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Origin and differentiation of recent basaltic magmas from Mount Etna

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With 9 Figures

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Summary

One hundred and fifty samples of recent Na-alkalic lavas from the south-eastern flank of Mt. Etna, dating from about 5,000 years B.P. to 1886 were analyzed. They grade in time from more acid to more basic lavas, and show an overall range of variation much larger toward the more felsic end than previously known. Chondrite-normalized REE patterns of the least differentiated samples show LREE enrichment and HREE depletion; trace element compositions suggest that Etnean products are similar to WPB, with a weak CAB signature. Sr-isotope ratios ranging from 0.70332 to 0.70355, vary even within samples from the same eruption, and generally tend to increase with time in historic lavas.

Our data suggest that processes other than simple crystal fractionation are, in part, responsible for the variation of the analyzed sequence. In fact, RTF processes with successive influxes of mafic melts, each having distinct, slightly different geochemical and isotopic features, into reservoirs of variously differentiated magmas, may explain the overall observed data.

The source region for Recent Mongibello lavas is located in the mantle, isotopically zoned, and Rb-depleted with respect to the Bulk Earth composition. Model and experimental data conform well with a low degree (< 5%) modal melting of a garnet lherzolite source, depleted by an earlier melting event with respect to primitive mantle composition.

Zusammenfassung

Herkunft und Differentiation von rezenten basaltischen Magmen des Berges Ätna

Es wurden 150 Proben von rezenten, Na-alkalischen Laven von der Südflanke des Ätna, die mit 5000 Jahren vor Christus bis 1886 datieren, analysiert. Die Laven zeigen mit der Zeit einen graduellen Übergang von sauer zu zunehmend basisch und weisen generell eine größere Variationsbreite in Richtung sauer auf als bisher angenommen.

Chondrit-normalisierte REE Verteilungskurven der am geringsten differentierten Proben zeigen LREE Anreicherung und eine Verarmung der HREE. Die Spurenelement-Zusammensetzungen deuten an, daß die Ätna-Produkte Ähnlichkeit mit WPB mit einer schwachen CAB-Signatur aufweisen. Die Sr-Isotopenverhältnisse reichen von 0.70332 bis 0.70355, variieren sogar innerhalb Proben aus ein und derselben Eruption und tendieren generell zu ansteigenden Werten mit der Zeit.

Unsere Daten weisen darauf hin, daß andere Prozesse als einfache Kristallfraktionierung, zumindest teilweise, für die Variation der analysierten Sequenz verantwortlich sind. In der Tat können RTF Prozesse mit sukzessiver Zufuhr von mafischen Schmelzen, jede mit leicht unterschiedlicher Geochemie und definierten Isotopenverhältnissen, in Reservoirs von unterschiedlich differentiierten Magmen, die vorliegenden Daten erklären.

Die Herkunftsregion der rezenten Mongibello Laven ist im Mantel angesiedelt, der bezüglich der Isotopenzusammensetzung zoniert und, verglichen mit der Erdzusammensetzung, an Rb verarmt ist. Die Modell- und experimentellen Daten stehen in guter Übereinstimmung mit einem niedrigen Grad (< 5%) der Aufschmelzung eines Granat-Lherzolites als Ausgangsmaterial, das, im Vergleich zum primitiven Mantel, durch einen früheren Aufschmelzungsvorgang verarmt ist.

Introduction

Etna, the largest volcano in Europe, active since Holocene (700,000–500,000 years B.P., *Romano*, 1982), is located on the northeastern coast of Sicily. Since this volcano has an historic record of documented eruptions going back over 2000 years, it offers an unique opportunity to study in detail the evolution of petrological, geochemical and isotopic characteristics of its Recent lavas with time, in order to provide important information on magma source region and crustal magma chamber/s processes.

Geological background

Etna activity should be considered within the framework of the geologic structure of eastern Sicily: the volcano sits adjacent to the boundary of the two most important structural units of this area (*Lentini*, 1982), at the continental edge of the Ionian basin: the northern Range, composed of several south-verging overthrusts originated from the Tyrrhenian crust, and the Hyblean Foreland, representing the little deformed northernmost part of the African Plate, chiefly composed of thick carbonate rock sequences from Trias to Pleistocene in age. Geophysical data (*Cristofolini* et al., 1985) suggest a thinned Tyrrhenian crust over-riding thickened African crust along a steeply north-dipping lithospheric fracture system, that gives rise at the surface to the E–W dextral transcurrent faults of the Mt. Kumeta—Alcantara system and to the Mt. Judica and Mt. Scalpello slices adjacent to the Catania Plain (*Ghisetti*, 1979).

