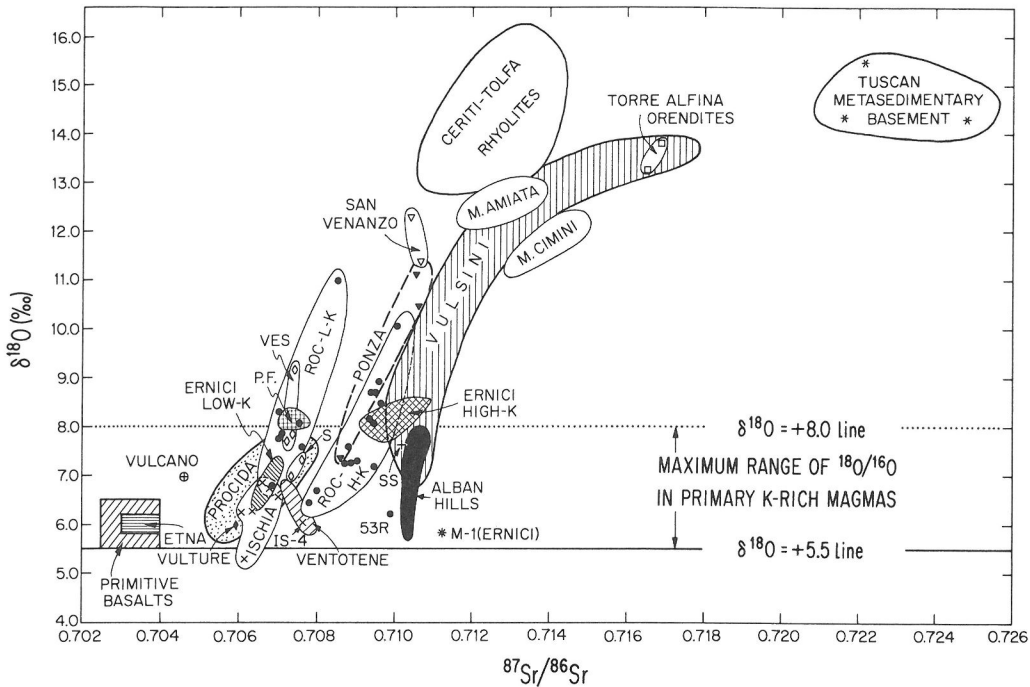


FIG. 7. Plot of $\delta^{18}\text{O}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ comparing the data from Fig. 6 with data from other localities referred to in the text, including the Tuscan Igneous Province (compare with Fig. 1).

At each center, the data-point envelope exhibits a steep, positive slope that projects downward toward a low- ^{18}O , low- ^{87}Sr end member; these low- ^{18}O end members all have a primitive $\delta^{18}\text{O} = +5.5$ to $+7.5$, but distinctly different $^{87}\text{Sr}/^{86}\text{Sr}$ (ranging from 0.706 to 0.710). The $^{87}\text{Sr}/^{86}\text{Sr}$ of the low- ^{18}O end member(s) changes systematically from lower values in the Low-K Series and/or in samples from the southern part of the Roman Province to higher $^{87}\text{Sr}/^{86}\text{Sr}$ in the High-K Series and/or in the northern part of the province. The highest $^{87}\text{Sr}/^{86}\text{Sr}$ values of the low- ^{18}O end member(s) are observed in the HKS lavas, as typified by the Alban Hills and M. Vulsini. Based on limited data from the Vico and M. Sabatini volcanoes, which lie geographically between M. Vulsini and the Alban Hills, similar isotopic effects appear to be characteristic of all HKS samples within this entire region to the north of Rome (see TAYLOR *et al.*, 1991).

The high- ^{18}O , high- $^{87}\text{Sr}/^{86}\text{Sr}$ end member(s) can be identified with the characteristic Tuscan metasedimentary basement rocks of central Italy (TAYLOR and TURI, 1976; TAYLOR *et al.*, 1991; VAREKAMP and KALAMARIDES, 1989). Hyperbolic mixing curves between various low- ^{18}O , variable- ^{87}Sr end member(s) and these metasedimentary basement rocks can explain all the convex-upward,

curved trajectories exhibited by the various data-point envelopes on Figs. 6 and 7 (compare with Fig. 9 of FERRARA *et al.*, 1986, or Fig. 21 of TAYLOR and SHEPPARD, 1986). Because of the extremely high Sr contents of the low- ^{18}O end members (typically 1000–2000 ppm Sr, or more; Table 1), these trajectories always start out with a near-vertical slope. Because the trends are very steep, there is virtually no ambiguity about the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the low- ^{18}O end member at each center (for example, at the Alban Hills, the HKS end member must have a remarkably uniform $^{87}\text{Sr}/^{86}\text{Sr}$ between 0.7100 and 0.7104 (FERRARA *et al.*, 1985). The strongly quartz-normative Tuscan rhyolites at Ceriti-Tolfa, San Vincenzo, and Roccastrada (TAYLOR *et al.*, 1991) plot very close to the field of Tuscan basement rocks, compatible with their anatectic origin from these rocks (Fig. 7). Also, the hybrid trachytic and latitic magmas at M. Amiata and M. Cimini were apparently formed by some type of mixing between these Tuscan anatectic magmas and potassic magmas analogous to those of the Roman Province, confirming the conclusions of TAYLOR and TURI (1976).

