Comparisons of $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ in Volcanic Rocks
From the Pontine Islands, M. Ernici, and Campania
With Other Areas in Italy*

Bruno Turi¹, Hugh P. Taylor, Jr.², Maria Preite Martinez¹,
Giorgio Ferrara³, and Pio Di Girolamo⁴

¹ Dipartimento Di Scienze Della Terra, Universita' La Sapienza, P.Le A. Moro-00100 Roma, Italy

² Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, U.S.A.

³ Istituto Di Geocronologia e Geochemica Isotopica, C.N.R., V. Cardinale Maffi 36, 56100 Pisa, Italy

⁴ Dipartimento Di Scienze Della Terra, Universita' Di Napoli, Via Mezzocannone, 8-80134 Napoli, Italy

*Contribution No. 3144, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125.
New $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ data dramatically confirm and extend the systematic regional isotopic and geographic correlations observed in the Quaternary lavas from Italy: (1) The $\delta^{18}O$ values of the rare, primitive (high-Ca) potassic parent magmas are relatively low, +5.5 to +7.5. (2) The much more abundant evolved (fractionated) magmas have a wide range of $\delta^{18}O$ (+6.0 to +13.0), with the SW centers (Ischia, Pontine Is., Procida) having much lower $\delta^{18}O$ (<+8.0) than elsewhere in Italy. (3) At a given center, the $^{18}O$-enrichments correlate with major-element changes (i.e. CaO depletion and K$_2$O and SiO$_2$ enrichment) attributable to fractional crystallization in crustal magma chambers (4 to 13 km depth?); because the $^{18}O$ enrichments cannot be produced in a closed-system, the data imply that AFC processes operated, particularly to the north, where they are enhanced by a dramatic increase in the temperature of the crust (due to the 0-7 Ma Tuscan anatectic event). (4) $^{87}Sr/^{86}Sr$ and Sr ppm in the primitive magmas define a Continental Mantle Mixing Line (CMML) (Ferrara et al., 1985) involving two end members, a low-K (LK), low-Sr type with $^{87}Sr/^{86}Sr$ ~ 0.7060, and a high-K (HK), high-Sr type with $^{87}Sr/^{86}Sr$ ~ 0.7110. (5) All of the potassic magmas can be explained by mixing between the HK and LK end members and two other end members: (a) a continental metasedimentary basement and (b) a MORB(?)-type component like the abyssal lavas of the Tyrrhenian Sea. Each of the volcanic centers in Italy occupies a well-defined position on a $^{87}Sr/^{86}Sr$ vs. 1/Sr diagram, lying within a quadrilateral bounded by the CMML, an LK-MORB line, and a line between the HK end member and the average Tuscan basement. 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. Another line at $^{87}Sr/^{86}Sr$ = 0.7100 divides the low-$^{18}O$, low-$^{87}Sr/^{86}Sr$ centers south of the Alban Hills from the higher-$^{18}O$ centers to the north.
1. INTRODUCTION

The purpose of this paper is to extend our knowledge of the oxygen and strontium isotope geochemistry of the Pleistocene and Holocene potassic volcanic rocks of central-southern Italy, building upon previous studies by 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).

The new localities studied in this paper 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 number of new samples were also analyzed from on-shore centers in Campania (Roccamonfina, Phlegrean Fields, Vesuvius, and Parete), as well as single samples from the more distant centers of Vulcano in the Aeolian Islands, Vulture in the southern Appennines, and from P. Pietre Nere in the Gargano peninsula on the Adriatic coast (Fig. 1). The Vulcano sample represents the southernmost occurrence of a leucite-bearing volcanic rock in Italy, and the latter two samples were studied because they are alkalic igneous rocks that Vollmer (1976) considered to be important end-members in that they have unusual Pb isotopic compositions and are also among the lowest $^{87}$Sr/$^{86}$Sr samples of any volcanic rocks from central Italy. Vulture conceivably could be a distant extension of the Roman Province. The Pietre Nere sample is a mafic alkali syenite that is much older (56 Ma) than the above-mentioned potassic rocks, and also located in a different geodynamic environment (Di Girolamo, 1987).

The Pontinian Archipelago is made up of five major volcanic islands situated just to the west of the southern (Campanian) part of the potassic
Roman volcanic province (Figs. 1 and 2). The rock types range from trachybasalt and phonolite (Ventotene, S. Stefano) to rhyolite and trachyte (Ponza, Palmarola, Zannone). Leucite-bearing rocks have been described only from Ventotene (Beccaluva et al. 1984), and they are very rare on that island. About 35 km ESE of the southernmost Pontine Islands are the islands of Ischia and Procida, which form the western portion of the Phlegraean Fields volcanic district (Fig. 2). At Procida the rocks are mainly trachybasalts with some analcimized leucite-bearing rocks, whereas at Ischia there is a wide variety of volcanic rocks ranging from sodalite phonolite, latite, and trachyte to trachyandesite and rare trachybasalt. No leucite-bearing rocks have yet been found on Ischia. Di Girolamo (1978; 1987) has proposed that all of the above-described volcanic centers along the Tyrrhenian border may be products of a converging plate margin (shoshonitic, calc-alkaline, and leucitite-leucite basanite associations).

The oldest products of the Pontine Archipelago have K/Ar ages of about 4-5 Ma (Barberi et al., 1967; Savelli, 1983), definitely older than those from all the centers of the Quaternary Roman Region. However, Ischia is much younger, with the earliest volcanic rocks being only about 130,000 years old (see Capaldi et al. 1985, and references therein). At Ischia and in the adjoining centers of Vesuvius and the Phlegraean Fields the volcanic activity continued up to historical times. Thus, there is a general indication of an eastward migration of the magmatism in this area since Pliocene time (Barbieri et al. 1979), analogous to the trend observed to the north of the Roman Region in Tuscany, where the offshore islands (K/Ar ages: 9.5 to 5 Ma) are generally older than the continental igneous rocks of the Tuscan Magmatic Province (5.7 to 0.43 Ma, Borsi et al., 1967; Nicoletti et al., 1981).
One of the concepts to be addressed in the present study is to determine the broad regional geochemical relationships among all these volcanic centers, as well as whether any genetic relationship exists among the SiO₂-undersaturated to oversaturated lavas of the offshore islands and the abundant SiO₂-undersaturated volcanic rocks of the Roman and Campanian Regions. According to Rittmann (1930, 1962), the volcanic rocks from Ischia and Procida are considered to be an extension of the Campanian volcanic fields; the neighborhood of Ischia may have been part of the mainland in late Tertiary time. Another interesting problem is the nature of the petrographic transition from southeast to northwest in the Pontine Islands group. The northwesterly islands contain rhyolites, suggesting a possible genetic link with Plio-Pleistocene rhyolitic Tuscan magmas farther to the north (Barberi et al., 1967; Taylor and Turi, 1976). Alternatively, these rhyolites might be related to the calc-alkaline andesitic lavas observed in drill holes in Campania (Di Girolamo et al. 1976).

2. REGIONAL PETROLOGICAL RELATIONSHIPS

Appleton (1972) used K₂O-SiO₂ 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. The HKS are strongly undersaturated leucitites, leucite tephrites, and leucite phonolites, with K₂O = 4 to 11 wt. %, K₂O/Na₂O = 3 to 5, and Al₂O₃ = 16 to 20 wt. %. The LKS rocks are trachybasalts, latites, and trachytes that are usually just slightly over- or just slightly undersaturated with respect to SiO₂. They typically have K₂O = 1-3 wt. % and K₂O/Na₂O = 0.5-1.5.

The LKS volcanic rocks are very abundant south of the Alban Hills, being common at Ernici, Roccamonfina, the Pontine Islands, and the Phlegraean Fields (Fig. 1). Except for minor occurrences at M. Vulsini, the LKS is virtually
non-existent north of M. Ernici. LKS rocks have not yet been identified at
the Alban Hills, M. Sabatini, or at Vico, which seem to be composed almost
exclusively of HKS lavas and pyroclastics. However, LKS volcanic rocks 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). HKS volcanic rocks are found in association with LKS rocks at Ernici,
Roccamonfina, Somma-Vesuvius, and the Aeolian Islands, as well as at M.
Vulsini, where they are much more abundant than the LKS rocks.