Integration of geological, morpho-structural, and petrological data has shown that the Etnean volcanic sequence is related to the activity of several distinct centres that followed each other in time (*Cristofolini* et al., 1981b; *Romano*, 1982). The informally defined Recent Mongibello (R.M.) sequence is currently defined as being related to the only still active and youngest eruptive centre. It started with a marked change in style and eruptive regime, about 5,000-3,000 y B.P. (*Cortesi* et al. 1988;

Romano, 1982), at the end of a cycle of violently explosive activity and caldera collapse, related to the Ellittico Centre (Ancient Mongibello). The R. M. main axis is located within the caldera and its volcanic sequence was suggested to be divided into two sections, related to a major caldera collapse episode which occurred around 2,000 years ago (*Romano*, 1982; *Kieffer*, 1979), evidence for which is found in the southern sector of the summit area (Cratere del Piano, 2,900 m a.s.l.). The younger section should be referred to the Modern Mongibello (*Kieffer*, 1979), although in the field no unequivocal distinction is possible for degraded products that might be related to either of the two sections.

Recently (*La Volpe* et al., 1992), eclusive use of unconformity bound and/or lithostratigraphic units has been suggested as criteria for formally defining elements of volcanic successions, and a new detailed sequence of these formally defined units was proposed for part of the "Etnean volcanic district"; in this sequence the "Piano Synthem" includes in its upper part all of what is here defined as Recent Mongibello. In our opinion, the suggested criteria may not be applied alone, as they do not take into account the petrologic features and the major changes in the eruptive regime, recorded in the volcanic sequence. In detail, the proposed synthem, would comprise either strongly to mildly differentiated volcanics related to several violently explosive episodes, or the most recent mafic lavas, related to a fairly continuous effusive activity.

Mild strombolian activity and lava effusion at the main craters gave rise to the summit cone, the locus of the present-day persistent activity of Mount Etna (*Guest*, 1982), whereas numerous parasitic vents fed lava flows that extensively covered the flanks of the volcano.

The analyzed sequence

Sampled lavas are refered to R.M. products as previously defined (*Vv. Aa.*, 1979), subdivided as follows:

—*Dated lavas*, on the grounds of historical records (from 1329 to 1886).
—*Undated lavas*:
- Recent lavas (with uncertain or unknown eruption date); R in Tables 1 and 2.
- Lavas with well-defined flow boundaries (D in Tables 1 and 2).
- Lavas with poorly-defined flow boundaries (N in Tables 1 and 2).

To characterize the R.M. products, we examined and analyzed about 150 samples from older undated to historically dated (up to 1886) lavas, from outcrops on the south-eastern flank of the volcano. Lavas more recent than 1886 were excluded from the present investigation, as they are already well described in numerous recent papers (*Armienti* et al., 1984, 1986, 1987; *Tanguy*, 1980; *Tanguy* and *Kieffer*, 1976; *Cristofolini* et al., 1987a; *Tanguy* and *Clochiatti*, 1984; *Scott*, 1983).

Analytical techniques

Mineral analyses were carried out at "Centro CNR di Studi Geominerari e mineralurgici", Cagliari using SEMQ-ARL electron microprobe by the standard program "MAGIC" with matrix correction according to "ZAF".

Major oxides were determined at the Istituto di Scienze della Terra, Catania by XRF on powder pellets except for MgO (AAS), FeO ($KMnO_4$ titration), L.O.I. (gravimetric analyses). Analytical uncertainty is lower than 1% except for MnO (= 1.7%).

Trace elements contents were measured at Actlabs, Canada by I.C.P. (Inductively Coupled Plasma Emission; Sr, Zr, U, V, Y, Cu, Ni) and I.N.A.A. (Instrumental Neutron Activation Analysis; Rb, La, Sm, Yb, Sc, Cs, Ce, Eu, Lu, Co, Ta, Nd, Tb, Cr). Analytical uncertainty is lower than 5% for all trace elements except Tb, Rb, Cs, Ta and Ni whose contents, in analyzed lavas, are close to instrumental detection limit.

Sr-isotope compositions were measured with a VG Micromass 54 E mass spectrometer at Dipartimento di Scienze della Terra dell' Università "La Sapienza", Rome, and at Dipartimento di Geofisica e Vulcanologia, Naples. Analytical uncertainty is below ± 0.00003. Ratios are corrected for mass fractionation relative to standards as follows: $^{87}Sr/^{86}Sr$ (0.71025, NBS987).

Petrography

The sampled lavas were petrographically analyzed to evaluate the control of the phenocryst phases on the overall rock compositions as, porphyritic varieties being dominant, lava compositions are not strictly representative of melts.