Some of the rhyolites from the Pontine Islands have markedly different isotopic compositions than the characteristic Tuscan rhyolites (Roccastrada,

San Vincenzo, Tolfa-Ceriti) and granites (Elba, Montecristo, Giglio). The Palmarola rhyolites are not plotted on Fig. 7 because the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of samples with such extremely low Sr concentrations (7 ppm) cannot be calculated unless the age of crystallization is *exactly* known; however, their initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios can be roughly estimated at about 0.708–0.710 (Table 1), and together with their $\delta^{18}\text{O}$ values of +7.0 to +7.1, we see that the Palmarola rhyolites approximately overlap with the most primitive Roccamonfina HKS and Alban Hills HKS samples on Fig. 7, even though they are chemically *much* different rock types.

None of these relatively low- ^{18}O rhyolites and trachytes from the off-shore islands of Ponza and Palmarola can be derived from melting of sedimentary or metasedimentary rocks of the type that make up the continental crust of Italy. Because they display isotopic compositions similar to those found in most other ocean islands, they could have been derived in a similar fashion as the typical trachytes and rhyolites from such islands (*e.g.*, Easter Island, Ascension, and Tristan de Cunha; see review by SHEPPARD, 1986). The two high- ^{18}O Ponza rhyolites (P0402,403) however, definitely require the admixture of a metasedimentary component, and some type of mixing between such a component and a Palmarola-type magma would be an adequate way to form such magmas. Such metasedimentary rocks do in fact occur nearby on the island of Zannone.

CONCLUSIONS

Although crustal assimilation (AFC) effects are readily apparent in the $^{18}\text{O}/^{16}\text{O}$ results, they are obscured in the Sr and Nd isotope data because of the extremely high Sr and rare earth concentrations in these potassic magmas. This is particularly true for the more fractionated lavas, and especially to the north of Rome where the potassic magmas were erupted upward through thick continental crust where the geothermal gradient was much higher than normal. Hence, in this situation the radiogenic isotopes are a sensitive monitor of the mantle source-region characteristics of these magmas, whereas the $^{18}\text{O}/^{16}\text{O}$ signatures are much more sensitive to continental crustal assimilation effects. The *major* Sr isotope variations in the volcanic rocks of the Roman Province are clearly a result of fairly recent mixing processes (*e.g.*, HURLEY *et al.*, 1966) in the upper mantle source regions of these magmas, as typified by the Continental Mantle Mixing Line (CMML) of FERRARA *et al.* (1985), shown in Figs. 8 and 9.

Except for the emphasis on AFC processes instead of simple closed-system fractional crystallization,

our new data fit nicely with most earlier conclusions by APPLETON (1972), CORTINI and HERMES (1981), and by HAWKESWORTH and VOLLMER (1979) concerning the origin of these magmas; the new data are also in thorough agreement with our previous results from other areas of the Roman Province (FERRARA *et al.*, 1985, 1986; TAYLOR *et al.*, 1987; TURI *et al.*, 1986). Our conclusions are, however, incompatible with certain conclusions of HOLM and MUNKSGAARD (1982), PECCERILLO (1985), PECCERILLO and MANETTI (1985), and VOLLMER (1989), as follows:

(1) We believe that the $\delta^{18}\text{O}$ values of the *primitive* HKS and LKS parent magmas at each volcanic center in Italy are quite low, typically +5.5 to +7.0. Although some of these magmas may begin the ascent from their mantle source regions with a $\delta^{18}\text{O}$ as high as $+7.5 \pm 0.3$, we can pretty well rule out the existence of *any* primary HKS or LKS magmas with $\delta^{18}\text{O} > +8.0$.

(2) In contrast to the *primitive* HKS and LKS magmas, which are actually quite rare as erupted products in Italy, the $\delta^{18}\text{O}$ values of the much more abundant, *evolved* (*i.e.*, fractionated) HKS and LKS magmas *commonly* have $\delta^{18}\text{O}$ values higher than +7.0, locally going up to +12.0 in the northernmost centers. These ^{18}O -enrichments correlate with major-element changes (*i.e.*, CaO depletion and K_2O and SiO_2 enrichment) which essentially all workers except VOLLMER (1989) agree must have been produced by fractional crystallization in *crustal* magma chambers (perhaps at about 4 to 13 km depth, based on fluid inclusion data at Somma-Vesuvius; BELKIN *et al.*, 1985). In some cases, fragments torn loose from the crystallized margins of these crustal magma chambers and erupted in pyroclastic deposits have extremely high $\delta^{18}\text{O}$ values (+9 to +11 at Roccamonfina, TAYLOR *et al.*, 1979; +12.6 for clinopyroxene from a biotite-pyroxenite nodule at the Alban Hills, BARBIERI *et al.*, 1975). Inasmuch as the ^{18}O enrichments in these nodules and in the fractionated lavas *cannot* be produced by closed-system magma processes, all of these chemical and isotopic changes must be a result of some type of AFC process such as was modelled by TAYLOR *et al.* (1979) and TAYLOR (1980), or to mixing with crustally derived anatectic magmas (*e.g.*, TAYLOR and TURI, 1976).

(3) The alkali-rich, *evolved* LKS magmas from the southwestern-most volcanic centers (Ischia, Pontine Islands) typically have much lower $\delta^{18}\text{O}$ values and higher Na/K ratios than the petrologically analogous magmas found onshore in central

Italy. This correlates with the fact that these centers are all on islands located off the Italian coast, away from the continental crust. However, in the northernmost Pontine Islands, where continental basement is locally exposed, we encounter some high- ^{18}O rhyolites analogous to those of the Tuscan Province.