In addition to the High-K Series and Low-K Series, of Appleton (1972),
two other much less abundant potassic volcanic rock types have recently been
singled out as separate classes within the Roman Province: (1) the San Ven-
anzo-Cupaello localities and (2) the Torre Alfina, Orciatico, and Montecatini
localities. All of these localities are in north-central Italy (Fig. 1);
Peccerillo and Manetti (1985) and Civetta et al. (1987) classified the San
Venanzo-Cupaello rocks as having kamafugitic affinities (KAM) and the other
group of rocks as orenditic (OR). The KAM are ultramafic, extremely
undersaturated in SiO₂, and contain normative larnite and kalsilite. They
have SiO₂ = 41 to 44 wt. %, and have higher K₂O/Na₂O and much lower Al₂O₃ and
Na₂O than the HKS volcanic rocks. The OR are intermediate in SiO₂ content
(55-58 wt. %), have a relatively high K₂O/Na₂O ratio (> 5), and are commonly
as Mg-rich as the most primitive HKS magmas (Mg number = 70 to 78).

3. GEOLOGICAL RELATIONSHIPS

3.1 Pontine Islands

The Pontine Islands (Fig. 2) 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 may be divided
into two geologically and geographically distinct groups, a northwestern group (Ponza, Palmarola and Zannone) and a southeastern group (Ventotene and S. Stefano). These islands lie along a lineament that trends subparallel to the Italian coast, intersecting the mainland at the Gulf of Naples. The Island of Ischia is situated in approximately the same lineament (Fig. 2). South of this lineament, the crust of the Tyrrhenian basin is as little as 10 km thick (Giese and Morelli, 1975).

In the southeastern Pontine Islands, the volcanic activity was dominantly subaerial and produced trachybasaltic (at Ventotene) to phonolitic (at S. Stefano) lava flows and pyroclastics. K/Ar age measurements of these rocks range from 1.7 to 2 Ma, respectively (Barberi et al., 1967). However, more recent K/Ar measurements by Santacroce et al. (unpubl. manuscript), quoted in Fornaseri (1985), give much younger ages ranging from 0.81 to 0.48 Ma for the pre-caldera activity at Ventotene. According to these authors, the youngest (post-caldera) shoshonitic products at Ventotene would only be about 0.2 m.y. old. A leucite-basanite lava flow has been recently recognized at the top of the shoshonitic sequence of this island; leucite-bearing xenoliths also occur in the pyroclastic products (Beccaluva et al., 1984).

Two types of volcanic rocks are identified on Ponza, which is the largest of the northwestern Pontine Islands. These are an older rhyolitic series and a younger group of SiO₂-undersaturated trachytic rocks, each erupted at different times and at different locations. The early rocks on Ponza are rhyolites and rhyodacites emplaced in a submarine environment on the northern and central parts of the island (Carmassi et al., 1987); K/Ar dating gives ages of 4.6 to 5.0 Ma for the lavas and 1.9 Ma for a dike (Barberi et al., 1967). Analogous volcanic activity occurred on the adjacent island of Palmarola (intrusion of a sodic rhyolite dome with a K/Ar age of 1.6 to 1.7
Ma). More recent K/Ar dating (Savelli, 1983) indicates that the rhyolitic dikes at Ponza are essentially coeval with the felsic host rocks, and that all the rocks are about 2 to 5 m.y. old. The youngest stage of volcanic activity at Ponza was dominantly trachytic and subaerial; this activity was confined to the southern part of the island, where it produced the M. La Guardia trachytic dome (K/Ar age: 1.1 to 1.2 Ma, Barberi et al., 1967).

The bulk of the Island of Zannone is rhyolite. However, the main feature of this northeasternmost member of the Pontinian Archipelago is that it is the only island where metamorphic rocks ("schistes lustres") and sedimentary rocks (Triassic dolomites and limestones and Paleogenic flysch) are found. These older rocks on Zannone are tentatively related to the basement rocks in Tuscany (Parotto and Praturlon, 1975).

3.2 Ischia

The Island of Ischia (Fig. 2) essentially consists of a volcano-tectonic horst made up of a 130,000 year old latitic and trachytic lava basement overlain by a thick (about 1000 m) alkali-trachyte pyroclastic flow (the "Green Tuff"); the latter was formed by a subaerial eruption about 55,000 years ago (Cassignol and Gillot, 1982; Gillot et al., 1982). Beach levels and the widespread occurrence of glauconite suggest that this formation sank below sea level after being erupted, and that it was then pushed upward again and broken up into large blocks (Capaldi et al., 1976; 1977). Mt. Epomeo, the highest point of the island (elevation 780 m), represents one edge of the tilted fault block of the horst.

The development of the horst was accompanied by volcanic activity at its periphery during the last 30,000 years; the latest eruption occurred in the year 1302 and produced a sodalite-alkali trachyte lava flow (the Arso flow). The chemical composition of the volcanic products at Ischia ranges from
olivine latite to alkali trachyte, these latter being dominant (Capaldi et al., 1985).

3.3 Procida

Although geographically and geologically linked by a NE-trending, deep-seated fault system to Ischia on the west and the Phlegrean Fields to the northeast (Fig. 2), the Island of Procida shows some unique petrographic features (see Albini et al., 1977, 1980, and references therein). The dominant volcanic rocks on Procida and in the Ischia Channel are trachybasalt, and these are scarce at both Ischia and the Phlegrean Fields. Subordinate amounts of trachyandesite, phonolite, trachyte, and analcimzed leucite-bearing rocks also occur. Except for an alkali-trachyte lava dome, almost all of the volcanic rocks from Procida are pyroclastic formations, which include hyaloclastites and large lava fragments of various types (Di Girolamo and Stanzione, 1973). These rocks have ages ranging from 40,000 to 14,000 years b.p. (Alessio et al., 1976), based on 14C dating of paleosols and carbonized wood.

3.4 Mts. Ernici

The Mts. Ernici or Media Valle Latina volcanic 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 and produced large amounts of pyroclastics and subordinate lava flows of both the High-K and Low-K Series between about 700 ± 20 and 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). Some of the HKS rocks have undergone a strong secondary alteration, which led to the transformation of leucite into analcime (Angelucci et al., 1974; Civetta et al., 1981).
3.5 Phlegraean Fields

The Phlegraean Fields are located just west of Naples and Vesuvius (Fig. 2). The beginning of the volcanic activity is not firmly established: the oldest outcropping products for which radiometric ages are available (pyroclastics and lavas, ranging in composition from trachyte to phonolitic trachyte) were erupted between about 45,000 and 35,000 years b.p. from a number of small centers, both subaerial and shallow submarine at the periphery of the area during the so-called pre-caldera phase of activity (see Capaldi et al., 1985; Rossi and Sbrana, 1987, and the references therein). However, xenoliths of leucite-bearing rocks are frequently found within the pyroclastic products of the Phlegraean Fields, as well as in those from the offshore islands of Procida and Ischia; this clearly indicates that the volcanic activity in this area certainly started before 50 Ka (Beccaluva et al., 1984).

About 33,000 years b.p., the huge eruption of the Campanian Ignimbrite (about 80 km³ of material, mostly composed of alkali-trachytyc products (Thunel et al., 1978) caused the collapse of the ancient volcanic area, producing a large caldera (about 14 km across) that was subsequently invaded by the sea. The post-caldera phase of activity has been subdivided into 4 stages (A, B, C, and D) on the basis of radiometric dating and paleogeographic evidence. This activity took place in both a subaerial and a submarine environment, and continued up until historical times (Monte Nuovo eruption, A.D. 1538). The products of the post-caldera phase include trachybasalt, latite, trachyte, and phonolitic alkali trachyte (Rossi and Sbrana, 1987, and references therein).

According to the above scheme, the samples analyzed in the present study can be classified as follows:
3.6 Somma-Vesuvius

Somma-Vesuvius is a composite strato-volcano (see Cortini and Hermes, 1981, and the references therein). The actual cone of M. Vesuvius (Fig. 2) was probably built up in the summit caldera of M. Somma since the Plinian eruption in the year 79. The volcanic activity is broadly contemporaneous with that of the nearby Phlegrean Fields, although Vesuvius has also been active in the last 300 years; the latest eruption occurred in the year 1944. According to Rittmann (1962), the early volcanic activity at Somma produced trachytic rocks; later, leucite phonolites, leucite tephrites and tephritic leucitites were erupted. Di Girolamo and Rolandi (1984) have suggested that the trachytic rocks in this area are derived from nearby centers in the Phlegrean Fields, and that the Somma activity is only of the leucitic type.