The common mineral association (pl + cpx (augite) + ol + mt) of Etnean lavas is shown by all of the analyzed samples, either as phenocrysts, or in the groundmass. Glomeroporphyritic textures are common, chiefly due to plagioclase clusters. Phenocrysts, either aggregated or isolated, are homogeneous in size, suggesting similar growth times, although not necessarily within the same environment, as shown by different zoning patterns and core compositions for crystals in the same lava (*Corsaro* and *Cristofolini*, 1993). "Gabbroic" (pl, cpx, ol ± mt) clusters are rare, whereas, either plagioclase or mafic mineral aggregates are commonly found. This appears consistent with the latter originating in parts of the magma column distinct from the former, a hypothesis supported by the much more homogeneous composition and simpler zoning patterns in mafic minerals than in plagioclase.

Modal analyses on 35 selected samples show that in the Dated Lavas erupted before 1600 A.D., $C.I._{phx}$ (= Mafic Mineral Phenocrysts/Total Phenocryst % Vol.) is less than 30, whereas in younger lavas it is higher. Porphyricity Index (P.I.) varies in the range 27–37, with values $< 15\%$ being most frequent among the Undated Lavas.

Microprobe data show plagioclase phenocryst compositions within a range (An_{45-82} Ab_{17-51} Or_{1-4}) similar to those found in other R.M. lavas (*Cristofolini* et al., 1987b; *Tanguy*, 1980). Different plagioclase crystals in the same rock show distinct zoning schemes with very heterogeneous and variable physical and chemical conditions during the growth history of plagioclase. This may explain the lack of any close correlation between whole rock composition and plagioclase core compositions, the departure from the theoretical size distribution pattern of phenocrysts (*Calvari* et al., 1994), the recognition of resorbed cores, and the presence of zones rich in cryptocystalline to glassy inclusions in plagioclase (*Gutmann*, 1977). Plagioclase phenocrysts in Dated Lavas are commonly more calcic than in older ones; microphenocrysts and groundmass microlites are more sodic than phenocrysts.

Average compositions of clinopyroxene phenocryst cores and rims are quite homogeneous, with microlites being slightly FeO_{tot} and K_2O enriched and Al_2O_3, MgO, and CaO depleted with respect to phenocryst rims. Their overall compositions plot in a restricted part of the salite field of the Wo–En–Fs diagram, as for previously analyzed R.M. pyroxenes (*Cristofolini* et al., 1987b).

Al^{IV} is rather high (0.089–0.243 a.f.u.), as already found for other Etnean pyroxenes (*Tanguy*, 1980; *Duncan* and *Preston*, 1980; *Cristofolini* et al., 1987b). Al^{VI} is constantly low (0.002–0.047 a.f.u.), a common character for Recent Mongibello lavas (*Duncan* and *Preston*, 1980; *Cristofolini* et al., 1987b), and suggests crystallization at $P < 0.5$ GPa (*Gibb*, 1973; *Muñoz* and *Sagredo*, 1974); on the other hand the wide Al^{IV} variation range shows large silica activity changes related to varying temperature, P_{H_2O}, and the contemporaneous growth of other Al-bearing phases (plagioclase).

Olivine phenocryst compositions are much more homogeneous than for other minerals ($Fo = 74$ mol%), probably due to ionic diffusion during high temperature re-equilibration. Microlites are substantially more Fe-rich ($Fo = 64$ mol%) than phenocrysts.

Ti- magnetite with USP contents between 32 and 67% mol is the only opaque mineral, with microlites being Ti-enriched (average USP_{60}) relative to phenocrysts (average USP_{40}).

Major element chemistry

All of the sampled rocks were chemically analyzed for major elements (Table 1), and fall in the Na-alkalic field, from hawaiites to benmoreites, as clearly shown by the TAS diagram (*Le Maitre*, 1989; Fig. 1). Since Mg_v^* $[(Mg/(Mg + Fe^{2+}))*100$ standardized for $Fe_2O_3/FeO = 0.15$; *Green* et al., 1974] is between 41 and 59, primitive lavas are not represented among the sampled products.

In detail, the Dated Lavas are chiefly hawaiites grading to basic mugearites, whereas Undated Lavas are mostly mugearites to benmoreites (Fig. 1a). Further examination of the Dated Lavas group shows that products earlier than 16th century are commonly hawaiites-mugearites and younger ones are clearly hawaiites (Fig. 1b). Thus, a temporal transition exists, from more ancient differentiated varieties to younger more mafic lavas. Still more mafic products (hawaiites to alkali basalts) are found among lavas erupted from 1974 to 1993.