(4) The oxygen-isotopic systematics delineated in Italy prove that there has been a grand-scale mixing between the low- ^{18}O , low- SiO_2 , mantle-derived primitive potassic magmas and a high- ^{18}O reservoir that may be readily identified as the continental crust of peninsular Italy. This identification is based on the geographic relationship described above (Fig. 9), and on the fact that the mixing process that increased the $\delta^{18}\text{O}$ values of these evolved magmas occurred during fractional crystallization within the crust, not in the upper mantle. Because the continental basement rocks have $^{87}\text{Sr}/^{86}\text{Sr}$ even higher than the HKS end member (*i.e.*, >0.725 , see Figs. 7 and 8), the $^{87}\text{Sr}/^{86}\text{Sr}$ signatures also permit a similar interpretation, particularly to the north of Rome, and particularly for the LKS magmas (FERRARA *et al.*, 1986; ROGERS *et al.*, 1985) as these tend to have lower $^{87}\text{Sr}/^{86}\text{Sr}$ and lower ppm Sr contents than the HKS magmas. The isotopic signature of this high- ^{18}O , high- ^{87}Sr component becomes much less apparent to the south along the Italian peninsula, and southwestward from the coast, presumably because of a lower $\delta^{18}\text{O}$ and lower $^{87}\text{Sr}/^{86}\text{Sr}$ in the offshore transitional crust, as well as because of systematic changes to the south and to the west in the average temperature and/or the thickness of the Italian continental crust. In this connection, we note that crustal thinning, oceanization, and uplift of the isogeotherms apparently took place in areas adjacent to the Tyrrhenian abyssal plain since Miocene time (SCANDONE, 1979). It is well known that crustal assimilation and AFC processes are greatly enhanced by an increase in either the temperature or the thickness of the crust (TAYLOR *et al.*, 1979; TAYLOR, 1980; DE PAOLO, 1981; TAYLOR and SHEPPARD, 1986).

(5) We agree in general with APPLETON (1972) and CUNDARI (1980) that the geochemical differences between the primitive HKS and LKS magmas are very likely a result of different degrees of potassium metasomatism combined with a low percent of partial melting of the upper mantle source rocks of these magmas. However, two distinct mantle source regions are required, and the LKS source region in particular may be related to a unique, recent subduction event (see below). The metasomatic fluids that produced the HKS source region were remarkably rich in K, Ba, Sr, rare earths,

and other incompatible elements, as well as in H_2O and other volatile constituents such as CO_2 , F, etc.; they also came from a time-integrated, Rb-enriched source region, and thus had high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that show a positive correlation with the level of K and Sr enrichment. These HKS $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were homogenized at an astonishingly uniform value of 0.710 to 0.711 over a wide area northwest from M. Ernici and the Alban Hills for at least 120 km, all the way to M. Vulsini. In agreement with CORTINI and HERMES (1981) and HAWKESWORTH and VOLLMER (1979), we have argued that this ^{87}Sr enrichment event was a fairly recent phenomenon (FERRARA *et al.*, 1985, 1986; TAYLOR *et al.*, 1987). By lowering the melting points of the mantle rocks, the event that introduced the H_2O -rich and CO_2 -rich metasomatic fluids may have been the "trigger" that initiated widespread melting in the upper mantle beneath Italy during the past million or so years.

(6) Prior to or during mantle metasomatism, both K-rich source regions in the upper mantle became slightly ^{18}O -enriched relative to MORB-type ($\delta^{18}\text{O} = +5.5$ to $+5.9$) source regions. Whether or not these slight ^{18}O enrichments are attributable to the metasomatic event, we cannot say, but the primary HKS magmas in Italy are locally as ^{18}O -enriched (up to $+7.5$ or $+8.0$?) as any that can be proven to be derived from ultramafic mantle anywhere in the world. Similar levels of metasomatic ^{18}O -enrichments have actually been observed in mantle nodules brought up in kimberlites and other alkalic volcanic rocks (KYSER *et al.*, 1982; GREGORY and TAYLOR, 1986a,b), and it is now well established that alkali-rich basaltic magmas in general are slightly enriched in ^{18}O (*e.g.*, $+6.0$ to $+6.5$, see KYSER, 1986). A slight degree of enrichment in ^{18}O seems to be a common characteristic that goes hand-in-hand with alkali enrichment in mafic igneous rocks, including most ultrapotassic volcanic rocks (TAYLOR *et al.*, 1984). Although it is difficult to look backward through all of the other ^{18}O -enrichment and fractionation events that have later been superimposed upon most of these potassic magmas, the $^{18}\text{O}/^{16}\text{O}$ ratio of the primitive LKS end member ($\delta^{18}\text{O} \sim +6$?) is almost certainly a little lower than that of the HKS end member ($\delta^{18}\text{O} \sim +7$?). For example, this difference can be observed directly in the positions of the Ernici LKS and HKS fields on Fig. 7. Also, some of the most Ca-rich M. Vulsini and Alban Hills HKS lavas have $\delta^{18}\text{O} \geq +7$ (FERRARA *et al.*, 1985, 1986), and the level of ^{18}O enrichment in the LKS samples at Ischia and Procida (Fig. 7) is distinctly lower than in the nearby HKS samples at Vesuvius. Thus, the HKS end member