3.7 The Parete Area

The Parete area is located NW of Naples (Fig. 2), between the Tyrrhenian Sea and a series of sedimentary carbonates of Mesozoic age. Deep drilling of this potential geothermal area has encountered a 1,500 m thick series of hydrothermally altered, calc-alkaline, basaltic to andesitic rocks (Di Girolamo et al., 1976), covered by about 250 m of alkali-potassic pyroclastic products. K/Ar dating gives an age of about 2 Ma for the rock from the bottom of the no. 2 drill hole (sample PAR-2; Barbieri et al. 1979).

3.8 Roccamonfina

The Roccamonfina volcanic center (Figs. 1 and 2) is located 140 km SE of Rome and 50 km NW of Naples at the intersection of NW-trending and NE-trending fault systems, genetically related to extensional tectonism along the Tyrrenhian margin of the Italian Peninsula since the Late Miocene.
(Messinian). This partially dissected strato-volcano, presently about 1,000 m in elevation with an elliptical (5x7 km) central caldera, erupted large quantities of pyroclastics and lavas belonging to both the High-K Series and Low-K Series. $^{40}\text{Ar}/^{39}\text{Ar}$ and K/Ar dating of samples from both series give ages ranging from about 1.5 to 0.05 Ma (Capaldi et al., 1985; Radicati di Brozolo et al., 1987). Although the ages of the HKS and LKS overlap, the latter tend to be younger (typically < 0.5 Ma, Radicati di Brozolo et al., 1987). The latest products of the volcanism at Roccamonfina were erupted just prior to their being covered by the 33,000 year-old Campanian Grey Tuff (Campanian Ignimbrite) that outpoured from fissures located in the northern part of the Phlegrean Fields, about 50 km to the south. The new Roccamonfina samples studied in the present paper are the same samples used by Radicati di Brozolo et al. (1987) in their detailed age study.

3.9 M. Vulture - P. Pietre Nere

These volcanic centers are located far to the east of the Campanian volcanic area in the foreland of the Apennine chain (Fig. 1). The geology and the petrography of these centers have been studied by Burri (1959), Hieke-Merlin (1967), and De Fino et al. (1982). Most rocks from M. Vulture are leucite-bearing, and are much younger than the mafic alkali syenite outcropping at P. Pietre Nere (Vollmer, 1976), for which Rb-Sr measurements give an age of 56 Ma.

4. 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 $^{18}O/^{16}O$ data obtained on these samples are reported in Table 1 in the familiar $\delta$ notation; the reference standard is Standard Mean Ocean Water
(SMOW). The mineral separates were obtained by conventional techniques and their purity, checked by XRD, was found to be generally better than 95%. Except for the plagioclase separate from PAR-2, all minerals are very fresh with no evidence of significant alteration.

All measured δ¹⁸O values of volcanic rocks that have been hydrated under low-temperature Earth-surface conditions are suspect and cannot be directly used to given information about the original magmas (Taylor, 1968; Taylor et al., 1984). Therefore, we have followed two different procedures that we and other workers (e.g. Muehlenbachs and Byerly, 1982) have previously used to calculate the original primary δ¹⁸O values of the lavas: (1) Calculation of the whole-rock δ¹⁸O by measuring the δ¹⁸O values of coexisting phenocrysts, and then assuming an appropriate equilibrium ¹⁸O/¹⁶O fractionation factor (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 δ¹⁸O increase due to hydration (Fig. 3).

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. The least-squares correlation line from the Alban Hills used by Ferrara et al. (1985; 1986) is shown on Fig. 3, along with two new lines based on extremely hydrated samples from Ischia and Ponza (IS-6 and PO-402). For these two lavas we have made direct measurements of both the phenocrysts and the hydrated lava itself, and the "correction" lines determined in this way for IS-6 and PO-402 are even somewhat steeper than the one obtained for the Alban Hills lavas. 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 (Fig. 2). In all cases the "corrections" are less than 0.8
per mil, except for one sample from Somma (PFSV-16), one from Ponza (___), 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). Fortunately for comparative purposes, these hydration corrections are always unidirectional (i.e. they give results that are always lower than the measured $\delta^{18}O$ value; see Fig. 3).

5. CORRELATIONS BETWEEN CHEMICAL AND ISOTOPIC COMPOSITIONS

5.1 $K_2O$ vs. $SiO_2$

Our new data from Table 1 are plotted on Fig. 4, where they are compared with $K_2O$ and $SiO_2$ in samples from the other volcanic centers south of Rome studied for both $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ (Alban Hills--Ferrara et al., 1985; Roccamonfina--Taylor et al., 1979, Hawkesworth and Vollmer, 1979). Linear trends upward and to the right on diagrams like Fig. 4 were attributed by Appleton (1972) to fractional crystallization of alkali-rich, mantle-derived primary magmas ($SiO_2 = 44-47$ wt. %) having 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 (Fig. 4). Two of these groupings show a clear correspondence with the HKS and LKS of Appleton (1972), and the third corresponds closely with the rhyolites of the Tuscan Magmatic 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 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 3 samples from Roccamonfina, together with the Ernici HKS and Somma-Vesuvius samples.

The $^{18}\text{O}/^{16}\text{O}$ variations are shown on the $\text{K}_2\text{O}-\text{SiO}_2$ plot of Fig. 4 in several different ways. For some samples, the actual $\delta^{18}\text{O}$ value is lettered alongside the data point, but for others only the range of $\delta^{18}\text{O}$ of a group of samples is shown. The $\text{K}_2\text{O}-\text{SiO}_2$ variations at Roccamonfina are indicated by the stippled patterns, with the dashed contours at $\delta^{18}\text{O} = +7$, +8, and +9 showing how the $\delta^{18}\text{O}$ values of the Roccamonfina samples change with chemical composition (plotting of the 4 new samples from Table 1 did not require any modification of these systematic $\delta^{18}\text{O}-\text{K}_2\text{O}-\text{SiO}_2$ patterns originally delineated by Taylor et al., 1979). Note that the increase in $\delta^{18}\text{O}$ upward and to the right for these Roccamonfina samples is much too large to be ascribed to simple, closed-system fractional crystallization as envisioned by Appleton (1972); either these $^{18}\text{O}/^{16}\text{O}$ and chemical compositions are primary phenomena inherited from the upper mantle source regions of these magmas, or they are due to AFC processes, as strongly favored by Taylor et al. (1979).

Trachybasalts with $\text{SiO}_2 < 50$ wt. % are the most primitive members of the Low-K Series analyzed in this study, and together with the Mt. Etna alkali basalts, these samples plot at the low-$\text{SiO}_2$, low-$\text{K}_2\text{O}$ end of the Roccamonfina LKS field (Fig. 4). This sub-group includes 3 Procida samples, one Ernici sample, and all 3 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 $\text{K}_2\text{O}-\text{SiO}_2$ 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. 2), and the Ventotene and S. Stefano samples together define a trend of slight $^{18}\text{O}$-enrichment with increasing $\text{K}_2\text{O}$ and $\text{SiO}_2$ (Fig. 4).
The Ischia samples overlap the trends described above, but they are overall shifted downward and to the right (note that this shift is not because they are less rich in total alkalis; the lower K$_2$O 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 $\delta^{18}$O values at Ischia also show a slight increase upward and to the right on Fig. 4, but the most important feature of the data is that, compared with other samples having similarly high SiO$_2$ concentrations (54-64 wt. %), these Ischia samples have the lowest $\delta^{18}$O values of any Quaternary volcanic rocks in Italy.

The 4 Ponza samples and the geographically closely associated rocks from Palmarola are chemically and isotopically very heterogeneous. However, the Ponza group is readily divisible into (1) a couple of very high-SiO$_2$ rhyolites (73-75 wt. % SiO$_2$) that have very high $\delta^{18}$O values (+10.2 to +11.1), and (2) a couple of lower-$\delta^{18}$O, lower-SiO$_2$, alkalic rocks (a trachyte and a sodic rhyolite dike with $\delta^{18}$O = +7.0 to +7.4). The high-$\delta^{18}$O group is analogous to the anatectic rhyolites of the Tuscan Magmatic Province on the mainland, compatible with the occurrence of rocks similar to those of the Tuscan metamorphic basement on the adjacent island of Zannone. The nearby Palmarola rhyolites are isotopically very similar to this second, or low-$\delta^{18}$O group of Ponza samples. It is remarkable that rhyolitic rocks from such a small geographic area (Fig. 2) display such a large range in $\delta^{18}$O.