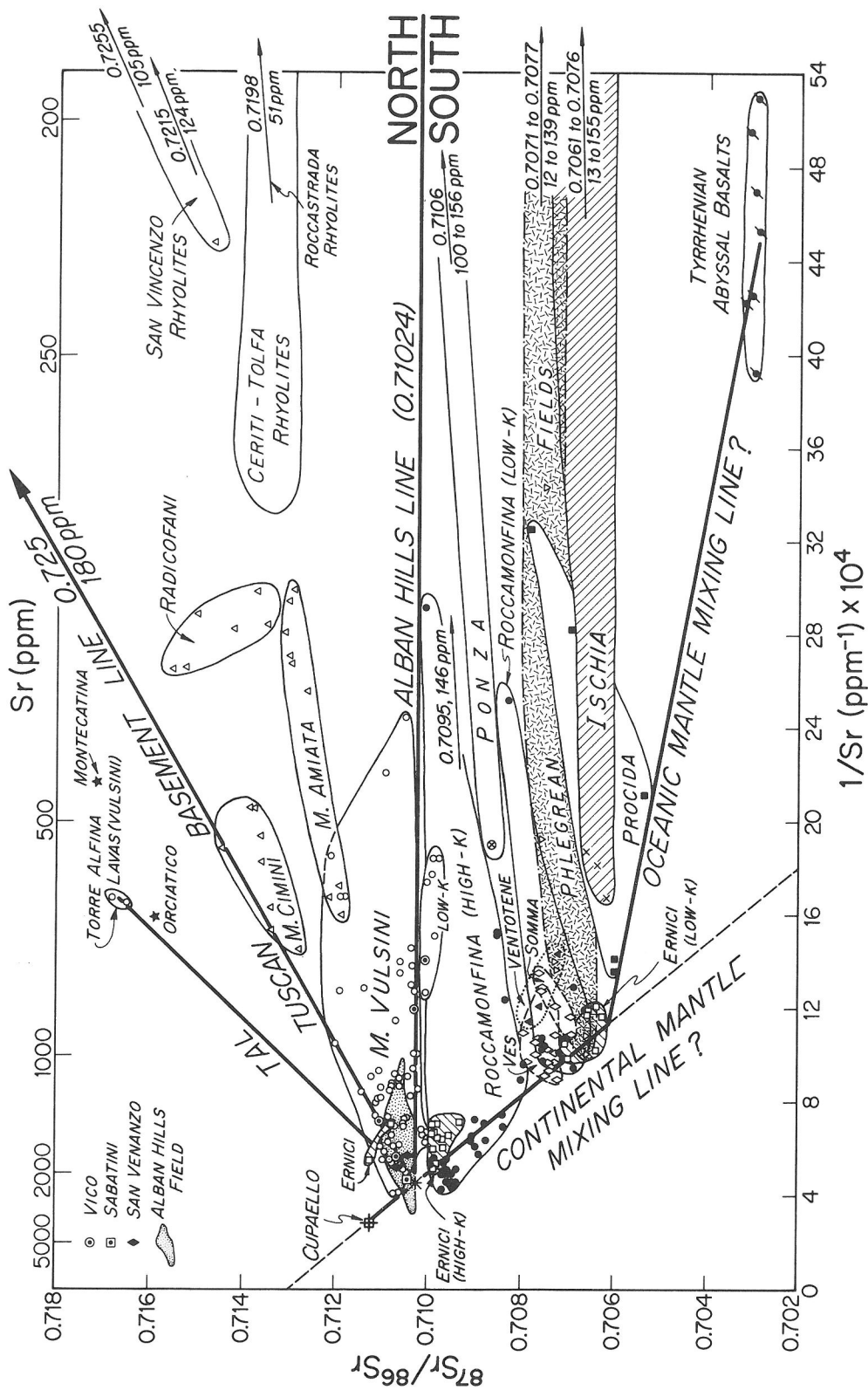


FIG. 8. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr} (\text{ppm}^{-1} \times 10^4)$ comparing data for samples analyzed in this work with previous data from other localities in Italy (for definitions of the major boundaries shown, and an indication of the $^{18}\text{O}/^{16}\text{O}$ variations in these same samples, see Fig. 9). The isotopic data plotted above are from the present work, from our own unpublished work, from Ferrara *et al.* (1985, 1986), and from a variety of other studies given in the list of references.

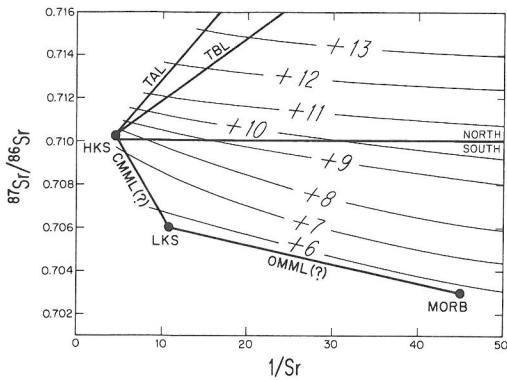


FIG. 9. Schematic plot of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}$ ($\text{ppm}^{-1} \times 10^4$) showing the major boundaries described in Fig. 8, together with generalized whole-rock $\delta^{18}\text{O}$ contours for the volcanic rocks of Italy. The major boundaries shown by the heavy lines are defined as follows: (1) the horizontal line at 0.71024 separates the HKS-dominated lavas and pyroclastics north of and including the Alban Hills from the LKS-dominated volcanics to the south; (2) the CMML is the continental mantle mixing line defined by Ferrara *et al.* (1985), and connects the primitive HKS and LKS end members; (3) the upper diagonal lines connect the HKS end member with two types of typical Tuscan basement (TAL, Torre Alfina Line; TBL, Tuscan Basement Line); (4) the lowermost diagonal line (OMML) is an oceanic mantle mixing line connecting the LKS primitive end member with the MORB-type basalts of the Tyrrhenian Sea.

is much higher in $^{87}\text{Sr}/^{86}\text{Sr}$, but only slightly higher in $\delta^{18}\text{O}$, than the LKS end member; *both* are strongly enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ and slightly enriched in ^{18}O compared to typical MORB samples.

(7) All of the magmas produced in Italy during the past five million years can be explained by mixing between the HKS and LKS parental end members and two other components: a continental metasedimentary basement end member and a MORB(?) type end member similar to the source of the abyssal lavas of the Tyrrhenian Sea. Each of the volcanic centers in Italy occupies a well-defined position on a $^{87}\text{Sr}/^{86}\text{Sr}$ versus $1/\text{Sr}$ diagram (Fig. 8), lying within a quadrilateral bounded by the CMML, an LKS-MORB line, and a line between the HKS end member and the average Tuscan basement; these boundaries are also shown in Fig. 9, along with generalized $\delta^{18}\text{O}$ contours. The fourth side of the quadrilateral is represented by the limit of very low ppm Sr values in the most fractionated lavas at each center. A horizontal line at $^{87}\text{Sr}/^{86}\text{Sr} = 0.71024$ (Figs. 8 and 9) neatly divides the low- ^{18}O , low- $^{87}\text{Sr}/^{86}\text{Sr}$ centers south of the Alban Hills (which are dominated by LKS magmas) from the higher- ^{18}O , higher $^{87}\text{Sr}/^{86}\text{Sr}$ centers to the north (which are dominated by HKS magmas).

(8) We now turn to the subducted-sediment theory of origin of the potassic Roman magmas (*e.g.*, BECCALUVA *et al.* 1991; PECCERILLO, 1985; ROGERS *et al.*, 1985; ELLAM *et al.*, 1989). One of the earliest formulations of this concept (THOMPSON, 1977) was based on the combined high $\delta^{18}\text{O}$ and high $^{87}\text{Sr}/^{86}\text{Sr}$ values discovered in the Roman magmas by TURI and TAYLOR (1976). Although the high $\delta^{18}\text{O}$ signatures indicate beyond doubt that these sedimentary or metasedimentary rocks were *somehow* involved in the genesis of these magmas, we believe we have demonstrated conclusively that the *major* ^{18}O enrichments were produced within the continental crust, not in the upper mantle; thus, these $\delta^{18}\text{O}$ effects are not attributable to *subducted* sediments (unless that subduction process was a shallow one that simply involved a doubling of the continental crust, as has been suggested for central-southern Italy by SCANDONE, 1979). Interactions between mantle-derived magmas and such a tectonically thickened crust are a perfectly feasible way to explain most of our isotopic data, but it is clear that most of the workers who favor involvement of subducted sediments are not referring to such a process.

Although the mantle-derived, primary HKS and LKS magmas in Italy are slightly enriched in ^{18}O and markedly enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ relative to MORB, they are *not* markedly enriched in either ^{18}O or $^{87}\text{Sr}/^{86}\text{Sr}$ relative to other potassic magmas throughout the world (VOLLMER and NORRY, 1983; COLLERSON and MCCULLOCH, 1983; TAYLOR *et al.* 1984; NELSON *et al.*, 1986; GARLICK, 1966; KYSER, 1986; KYSER *et al.*, 1982). The new data from the off-shore islands of Ischia, Ventotene, and Vulcano are particularly compelling in this regard. Therefore, based simply on the *isotopic* data, there is no more reason to invoke subducted sediments in the *source* regions of the potassic magmas beneath Italy than in any other areas of potassic volcanism. The enrichment of both ^{18}O and ^{87}Sr that is observed in virtually all potassic magmas on Earth may be (probably is?) related to ancient subduction events that recycled high- ^{18}O , LIL-enriched material into the upper mantle and changed the fundamental geochemical characteristics of the sub-continental lithosphere. However, this need have nothing to do with any *recent* subduction event, as favored by PECCERILLO (1985), ROGERS *et al.* (1985), and HOLM and MUNKSGAARD (1982). If there is sufficient evidence of another kind to require it, we would not quarrel with such an interpretation, but the very high $\delta^{18}\text{O}$ values of the Italian volcanic rocks should not be used as *evidence* for a recent

subduction event. In fact, we believe that the astonishingly uniform and elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7100 to 0.7110 exhibited by the HKS end member over a wide area in Italy are difficult to reconcile with a recent subduction event, which would probably be associated with much more heterogeneous and lower $^{87}\text{Sr}/^{86}\text{Sr}$ values. It is perhaps more plausible to relate just the LKS end member to the recent subduction event, although fluids derived from dehydration of the subducted material conceivably might also have contributed to the required metasomatic homogenization of the HKS source.