The new HKS samples from Roccamonfina also show some systematic relationships on Fig. 4. If the 3 samples are arranged in sequence, with SiO$_2$ and K$_2$O increasing, respectively, from 46.1 and 7.0, to 50.4 and 7.5, and finally to 60.1 and 9.6, the $\delta^{18}$O values can be seen to increase in the same order (+6.2 to +7.1 to +8.7). We also note that the lowest-$\delta^{18}$O sample (53R) is among the
youngest of the products of the Roccamonfina volcano (only 53,000 years old), as indicated in the detailed age study by Radicati di Brozolo et al. (1987).

The M. Ernici HKS samples overlap the Alban Hills field on Fig. 4, and both geochemically and geographically, these are the closest lavas to the Alban Hills (Fig. 1). Note that they also display a range of δ¹⁸O similar to that at the Alban Hills (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.

5.2 CaO vs. δ¹⁸O

On Fig. 5 we present a schematic diagram that shows the kinds of changes expected in CaO and δ¹⁸O during various magmatic processes that might be applicable to the Quaternary volcanic centers of Italy: closed-system fractional crystallization, combined assimilation-fractional crystallization (AFC), and simple mixing. Appleton (1972) and most subsequent workers have attributed great importance to the most Ca-rich and SiO₂-depleted lavas in the volcanic series of Italy, because these are among the best candidates for primitive magmas in the Roman Province. Although fractional crystallization of olivine and clinopyroxene will drive such magmas toward higher SiO₂ and K₂O (Appleton, 1972), thereby explaining much of the major element variation in these K-rich lavas (Fig. 4), this process cannot account for most of the isotopic variations (Taylor et al., 1979; Ferrara et al., 1985; 1986).

On a CaO-δ¹⁸O plot (Fig. 5), the above-described fractional crystallization process drives the more evolved magmas nearly horizontally off to the left toward lower CaO contents. As shown by Garlick (1966), Taylor (1968), Matsuhisa (1979), Muehlenbachs and Byerly (1982), Sheppard and Harris (1985), and Taylor and Sheppard (1986), there is probably a slight enrichment of δ¹⁸O
during such a closed-system process, but it will be very small for such high-
temperature magmas, certainly no more than 1 per mil and probably less than
0.5 per mil for the range of SiO₂ contents shown in Fig. 4. Thus, a diagram
like Fig. 5 can provide a sensitive test of closed-system fractional crystal-
lization.

Simple mixing curves are essentially straight lines on diagrams like Fig.
5, because the oxygen contents of most rocks and magmas are similar. Also,
for a specific pair of end members, processes of combined assimilation-
fractional crystallization (AFC, see Taylor, 1980) will also be essentially
straight lines at a given R value (ratio of cumulates to assimilated rock, see
Taylor and Sheppard, 1986). These AFC curves will thus lie at intermediate
positions between the closed-system fractional crystallization "line" and the
simple mixing line.

In order to place the new data from the present study in proper context,
on Fig. 6 we show how the δ¹⁸O values of lavas from other volcanic centers on
the Italian mainland change with CaO concentration. The two best-studied
volcanic centers that show the greatest range in CaO, and that also have erup-
ted 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).

Note that the most Ca-rich samples from both Roccamonfina and Vulsini
have relatively low δ¹⁸O values. Thus, both the CaO contents and the δ¹⁸O
values show "primitive" characteristics. However, with decreasing CaO, the
lavas of both volcanoes, but particularly those from M. Vulsini, display a
sharp increase of δ¹⁸O. Essentially all workers who have studied the Italian
volcanic rocks in any detail are in agreement that the trend of decreasing CaO
in the lavas at each of these volcanoes is a result of fractional crystalliza-
tion at relatively low pressures in a crustal magma chamber. The only way
that this strong consensus in favor of a relatively low-pressure fractional crystallization process can be reconciled with the $^{18}O/^{16}O$ data in Fig. 6 is to combine the process of fractional crystallization with a simultaneous and concurrent enrichment in $^{18}O$ due to assimilation of high-$^{18}O$ country rocks.

As shown on Fig. 6 and elaborated on in several recent papers (Taylor and Sheppard, 1986; Taylor et al., 1987; Ferrara et al., 1986), there are great geographic differences in Italy in the observed $^{18}O/^{16}O$ effects attributable to AFC processes. For example, the most Ca-rich lavas at both Vulsini and Roccamonfina have relatively low $\delta^{18}O$ values, but the more evolved magmas are consistently much richer in $^{18}O$ at Vulsini than at Roccamonfina (Fig. 6). Thus, although both volcanoes display CaO-$\delta^{18}O$ variations that can only be explained by some type of AFC process, the AFC processes at Vulsini for some reason produced much greater $^{18}O$ enrichments. Going back to our original papers on this problem (Turi and Taylor, 1976; Taylor and Turi, 1976), we have consistently 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 that widespread melting of the continental crust occurred. This melting produced the characteristic high-$^{18}O$ granites and rhyolites of the Tuscan Magmatic Province, some examples of which are also plotted on Fig. 6, namely the Ceriti-Tolfa rhyolites (Taylor et al., 1988). Mixing between these anatetic Tuscan magmas and the mantle-derived Roman magmas also was fairly widespread, particularly at the even more $^{18}O$-rich, hybrid M. Cimini center that lies just SE of, and is partially covered by, the products of the M. Vulsini center (Taylor and Turi, 1976).

Because of heat-balance considerations, the isotopic effects produced by AFC processes can be dramatically enhanced if the country-rock temperatures
are raised significantly above those characteristic of a normal geothermal gradient (Taylor, 1980). Although R values of 7 to 9 might be appropriate for "cold" wall rocks, R values as low as 1 to 3 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 Tuscan magmatic episode, but that south of Rome such activity 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 δ¹⁸O differences between the Vulsini and Roccamonfina magmas on Fig. 6 (compare with Fig. 5).

With the above discussion as background, on Fig. 7 we plot the CaO-δ¹⁸O relationships observed in the new samples analyzed in the present study. This diagram elaborates on certain features in the K₂O-SiO₂ plot (Fig. 4), including the correspondence between the Procida and the Ventotene-S. Stefano trends and the fact that on a CaO-δ¹⁸O plot the lavas from these islands plot between the Ischia field and the Vulsini field, and are coincident with the low-¹⁸O portion of the Roccamonfina HKS field. All of these trends project toward a possible primitive parent magma having a δ¹⁸O somewhere in the range +5.5 to +7.5 and a CaO content of about 14 to 17 wt. %. Interestingly, the lowest ¹⁸O 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 and some of the Ponza-Palmarola rhyolites. This may be correlated with the fact that these centers are located at the margin of the high-¹⁸O continental crust that makes up the Italian peninsula. For example, can it just be a coincidence that the sequence of increasing δ¹⁸O in the Quaternary lavas erupted within a relatively small area in the vicinity of the Gulf of Naples is Ischia---
Procida—Phleegran Fields? This is identical to the geographic sequence for these volcanic centers crossing from west to east and going from low-$^{18}$O oceanic crust toward high-$^{18}$O continental crust; this geochemical transition takes place over a lateral distance of only 30 km (Fig. 2).

5.3 CaO vs. $^{87}$Sr/$^{86}$Sr

On a CaO-$^{87}$Sr/$^{86}$Sr diagram like Fig. 8, a path of closed-system fractional crystallization will be along an exactly horizontal trajectory pointing toward the left. However, in comparing Fig. 8 with Figs. 6 and 7, this simplifying feature is counterbalanced by two features of the strontium isotope geochemistry of the potassic volcanic rocks of Italy that make it much more difficult to distinguish between closed-system fractional crystallization and country-rock assimilation effects on Fig. 8: (1) Although the $\delta^{18}$O values of all of the primitive, Ca-rich magmas in Italy appear to be fairly uniform at about +5.5 to +7.5, regardless of geography or whether we are dealing with HKS or LKS magmas, the $^{87}$Sr/$^{86}$Sr ratios of these "primitive" magmas are widely variable (Fig. 8). (2) The alkalic magmas in Italy are characteristically extremely rich in strontium (800 to 3000 ppm Sr) and rich in $^{87}$Sr as well ($^{87}$Sr/$^{86}$Sr = 0.706 to 0.711), whereas the possible wall-rock contaminants are typically very low in Sr (< 200 ppm Sr), and also not all that much more radiogenic (0.715-0.735). Thus, a fairly large amount of crustal contamination of these Sr-rich magmas could have occurred and we will not be able to discern this from the $^{87}$Sr/$^{86}$Sr ratios alone. Therefore, the $\delta^{18}$O signature is much more indicative of crustal contamination in these Sr-rich Italian magmas than is the Sr isotope signature.

In spite of the above complications, the $^{87}$Sr/$^{86}$Sr data in Fig. 8 do in fact display several features that are compatible with AFC or crustal assimilation effects. Most of the data-point envelopes on Fig. 8 display crude, negative slopes, and the $^{87}$Sr/$^{86}$Sr values at each locality tend to increase as
the CaO content decreases. All of the results plotted on Fig. 8 could therefore conceivably be explained by AFC processes operating on series of hypothetical "primitive" parent magmas represented by the large asterisks on the right-hand side of the diagram. However, it is not yet certain that the primary, mantle-derived magmas at each volcanic center were as homogeneous in $^{87}\text{Sr}/^{86}\text{Sr}$ and CaO as is indicated by the large asterisks. First, it is difficult to determine the exact $^{87}\text{Sr}/^{86}\text{Sr}$ range of the primary, uncontaminated magmas at each locality, and second, mixing variations along the CMML (see below) in fact might have produced a range of primary values at a given volcanic center.

Nevertheless, at least at one center, namely the Alban Hills, the primary $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are known to have been very uniform (no lower than 0.7100 and certainly no higher than 0.7106, Ferrara et al., 1985). Most of the lavas at the Alban Hills display a narrow range of chemical and isotopic compositions (Figs. 4 and 8), compatible with the suggestion of Appleton (1972) that these lavas have not been strongly fractionated relative to their parent magmas that came from the upper mantle. Ferrara et al. (1986) have argued that the primary M. Vulsini magmas also had uniform isotopic compositions very similar to the Alban Hills lavas.

5.4 $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\delta^{18}O$

On Fig. 9, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the new samples from this study are plotted against $\delta^{18}O$. Also included are all available data from Roccamonfina (Taylor et al., 1979; Hawkesworth and Vollmer, 1979). Two important features are indicated on Fig. 9, both of which were previously pointed out at Roccamonfina by Taylor et al. (1979): (1) There is a steep positive correlation between $\delta^{18}O$ 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 higher $^{87}\text{Sr}/^{86}\text{Sr}$ than the LKS.
The trends shown on Fig. 9 clearly require some type of mixing process involving a high-$\delta^{18}O$, $^{87}$Sr-rich end member(s) and a low-$\delta^{18}O$, $^{87}$Sr-poor end member(s). The $\delta^{18}O$ values of the latter end members are everywhere relatively uniform ($\approx +5.5$ to $+7.0$), whereas the $^{87}$Sr/$^{86}$Sr ratios are quite variable. There is a clear consensus among all workers who have studied these rocks that the low-$\delta^{18}O$, $^{87}$Sr-poor end members are derived from an upper mantle source region(s) of some type, and although the origin of the high-$\delta^{18}O$, $^{87}$Sr-rich end member is more controversial, it is most readily inferred to be the Italian continental crust itself (Taylor et al., 1979; 1984; Ferrara et al., 1985; 1986).

Three samples with "primitive" $\delta^{18}O$ values (+5.8 to +6.2) are singled out as somewhat anomalous on Fig. 9. Each of these is richer in $^{87}$Sr than the bulk of the other samples collected at that locality. Sample IS-4 (=RE-17 of Cortini and Hermes, 1981) is particularly K-rich compared to other Ischia samples, and it has the highest $^{87}$Sr/$^{86}$Sr ratio yet measured on this island (Table 1). Sample 53R from Roccamonfina is a Mg-rich leucitite that is the youngest of the samples studied by Radicati di Brozolo et al. (1987), only 53,000 years old. Sample M-1 from the HKS at Ernici (Civetta et al., 1981) has the highest $^{87}$Sr/$^{86}$Sr ratio of any volcanic rock in Italy collected south of Rome. Unfortunately, it also is the most heavily hydrated and altered sample at Ernici (Table 1; $H_2O^+ = 1.83$ wt. %).

The data from Fig. 9 are compared with available data from other Italian volcanic centers in Fig. 10. The data in Fig. 10 confirm and amplify the conclusions made above regarding Fig. 9, as well as those made by Taylor et al. (1979) for Roccamonfina. At each center, the data-point envelope exhibits a steep, positive slope that projects downward toward a low-$\delta^{18}O$, low-$^{87}$Sr end member; these various end members all have a uniform and primitive $\delta^{18}O = +5.5$ to +7.0, but widely variable $^{87}$Sr/$^{86}$Sr. The $^{87}$Sr/$^{86}$Sr ratio of the low-$\delta^{18}O$
end member(s) changes systematically from very low values in the Low-K Series samples and/or in samples from the southern part of the Roman Comagmatic Province to very high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the High-K Series and/or in the northern part of the Roman Province. The highest $^{87}\text{Sr}/^{86}\text{Sr}$ values of the low-$^{18}O$ end member(s) are observed to the north in the HKS lavas of 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 HKS samples within this entire region to the north of Rome.

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., 1987b). Hyperbolic mixing curves between a low-$^{18}O$, low-$^{87}\text{Sr}$ end member and these metasedimentary basement rocks can explain all the convex-upward, curved trajectories exhibited by these various data-point envelopes on Fig. 10 (also see Fig. 9 of Ferrara et al., 1986). The strongly quartz-normative Tuscan rhyolites at Ceriti-Tolfa, San Vincenzo, and Roccastrada plot very close to the field of Tuscan basement rocks, compatible with their anatectic origin from these rocks (Fig. 10). Also, the hybrid trachytic and latitic magmas at M. Amiata and M. Cimini were apparently formed by mixing between Tuscan and Roman magmas (Taylor and Turi, 1976; Poli et al., 1984), as reflected by the fact that they plot on Fig. 10 at positions intermediate between the Tuscan basement rocks and the potassic magmas of the Roman Province.

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 Figs. 9 and 10 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 $\delta^{18}O$ 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. 10, even though they are chemically much different rock types. They are also isotopically similar to the samples of trachyte and sodic rhyolite from Ponza (the latter sample is also not plotted on Fig. 10, again because its age is not exactly known).

None of these relatively low-$^{18}O$ rhyolites and trachytes from 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 have isotopic compositions similar to those of most ocean islands, they could have been derived in a similar fashion as the typical trachytes and rhyolites from islands such as Ascension and Tristan de Cunha (see review by Sheppard, 1986); plausible modes of origin might be either the partial melting of rocks of basaltic composition or "differentiation" of alkali-basalt magmas. However, these samples are also isotopically similar to many rhyolitic lavas from calc-alkaline island arcs (see review by Taylor, 1986), and therefore an island-arc origin for these magmas certainly cannot be excluded, particularly in view of the recognition of abundant lavas of this type from the nearby Parete area (Di Girolamo et al., 1976). Also, rhyolites of the Aeolian Island Arc off the coast of southern Italy (Fig. 1) are known to have similar isotopic compositions (Javoy, 1976; Barberi et al., 1974).

The two high-$^{18}O$ Ponza rhyolites (P0402, 403) do, however, 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. Note that such metasedimentary rocks do in fact occur nearby on the island of Zannone.
Two horizontal lines at $\delta^{18}O = +5.5$ and $\delta^{18}O = +8.0$ are drawn on Fig. 10 to (very conservatively) encompass the possible range of "primitive" (i.e. primary, mantle-derived, and uncontaminated) magmas at all of the major Quaternary volcanic centers of Italy. It is likely that the $\delta^{18}O$ range of the primary magmas at a given center is typically even smaller than this (+5.5 to +7.0?), but we cannot narrow it down more exactly because of the ubiquitous crustal assimilation effects and because of the crude hydration corrections we are forced to make on these lavas (see Section 4), and also because there is probably considerable isotopic inhomogeneity in the various mantle and crustal end members. This makes it difficult to determine precisely how much country-rock assimilation has occurred in any given magma chamber. Also, we do not know if any of the lavas yet analyzed in Italy truly represent unmodified and uncontaminated primary magmas having the same compositions they had when they departed from their source regions in the upper mantle. All of these magmas have very likely been at least somewhat modified by both closed- and open-system processes during ascent, emplacement into a crustal magma chamber(s), and subsequent fractional crystallization. It may be virtually impossible to determine the exact chemical and isotopic characteristics of the original primary magmas.