It seems to us that the primitive potassic magmas of Italy probably formed in an extensional tectonic environment more-or-less analogous to the way other potassic volcanic rocks on Earth seem to have formed. However, superimposed on these tectonic events (recent subduction? back-arc spreading? local pull-apart basins?) are a large number of complexities unique to the late Tertiary and Quaternary geology and geography of Italy. These produced two distinct "enriched" upper mantle reservoirs with unusual trace-element and radiogenic isotope patterns, in close proximity to the MORB-type reservoir that produced the basalts of the Tyrrhenian Sea. Subsequently, interactions between the continental crust and potassic magmas derived from the two different sub-continental reservoirs locally produced higher $\delta^{18}\text{O}$ values in the evolved potassic magmas than those seen anywhere else on Earth.

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REFERENCES

- ALBINI A., CRISTOFOLINI R., DI GIROLAMO P., NARDI G., ROLANDI G. and STANZIONE D. (1977) Rare earth element and thorium distribution in volcanic rocks of the potassic kindred from Procida Island and Phlegraean Fields, southern Italy. *Acc. Naz. Lincei Red. Cl. Sci. Fis. Mat. Nat.* **63**(5), 416–429.
- ALBINI A., CRISTOFOLINI R., DI GIROLAMO P. and STANZIONE D. (1980) Rare earth and other trace-element distribution in the calc-alkaline volcanic rocks from deep boreholes in the Phlegraean Fields, Campania (South Italy). *Chem. Geol.* **28**, 123–133.
- APPLETON J. D. (1972) Petrogenesis of potassium-rich lavas from the Roccamonfina Volcano, Roman Region, Italy. *J. Petrol.* **13**, 425–456.
- BARBERI F., BORSI S., FERRARA G. and INNOCENTI F. (1967) Contributo alla conoscenza vulcanologica e magmatologica delle isole dell' Arcipelago Pontino. *Mem. Soc. Geol. Ital.* **6**, 581–606.
- BARBIERI M., PENTA A. and TURI B. (1975) Oxygen and strontium isotope ratios in some ejecta from the Alban Hills volcanic area, Roman Comagmatic Region. *Contrib. Mineral. Petrol.* **51**, 127–133.
- BARBIERI M., PECCERILLO A., POLI G. and TOLOMEO L. (1988) Major, trace element, and Sr isotopic composition of lavas from Vico volcano (Central Italy) and their evolution in an open system. *Contrib. Mineral. Petrol.* **99**, 485–497.
- BARTON M., VAREKAMP J. C. and VANBERGEN M. J. (1982) Complex zoning of clinopyroxenes in the lavas of Vulcini, Latium, Italy: Evidence for magma mixing. *J. Volcanol. Geotherm. Res.* **14**, 361–388.
- BASILONE P. and CIVETTA L. (1975) Datazione K/Ar dell' attivita vulcanica dei Monti Ernici (Latina). *Rend. Soc. Ital. Mineral. Petrol.* **31**, 175–179.
- BECCALUVA L., DI GIROLAMO P. and SERRI G. (1991) Petrogenesis and tectonic setting of the Roman Volcanic Province, Italy. *Lithos* **26**, 191–221.
- BELKIN H. E., DE VIVO B., ROEDDER E. and CORTINI M. (1985) Fluid inclusion geobarometry from ejected Mt. Somma-Vesuvius nodules. *Amer. Mineral.* **70**, 288–303.
- CAPALDI G., CIVETTA L. and GILLOT P. Y. (1985) Geochronology of Plio-Pleistocene volcanic rocks from southern Italy. *Rend. Soc. Ital. Mineral. Petrol.* **40**, 25–44.
- CARMASSI M., DE RITA D., DE FILIPPO M., FUNICELLO R. and SHERIDAN M. F. (1987) Geology and volcanic evolution of the island of Ponza, Italy (unpubl. ms.).
- CHIVAS A. R., ANDREW A. S., SINHA A. K. and O'NEIL J. R. (1982) Geochemistry of a Pliocene-Pleistocene oceanic-arc plutonic complex, Guadalcanal. *Nature* **300**, 139–143.
- CIVETTA L., INNOCENTI F., MANETTI P., PECCERILLO A. and POLI G. (1981) Geochemical characteristics of potassic volcanics from Mts. Ernici (Southern Latium, Italy). *Contrib. Mineral. Petrol.* **78**, 37–47.
- COLLIERSON K. D. and McCULLOCH M. T. (1983) Nd and Sr isotope geochemistry of leucite-bearing lavas from Gaussberg, East Antarctica. *Proc. 4th Symp. Antarctic Earth Sci.*, 676–680.
- CORTINI M. and HERMES O. D. (1981) Sr isotopic evidence for a multi-source origin of the potassic magmas in the Neapolitan area (S. Italy). *Contrib. Mineral. Petrol.* **77**, 47–55.
- COX K. G., HAWKESWORTH C. J., O'NIONS R. K. and APPLETON J. D. (1976) Isotopic evidence for the derivation of some Roman region volcanics from anomalously enriched mantle. *Contrib. Mineral. Petrol.* **56**, 173–180.
- CUNDARI A. (1980) Role of subduction in the genesis of leucite-bearing rocks, facts or fashion? Reply to A. D. EDGAR'S discussion paper. *Contrib. Mineral. Petrol.* **73**, 432–434.
- DE PAOLO D. J. (1981) Trace element and isotopic effects