5.5 $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}$

Fig. 11 is a schematic diagram for $^{87}\text{Sr}/^{86}\text{Sr}$ and strontium concentration analogous to that shown for $\delta^{18}O$ and CaO in Fig. 5. The schematic trajectories in Fig. 11 may be compared with Fig. 12, where we plot our new data together with all of the available Sr-isotope data on the Pliocene to Quaternary volcanic rocks of central Italy and the adjacent offshore islands. Fig. 12 is an expanded version of Figs. 8, 10, and 11 in Ferrara et al. (1986), and these figures should be consulted for details regarding the north areas of the Alban Hills. Such plots of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $1/\text{Sr}$ are useful
because simple two end-member mixing phenomena produce straight lines on such diagrams, as do simple AFC processes (at constant R values, Fig. 11; also see Fig. 8 in Taylor and Sheppard, 1986). Fractional crystallization of a well-mixed, equilibrated magma system will produce an exactly horizontal line at a constant $^{87}\text{Sr}/^{86}\text{Sr}$ on Fig. 11 or Fig. 12, heading off to the left if clinopyroxene and olivine alone are crystallizing and off to the right if plagioclase is crystallizing.

We show a number of somewhat hypothetical mixing and fractionation lines on Fig. 12. For example, the diagonal line labelled Continental Mantle Mixing Line? or CMML(?) was drawn by Ferrara et al. (1985) through the most primitive lavas found at each volcanic center, including Ernici (LKS), Ernici (HKS), Vesuvius, Phlegrean Fields, Roccamonfina (LKS), Roccamonfina (HKS) and the Alban Hills.

The Tuscan Basement Line (TBL) is a hypothetical mixing line drawn between an average value for Tuscan metasedimentary basement and the data-point for the Villa Senni Tuff (the most abundant magma type and also one of the most "primitive" magmas at the Alban Hills). Another possible mixing line labelled TAL, having a somewhat steeper slope, connects the primitive HKS magmas with the orenditic lavas of Torre Alfina; the latter are perhaps the oldest and certainly the most heavily contaminated magmas in the M. Vulsini area ($\delta^{18}O = +13.9$ to $+14.4$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7165$ to $0.7168$, with abundant country-rock xenoliths and xenocrysts, Ferrara et al., 1986). Other orenditic lavas at the very tiny, closely-spaced volcanic centers of Montecatini and Orciatico also appear to be heavily contaminated (Fig. 12).

A curve that is newly-defined in this paper and labelled Oceanic Mantle Mixing Line? or OMML(?) is drawn from the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values on the CMML(?) toward the values obtained from MORB-type abyssal basalts (< 5 Ma) dredged from the Tyrrhenian Sea, which lies just to the west of the Italian peninsula and southwest of the Pontine Island lineament (Figs. 1 and 2).
The horizontal line at 0.71000 (Fig. 12) simply and conveniently separates samples north of (and including) the Alban Hills from those collected from the volcanic centers farther south. This line would also closely approximate a closed-system fractional crystallization trajectory for the primitive HKS magmas of the Alban Hills and M. Vulsini. Remarkably, this 0.71000 line is also virtually a perfect geographic division boundary, except for: (1) two samples of Ernici HKS, one of which is the aforementioned anomalous M-1, and (2) the Vulsini LKS samples which, like the other Low-K Series lavas throughout Italy, are invariably lower in $^{87}\text{Sr}/^{86}\text{Sr}$ than the coexisting HKS rocks from the same volcanic center. With these exceptions, the 0.71000 line provides a perfect separation between the northern and southern parts of the Roman Comagmatic Province, as well as also separating the magmas of the southern part of the Roman Province from those produced in the Tuscan Province.

Some remarkable systematics are displayed on Fig. 12. North of a hypothetical E-W line drawn just south of the Gulf of Naples (Fig. 1), essentially all of the magmas produced during the past 5 million years plot within a well-defined quadrilateral; this 4-sided region is bounded on the top by the TAL or TBL lines, on the left by the CMML(?), and on the bottom by the OMML(?). The right-hand boundary lies off the diagram, being limited only by the degree of strontium depletion produced either by strong fractional crystallization of these magmas or by anatectic melting of the Tuscan metamorphic basement (some of these highly evolved magmas have ppm Sr contents as low as 10 ppm, equivalent to a 1/Sr x 10^4 value of 1000). The other 3 boundaries all represent hypothetical mixing lines among 4 broadly defined end-member components: (1) A primitive LKS end member represented by M. Ernici or by the most Ca-rich LKS lavas at Roccamontfina or Procida; (2) A MORB-type basaltic end member represented by the oceanic crust of the Tyrrhenian Sea; (3) An
extremely heterogeneous end member represented by the continental crust of the Italian peninsula; and (4) A primitive HKS (or KAM) end member typified by the Alban Hills lavas and the Ca-rich Vulsini lavas (or possibly by the 180-corrected, extremely Sr-rich San Venanzo-Cupaello lavas). Note that the measured 180/160 ratios of the latter lavas are not primary values (Taylor et al., 1984); on the other hand, because of their extremely high Sr contents (> 3000 ppm), the measured 87Sr/86Sr ratios at San Venanzo and Cupaello should be very close to the original values in their mantle source regions.

Mixing processes involving these 4 broadly defined end members can be expected to be extremely complex. They conceivably could involve the parent rocks in the 4 source regions, the metasomatic fluids that have affected these source regions, the magmas produced by partial melting of the 4 source regions, or some combination of any or all these possibilities. In addition, it is to be expected that these mixing phenomena will in general be modified by fractional crystallization (i.e. horizontal trajectories on Figs. 11 and 12) or by AFC processes (which for constant R values will generate linear trajectories on Figs. 11 and 12, typically having gentle positive slopes). Note that many of the data-point envelopes on Fig. 12 do indeed show gentle positive slopes, reflecting a slight enrichment in 87Sr/86Sr as one moves off to the right toward more evolved magmas with lower Sr concentrations.

We should point out that the CMML (?) is not drawn through the most Sr-rich data points at each locality. It is instead drawn through the groups of samples at the Alban Hills, Ernici, Roccamonfina, Vesuvius, and the Phlegrean Fields with the most "primitive" chemical characteristics (i.e. highest CaO, lowest SiO2). The samples that plot slightly to the left of the CMML (?) on Fig. 12 were apparently enriched in Sr by an early-stage, plagioclase-absent fractional crystallization process. Only after plagioclase started to crystallize did these trajectories turn off toward the right; thereafter, as
the Sr contents of the magmas decrease, it becomes increasingly easy to observe the Sr-isotope signature of the crustal assimilation process.

6. CONCLUSIONS

Our new data fit in nicely with most of our earlier conclusions concerning the origin of the Quaternary volcanic rocks of central Italy. With a few modifications, such as emphasizing AFC processes instead of simple closed-system fractional crystallization, they also agree with most of the concepts put forward by Appleton (1972), Hawkesworth and Vollmer (1979), and Cortini and Hermes (1981). However, probably because we are focusing on the oxygen-isotope approach as a sensitive indicator of interactions with the continental crust, we place a great deal more emphasis on crustal assimilation effects than do the above authors, particularly for the more fractionated lavas, and especially in the area to the north of Rome where the potassic magmas of the Roman Province were erupted upward through thick continental crust where the geothermal gradient was much higher than normal. Although crustal assimilation effects are readily apparent in the $^{18}O/^{16}O$ results, they are obscured in the $^{87}$Sr/$^{86}$Sr data because of the extremely high Sr concentrations in these potassic magmas. We thus want to make it clear that we are in thorough agreement with earlier authors, including Hurley et al. (1966), that the major Sr isotope variations observed in the magmas of the Roman Province are a result of fairly recent processes taking place in the upper mantle source regions of these magmas, as typified by the $^{87}$Sr/$^{86}$Sr variations along the CMML(?) in Fig. 12. In the area to the south of Rome, the crustal assimilation processes that we are describing have had only a second-order effect on $^{87}$Sr/$^{86}$Sr (and $\epsilon_{Nd}$) values.

Our results are, however, in serious disagreement with many of the conclusions reached by certain other workers who have studied these potassic magmas, notably Holm and Munksgaard (1982), Peccerillo (1985), Peccerillo and
Manetti (1985), and Civetta et al. (1987). Some of these areas of disagreement are outlined below, as we briefly summarize our major conclusions:

(1) The $\delta^{18}O$ values of the primitive HKS and LKS parent magmas at each volcanic center in Italy are relatively low, typically $+5.5$ to $+7.0$. Although a few of these magmas may be coming from their mantle source regions with $\delta^{18}O$ values as high as $+7.5 \pm 0.3$, we can pretty well rule out the existence of any primary HKS or LKS magmas with $\delta^{18}O > +8.0$. This conclusion conflicts strongly with the conclusions of Holm and Munksgaard (1982) and Civetta et al. (1987).

(2) In contrast to the primitive HKS and LKS magmas, which are actually quite rare as erupted products in Italy, the $\delta^{18}O$ values of the much more abundant, evolved (i.e. fractionated) HKS and LKS magmas commonly have $\delta^{18}O$ values higher than $+7.0$, locally going up to values as high as $+12.0$. These enrichments in $^{18}O$ commonly correlate with major-element changes (i.e. CaO depletion and K$_2$O and SiO$_2$ enrichment) which essentially all workers 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, the cumulate nodules that were torn loose from the margins of these crustal magma chambers and erupted in pyroclastic deposits have extremely high $\delta^{18}O$ 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 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).
The alkali-rich evolved LKS magmas from the southwestern-most volcanic centers (Ischia, Pontine Islands, Procida) have much lower $\delta^{18}O$ values than any of the petrologically analogous magmas found elsewhere in central Italy. This correlates with the fact that these centers are all offshore islands located near the edge of the continental platform of the Italian peninsula.

The isotopic systematics delineated in Italy prove that there has been some type of grand-scale mixing between the low-$^{18}O$, mantle-derived potassic magmas and a high-$^{18}O$ reservoir. The high-$^{18}O$ reservoir may be readily identified as the continental crust itself, because of the geographic relationship described above, and because the mixing process that increased the $\delta^{18}O$ values of these evolved magmas can be shown to have occurred during fractional crystallization within the crust, and not in the upper mantle; hence, it must be the result of AFC processes or mixing with crustally-derived anatetic magmas, or both. The $\delta^{18}O$ signatures are most clear-cut in this regard, but the $^{87}Sr/^{86}Sr$ signatures also allow this interpretation, particularly in the north where the crustal interaction and assimilation effects are very large, and particularly for the LKS magmas (Ferrara et al., 1986; Rogers et al., 1985), as these tend to have much lower ppm Sr contents than the HKS magmas. The isotopic effects become much less important to the south along the Italian peninsula, and westward from the coast, presumably because of a lower $\delta^{18}O$ 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; 1986; Taylor and Sheppard, 1986). Some other good examples of this phenomenon are provided by the regional $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ effects observed along the 8000 km-long chain of calc-alkaline volcanoes in the Andes of South America (Harmon and Hoefs, 1984; Hickey et al., 1984; Harmon et al., 1984; Stern et al., 1984a; 1984b; Taylor, 1986).

(5) The $^{87}Sr/^{86}Sr$ ratios and Sr concentrations of the primitive HKS and LKS magmas in Italy define a hypothetical mixing line (Ferrara et al., 1985), here termed the CMML(?). The end members that define the CMML(?) clearly reside within the upper mantle beneath the Italian peninsula, and in contrast to the fairly uniform and relatively "primitive" $\delta^{18}O$ values (+5.0 to +7.5), the $^{87}Sr/^{86}Sr$ variations in these source regions are "enriched" and quite variable (0.7060 to 0.7110). The lowest $^{87}Sr/^{86}Sr$ values are associated with the lowest ppm Sr concentrations and are characteristic of the southernmost centers, which are dominated by the LKS end member. The highest $^{87}Sr/^{86}Sr$ values observed in these mantle-derived magmas are characteristic of the HKS or KAM end members and of the northernmost volcanic centers.

(6) We in general agree with Appleton (1972) and Cundari (1980) that the geochemical differences between the primitive HKS and LKS magmas are most 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. The metasomatic fluids were 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 $^{87}Sr/^{86}Sr$ ratios that show a positive correlation with the level of K and Sr enrichment. 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$_2$O-rich and CO$_2$-rich metasomatic fluids may have been the "trigger" that initiated the widespread melting of the upper mantle that took place beneath Italy during the past million or so years.

(7) These metasomatic fluids were also apparently somewhat H$_2$O-rich, at least relative to MORB-type ($\delta^{18}O = +5.5$ to $+5.9$) source regions in the upper mantle. The K-rich, primary 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 source regions 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 (Gregory and Taylor, 1986a; 1986b), and it is now well established that alkali-rich basaltic magmas throughout the Earth in general tend to be slightly enriched in $^{18}O$ relative to MORBs (e.g. $+6.0$ to $+6.5$, see Kyser, 1986). A slight degree of enrichment in $^{18}O$ thus 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 these primary magmas, there is an indication that the $^{18}O/^{16}O$ ratio of the primitive LKS end member ($\delta^{18}O = +6?$) is characteristically somewhat lower than that of the HKS end member ($\delta^{18}O = +7?$). 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 $\delta^{18}O \geq +7$ (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. Therefore, in spite of the many complexities exhibited in these various volcanic centers in Italy, we can tentatively discern a rough positive correlation between $\delta^{18}O$
and $^{87}\text{Sr}/^{86}\text{Sr}$ in the primary, mantle-derived Roman magmas. The HKS end member tends to be slightly enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{18}O$ relative to the LKS end member, and both are distinctly enriched in $^{18}O$ and $^{87}\text{Sr}/^{86}\text{Sr}$ compared to typical MORB values.

(8) Some of the major geochemical features of the Quaternary igneous rocks of Italy are indicated schematically on Fig. 13. This diagram shows that the first-order $^{18}O/^{16}O$ effects in these magmas are all attributable to interactions with the continental crust, as typified by analyses of the Tuscan metasedimentary basement rocks. Four hypothetical end members define the quadrilateral bounded by the CMML(?), OMML(?), and TAL-TBL lines on Figs. 12 and 13. There is a distinct geographical as well as a geochemical flavor with respect to the positions of the respective data-point envelopes on Fig. 12 and the locations of the volcanic centers on a map of Italy (Figs. 1 and 2). In addition, the locations of the volcanic centers and the positions of their data-point envelopes are both clearly related to the plotted positions of the 4 hypothetical end members on Figs. 12 and 13, as well as to the particular geographic province where each end member is most dominant in the erupted lavas. For example, not only do the Procida and Ischia samples plot adjacent to both the LKS end member and the OMML(?) line on Figs. 12 and 13, these two eruptive centers are also geographically closest to both the most important zone of eruption of LKS magmas in Italy and to the abyssal MORB-type basaltic crust of the Tyrrhenian Sea itself (Barberi et al., 1973). Similarly, in terms of both geography and their positions on Figs. 12 and 13, the high-$^{18}O$, high-$^{87}\text{Sr}$ Vulsini, Cimini, and Amiata eruptive centers are closest to the higher-$^{18}O$, higher-$^{87}\text{Sr}$ Tuscan anatectic rhyolite-granite localities of San Vincenzo, Roccastrada, Elba, Montecristo, and Giglio (see Taylor and Turi, 1976). It is this remarkable intermingling of systematic correlations among various facets of geography, petrology, and isotope geochemistry, as well as
their extremely young ages, that makes these Quaternary igneous rocks of Italy so challenging and interesting.