- of combined wall rock assimilation and fractional crystallization. *Earth Planet. Sci. Lett.* **53**, 189–202.
- ELLAM R. M., HAWKESWORTH C. J., MENZIES M. A. and ROGERS N. W. (1989) The volcanism of southern Italy: role of subduction and the relationship between potassic and sodic alkaline magmatism. *J. Geophys. Res.* **94**, 4589–4601.
- FERRARA G., LAURENZI M. A., TAYLOR H. P., JR., TONARINI S. and TURI B. (1985) Oxygen and strontium isotope studies of K-rich volcanic rocks from the Alban Hills, Italy. *Earth Planet. Sci. Lett.* **75**, 13–28.
- FERRARA G., PREITE-MARTINEZ M., TAYLOR H. P., JR., TONARINI S. and TURI B. (1986) Evidence for crustal assimilation, mixing of magmas, and a ^{87}Sr -rich upper mantle: An oxygen and strontium isotope study of the M. Vulsini volcanic area, Central Italy. *Contrib. Mineral. Petrol.* **92**, 269–280.
- FORNASERI M. and TURI B. (1969) Carbon and oxygen isotopic composition of carbonates in lavas and ejectites from the Alban Hills, Italy. *Contrib. Mineral. Petrol.* **23**, 224–256.
- GARLICK G. D. (1966) Oxygen isotope fractionation in igneous rocks. *Earth Planet. Sci. Lett.* **1**, 361–368.
- GREGORY R. T. and TAYLOR H. P., JR. (1986a) Non-equilibrium, metasomatic $^{18}\text{O}/^{16}\text{O}$ effects in upper mantle mineral assemblages. *Contrib. Mineral. Petrol.* **93**, 124–135.
- GREGORY R. T. and TAYLOR H. P., JR. (1986b) Possible non-equilibrium $^{18}\text{O}/^{16}\text{O}$ effects in mantle nodules, an alternative to the Kyser-O'Neil-Carmichael $^{18}\text{O}/^{16}\text{O}$ geothermometer. *Contrib. Mineral. Petrol.* **93**, 114–119.
- HAWKESWORTH C. J. and VOLLMER R. (1979) Crustal contamination versus enriched mantle: $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ evidence from Italian volcanics. *Contrib. Mineral. Petrol.* **69**, 151–165.
- HOLM P. M. and MUNKSGAARD N. C. (1982) Evidence for mantle metasomatism: An oxygen and strontium isotope study of the Vulsinian District, central Italy. *Earth Planet. Sci. Lett.* **60**, 376–388.
- HURLEY P. M., FAIRBAIRN H. W. and PINSON W. H. (1966) Rb-Sr isotopic evidence on the origin of potash-rich lavas of western Italy. *Earth Planet. Sci. Lett.* **1**, 301–306.
- KYSER T. K. (1986) Stable isotope variations in the mantle. In *Stable Isotopes in High-Temperature Geological Processes* (eds. J. W. VALLEY, H. P. TAYLOR JR. and J. R. O'NEIL); *Reviews in Mineralogy* **16**, pp. 141–164. Mineralogical Society of America.
- KYSER T. K., O'NEIL J. R. and CARMICHAEL I. S. E. (1982) Genetic relations among basic lavas and ultramafic nodules: evidence from oxygen isotope compositions. *Contrib. Mineral. Petrol.* **81**, 88–102.
- MATSUHISA Y. (1979) Oxygen isotopic compositions of volcanic rocks from the East Japan island arcs and their bearing on petrogenesis. *J. Volcanol. Geotherm. Res.* **5**, 271–296.
- MUEHLENBACHS K. and BYERLY G. (1982) ^{18}O -enrichment of silicic magmas caused by crystal fractionation at the Galapagos spreading center. *Contrib. Mineral. Petrol.* **79**, 76–79.
- MUEHLENBACHS K. and CLAYTON R. N. (1972) Oxygen isotope studies of fresh and weathered submarine basalts. *Canadian J. Earth Sci.* **9**, 172–184.
- NELSON D. R., MCCULLOCH M. T. and SUN S. S. (1986) The origins of ultrapotassic rocks as inferred from Sr, Nd, and Pb isotopes. *Geochim. Cosmochim. Acta.* **50**, 231–245.
- PAROTTO M. and PRATURLON A. (1975) Geological summary of the Central Appennines. In *Structural Model of Italy* (eds. L. OGNIBEN, M. PAROTTO and A. PRATURLON); *C. N. R. Quaderni de "La Ricerca Scientifica"* **90**, pp. 257–311.
- PECCERILLO A. (1985) Roman comagmatic province (Central Italy): Evidence for subduction-related magma genesis. *Geology* **13**, 103–106.
- PECCERILLO A. and MANETTI P. (1985) The potassium-alkaline volcanism of central-southern Italy: A review of the data relevant to petrogenesis and geodynamic significance. *Trans. Geol. Soc. S. Africa* **88**, 379–394.
- RADICATI DI BROZOLO F., DI GIROLAMO P., TURI B. and ODDONE M. (1988) $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar dating of the K-rich volcanic rocks from the Roccamonfina volcano, Roman Comagmatic Region, Italy. *Geochim. Cosmochim. Acta.* **52**, 1435–1441.
- ROGERS N. W., HAWKESWORTH C. J., PARKER R. J. and MARSH J. S. (1985) The geochemistry of potassic lavas from Vulsini, central Italy and implications for mantle enrichment processes beneath the Roman region. *Contrib. Mineral. Petrol.* **90**, 244–257.
- SCANDONE P. (1979) Origin of the Tyrrhenian Sea and Calabrian arc. *Boll. Soc. Geol. Ital.* **98**, 27–34.
- SHEPPARD S. M. F. (1986) Igneous rocks: III. Isotopic case studies of magmatism in Africa, Eurasia, and oceanic islands. In *Stable Isotopes in High-Temperature Geological Processes* (eds. J. W. VALLEY, H. P. TAYLOR JR. and J. R. O'NEIL); *Reviews in Mineralogy* **16**, pp. 319–371. Mineralogical Society of America.
- SHEPPARD S. M. F. and HARRIS C. (1985) Hydrogen and oxygen isotope geochemistry of Ascension Island lavas and granites: Variations with crystal fractionation and interaction with sea water. *Contrib. Mineral. Petrol.* **91**, 74–81.
- TAYLOR H. P., JR. (1968) The oxygen isotope geochemistry of igneous rocks. *Contrib. Mineral. Petrol.* **19**, 1–71.
- TAYLOR H. P., JR. (1980) The effects of assimilation of country rocks by magmas on $^{18}\text{O}/^{16}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ systematics in igneous rocks. *Earth Planet. Sci. Lett.* **47**, 243–254.
- TAYLOR H. P., JR. and EPSTEIN S. (1962) Relationship between $^{18}\text{O}/^{16}\text{O}$ ratios in coexisting minerals of igneous and metamorphic rocks. Part I: Principles and experimental results. *Bull. Geol. Soc. Amer.* **73**, 461–480.
- TAYLOR H. P., JR. and SHEPPARD S. M. F. (1986) Igneous rocks: I. Processes of isotopic fractionation and isotope systematics. In *Stable Isotopes in High-Temperature Geological Processes* (eds. J. W. VALLEY, H. P. TAYLOR JR. and J. R. O'NEIL); *Reviews in Mineralogy* **16**, pp. 227–271. Mineralogical Society of America.
- TAYLOR H. P., JR. and TURI B. (1976) High- ^{18}O igneous rocks from the Tuscan magmatic province, Italy. *Contrib. Mineral. Petrol.* **55**, 33–54.
- TAYLOR H. P., JR., GIANNETTI B. and TURI B. (1979) Oxygen isotope geochemistry of the potassic igneous rocks from the Roccamonfina volcano, Roman Comagmatic region, Italy. *Earth Planet. Sci. Lett.* **46**, 81–106.
- TAYLOR H. P., JR., TURI B. and CUNDARI A. (1984) $^{18}\text{O}/^{16}\text{O}$ relationships in leucite-bearing volcanic rocks from New South Wales, Australia, Birunga, Africa, and San Venanzo-Cupaello, Italy. *Earth Planet. Sci. Lett.* **69**, 263–275.
- TAYLOR H. P., JR., GREGORY R. T. and TURI B. (1987) $^{18}\text{O}/^{16}\text{O}$ evidence for fluid-rock interaction in the upper