(9) Holm and Munksgaard (1982), Holm et al. (1982), Peccerillo (1985), Peccerillo and Manetti (1985), and Civetta et al. (1987) strongly discount the importance of interactions with the continental crust in discussing the geochemistry of the potassic igneous rocks of Italy, even for the evolved, Ca-depleted samples. Some of these authors carry this concept even to the extreme of asserting that the Torre Alfina lavas at M. Vulsini are primary magmas derived directly from the upper mantle. We take particular exception to the conclusions of Civetta et al. (1987) regarding the orenditic lavas produced at the tiny eruptive centers of Torre Alfina, Montecatini, and Orciatico. The relatively SiO$_2$-rich Torre Alfina lavas (Fig. 12) have by far the highest $\delta^{18}O$ and the highest $^{87}$Sr/$^{86}$Sr of any potassic magmas in Italy, and they contain abundant high-$^{18}O$ gneissic xenoliths and xenocrysts. One simply cannot ever assume that the $\delta^{18}O$ values of small, pipe-like or dike-like magma bodies necessarily reflect the $\delta^{18}O$ values that those magmas had as they departed their source regions. This is particularly true if such magma bodies with high surface-to-volume ratios are intruded into country rocks with distinctly different $^{18}O/^{16}O$ ratios. Such magmas always exchange oxygen isotopes with their surroundings, especially if the adjacent wall rocks are already at high temperatures, and/or if the magmas are markedly out of chemical equilibrium with their country rocks (i.e. SiO$_2$-undersaturated magmas emplaced into quartz-bearing wall rocks). In order to have even a remote chance of obtaining a mantle-source $\delta^{18}O$ signature, the magma body being sampled needs to have a high volume-to-surface ratio, and one must sample the interior of the magma chamber. The edges of plutonic magma bodies (100 to 200 m from the margin) are always contaminated in terms of $^{18}O/^{16}O$ (see Turi and Taylor, 1971; Shieh and Taylor, 1969; Taylor and Sheppard, 1986). In order to
see a mantle-source $\delta^{18}O$ signature in a volcanic or hypabyssal rock, the sample should preferably be from a volcanic conduit that has previously erupted a large volume of magma. Thus, the sample should definitely not be one of the earliest eruptions at that center, as those are expected to be the most heavily contaminated (in this connection, note that the Torre Alfina lavas are among the oldest known eruptions from M. Vulsini). Only after the volcano has "cleared its throat" and erupted sufficient magma can we expect the volcanic conduit to be sufficiently chemically insulated from its surroundings that the magma "plumbing system" will be relatively free of wall-rock $^{18}O$ exchange effects. This concept has been discussed in several earlier papers on the Italian rocks (Taylor et al., 1984; Turi et al., 1986), and we also note that Marsh (1985) and Myers et al. (1985) emphasize these concepts in some recent publications.

(10) We now turn to the subducted-sediment theory of origin of the potassic Roman magmas that has recently gained some acceptance among certain workers (e.g. Beccaluva et al. 1984; Peccerillo, 1985; Rogers et al., 1985). One of the earliest formulations of this concept (Thompson, 1977) was based on the high $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ values in the Roman magmas. Although the $\delta^{18}O$ signatures indicate beyond doubt that sedimentary or metasedimentary rocks were somehow involved in the genesis of these magmas, the major $^{18}O/^{16}O$ effects were produced in the upper mantle, and are thus 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 in the genesis of these potassic magmas are not referring to such a hypothetically-thickened continental crust.
Although the mantle-derived, primary HKS and LKS magmas are slightly enriched in $^{18}O$ and $^{87}Sr/^{86}Sr$ relative to MORB, they are not markedly enriched in $^{18}O$ or $^{87}Sr/^{86}Sr$ relative to other potassic magmas throughout the world (Taylor et al., 1984; Garlick, 1966; Kyser, 1986; Kyser et al., 1982). Therefore, based simply on these 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 slight enrichment of both $^{18}O$ and $^{87}Sr$ that is observed in almost all potassic magmas on Earth may be (probably is?) related to an (ancient) subduction event that emplaced high-$^{18}O$, high-Rb material into the upper mantle. Subduction is obviously the most logical way of inserting $^{18}O$-rich and $^{87}Sr$-rich material into the mantle, but this need have nothing to do with any recent subduction event, as favored by Peccerillo (1985), Rogers et al. (1984), and Holm and Munksgaard (1982). If there is sufficient evidence of another kind to require it, however, we would not quarrel with such an interpretation, but the $^{18}O/^{16}O$ data should not be used as evidence for a recent subduction event. We also question whether such a scenario will ever be proved one way or the other, in view of the extensive isotopic overprinting that occurred as the potassic magmas interacted with the continental crust of Italy, thereby obscuring the upper-mantle geochemical processes. Thus, the primitive potassic magmas of Italy may have formed in an essentially extensional tectonic environment more-or-less analogous to the way other potassic volcanic rocks on Earth seem to have formed. Superimposed on these extensional tectonic events (back-arc spreading? local pull-apart basins?) are a large number of complexities that are unique to Italy, and which, within the continental crust, locally produced much higher $\delta^{18}O$ values in the evolved potassic magmas. These unusual effects can be attributed to specific circumstances associated with the late Tertiary and Quaternary geology and geography of Italy and the Mediterranean Sea.
Acknowledgements

We are indebted to S. Tonarini in Pisa for her efforts in obtaining the Sr-isotope analyses and to C. Trudu for his help in that portion of the laboratory work carried out at the University of Rome. We thank S. Epstein, J. Coulson, and J. Goris for their help in the laboratory work carried out at Caltech. The Sr-isotope analyses of some samples from M. Etnici were kindly made by M. Barbieri. Thanks are also due to R. Vollmer and M. Cortini for supplying several samples. We are also grateful to M. Barbieri and A. Taddeucci for permitting us to report unpublished data on the 1971 Etna lava flow. Funding for Taylor was provided by the United States National Science Foundation, Grant No. 83-13106, and funding for Turi was provided by the Consiglio Nazionale delle Ricerche through the Centro Studi per la Geochimica Applicata alla Stratigrafia Recente and the Cooperative U.S. - Italy Program, C.N.R. Grant No. 86.00709.05, and by the Ministero della Pubblica Istruzione.
REFERENCES


Appleton JD (1972) Petrogenesis of potassium-rich lavas from the Roccamonfina Volcano, Roman Region, Italy. J Petrol 13: 425-456


Borsi S, Ferrara G, Tongiorgi E (1967) Determinazione con il metodo del K/Ar
delle età delle rocce magmatiche della Toscana. Boll. Soc. Geol. It.,
86: 403-410.

Burri C (1959) Zur Kenntnis der Eruptivgesteine der Punta delle Pietre Nere

Cagnetti V, Di Sabatino B, Trigila (1973) Considerazioni chimiche e
petrologiche su alcune particelle cineritiche dell' Etna (eruzione

Capaldi G, Civetta L, Gasparini P (1976/77) Volcanic history of the island of
Ischia (South Italy). Bull Volcanol 40: 11-22

Capaldi G, Civetta L, Gillot PY (1985) Geochronology of Plio-Pleistocene
volcanic rocks from southern Italy. Rend Soc Ital Mineral Petrol 40:
25-44

and volcanic evolution of the island of Ponza, Italy (unpublished
manuscript)

derived from enriched and depleted source regions: Nd and Sr-isotope
evidence. Earth Planet Sci Lett 37: 401-408


Cox KG, Hawkesworth CJ, O'Nions RK, Appleton JD (1976) Isotopic evidence for the derivation of some Roman region volcanics from anomalously enriched mantle. Contrib Mineral Petrol 56: 173-180


Di Girolamo P (1978) Geotectonic setting of Miocene-Quaternary volcanism in and around the eastern Tyrrhenian Sea border Italy) as deduced from major elements geochemistry. Bull Volcanol 41: 229-250


Di Girolamo P, Rolandi G (1984) Absence of a trachytic period on Somma-Vesuvius (southern Italy) and petrological implications for the genesis of leucite-bearing rocks. n Jb Miner Mh 9: 424-432


Gregory RT, Taylor HP Jr (1986b) Possible non-equilibrium $^{18}O/^{16}O$ effects in mantle nodules, an alternative to the Kyser-O'Neil-Carmichael $^{18}O/^{16}O$ geothermometer. Contrib Mineral Petrol 93: 114-119


Hawkesworth CJ, Vollmer R (1979) Crustal contamination versus enriched mantle: $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ evidence from Italian volcanics. Contrib Mineral Petrol 69: 151-165

petrogenesis. In: Chemical and Isotopic Constraints on Andean Magmatism, ed. Harmon RS, Barreiro B, Shiva Press, Nantwich, UK, 72-95


Javoy (1976)


Marsh B (1985)


Myers JD, Marsh BD, Sinha AK (1985) Strontium isotopic and selected trace element variations between two Aleutian volcanic centers (Adak and Atka): Implications for the development of arc volcanic plumbing systems. Contrib Mineral Petrol 91: 221-234


Radicati di Brozolo F, Di Girolamo P, Turi B, Oddone M (1987) $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar dating of the K-rich volcanic rocks from the Roccamonfina volcano, Roman Comagmatic Region, Italy. Wasserburg Symposium Pasadena
Rittmann A (1930) Geologie der Insel Ischia. Zeitschr Vunkanol, Berlin, 6


Rogers NW, Hawkesworth CH, Parker RJ, Marsh JS (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


Santacroce R, Savelli C, Rejec S L; Isola di Ventotene: uno strato-vulcano quaternario tipo Somma nel Mar Tirreno centro-orientale (unpublished manuscript)