- mantle: Data from ultramafic nodules and K-rich volcanic rocks in Italy. In *Chemical Transport in Metasomatic Processes* (ed. H. C. HELGESON); *NATO ASI Series C 218*, pp. 1–37. D. Reidel.
- TAYLOR H. P., JR., FERRARA G., TURI B. and TONARINI S. (1991) Comparisons of $^{18}\text{O}/^{16}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ in volcanic rocks from the Tuscan Igneous Province with other areas in Italy (in prep).
- THOMPSON R. N. (1977) Primary basalts and magma genesis. III. Alban Hills, Roman comagmatic province, Central Italy. *Contrib. Mineral. Petrol.* **50**, 91–108.
- TURI B. and TAYLOR H. P., JR. (1976) Oxygen isotope studies of potassic volcanic rocks of the Roman Province, Central Italy. *Contrib. Mineral. Petrol.* **55**, 1–31.
- TURI B., TAYLOR H. P., JR. and FERRARA G. (1986) A criticism of the Holm-Munksgaard oxygen and strontium isotope study of the Vulsinian District, Central Italy. *Earth Planet. Sci. Lett.* **69**, 447–453.
- TURI B., TAYLOR H. P., JR., FERRARA G., MARTINEZ M. P., TONARINI S. and DI GIROLAMO P. (1991) $^{18}\text{O}/^{16}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ Ratios in volcanic rocks from the Pontine Islands, M. Ernici, and Campania, Italy. *Lithos* (in press).
- VAREKAMP J. C. and KALAMARIDES R. I. (1989) Hybridization processes in leucite tephrites from Vulcini, Italy, and the evolution of the Italian potassic units. *J. Geophys. Res.* **94**, 4603–4618.
- VEZZOLI L. (1988) Island of Ischia. *Quaderni de "La Ricerca Scientifica." Progetto Finalizzato Geodinamica, Monografie Finali* **10**, 133 pp. C.N.R., Roma.
- VOLLMER R. (1976) Rb-Sr and U-Th-Pb systematics of alkaline rocks: The alkaline rocks from Italy. *Geochim. Cosmochim. Acta* **40**, 283–295.
- VOLLMER R. (1989) On the origin of the Italian potassic magmas 1. A discussion contribution. *Chem. Geol.* **74**, 229–239.
- VOLLMER R. and NORRY M. J. (1983) Possible origin of K-rich volcanic rocks from Virunga, East Africa, by metasomatism of continental crustal material: Pb, Nd and Sr isotopic evidence. *Earth Planet. Sci. Lett.* **64**, 374–386.