Although in variation diagrams (Fig. 2) the trends for most oxides match the behaviour predicted from simple differentiation, a noteworthy character is the wide scatter around the average trends, much larger than analytical uncertainty.

Trace elements distribution

Trace elements composition in samples representing the temporal and compositional spectrum for the whole group confirm that Undated Lavas are, on the whole, more differentiated than the Dated ones (Table 2; Fig. 3).

Contents of LILE (Rb, Cs, Sr, Ba), HFSE (U, Th, Zr, Hf, Ta, Y), REE (La, Ce, Sm, Nd, Eu, Tb, Yb, Lu) and ferromagnesian elements (Ni, Co, Cr, V, Sc, Cu) fall within the range already known for the R. M. lavas and for the whole Etnean alkalic sequence (*Armienti* et al., 1988, 1989; *Cristofolini* et al., 1981a, 1984; *Carter* and

Table 1. *Selected major element analyses (%weight) of R.M. lavas. Dat = Dated lavas; Und. = Undated lavas. The whole set is found in Corsaro and Cristofolini (1993) and may be requested of the authors*

sample		SiO_2	TiO_2	A_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O-	H_2O+	TOT	Mgv^*_v
329M	Dat.	51,37	1,31	19,26	2,60	4,59	0,15	3,63	8,75	5,31	1,76	0,58	0,23	0,46	100,00	52
334D	Dat.	52,85	1,38	18,68	4,84	2,30	0.16	3,21	7,59	5,61	1,99	0,70	0,20	0,49	100,00	49
381C	Dat.	50,68	1,39	18,94	2,17	5,26	0,15	4,69	8,60	5,10	1,65	0,62	0,06	0,69	100,00	57
408D	Dat.	50,19	1,42	19,27	2,70	5,31	0,16	4,80	9,30	4,16	1,55	0,53	0,22	0,41	100,02	56
444D	Dat.	52,22	1,43	19,26	4,73	2,44	0,16	2,96	8,27	5,37	1,86	0,67	0,17	0.44	99,98	47
537C	Dat.	51,54	1,29	18,97	2,35	4,94	0,15	4,58	8,00	5,15	1,87	0,60	0.07	0.48	99,99	57
634G	Dat.	48,99	1,36	19,41	4,11	4,26	0,16	5,26	9,59	4,30	1,46	0,49	0,20	0,39	99,98	57
669D	Dat.	47,18	1,55	18,59	3,73	6,58	0,20	7,01	9,25	3,67	1,37	0,46	0,17	0,24	100,00	59
766A	Dat.	49,15	1,49	18,74	3,34	5,48	0,17	5,24	9,61	4,39	1,47	0,54	0,18	0,21	100,01	56
792L	Dat.	49,38	1,49	18,86	3,29	5,54	0,18	5,10	9,46	4,28	1,53	0,47	0,12	0,30	100,00	55
886A	Dat.	48,76	1,45	18,93	2,78	5,80	0,19	5,56	9,46	4,52	1,50	0,48	0,10	0,47	100,00	58
RB1	Und.	51,19	1,35	19,47	3,42	4,18	0,16	3,75	9,25	4,56	1,51	0,50	0,21	0,43	99,98	51
RF7	Und.	53,22	1,43	18,21	3,12	4,22	0,16	3,35	7,27	5,39	2,22	0,74	0,09	0,57	99,99	49
RF10	Und.	52,57	1,17	19,23	1,81	4,94	0,15	3,82	8,19	5,35	1,86	0,62	0,03	0,26	100,00	54
RH4	Und.	52,25	1,21	19,51	3,31	3,73	0,15	3,26	8,54	5,05	1,79	0,69	0,13	0,37	99,99	50
RH9	Und.	53,15	1,54	17,96	5,75	2,39	0,17	3,16	7,82	4,90	1,97	0,68	0,06	0,46	100,00	46
R13	Und.	51,18	1,35	18,67	2,53	4,84	0,15	5,13	8,00	5,07	2,00	0,74	0,08	0,29	100,03	59
RI11	Und.	49,96	1,36	18,72	2,25	5,80	0,16	5,56	8,69	4,56	1,68	0,66	0,14	0,47	100,01	59
DC3	Und.	53,50	1,42	18,37	3,88	3,40	0,16	3,06	7,45	5,53	1,98	0,66	0,16	0,42	99,99	47
DE3	Und.	54,68	1,45	17,03	2,19	5,06	0,18	2,96	6,08	6,49	2,53	0,83	0,05	0,46	99,99	46
DF5	Und.	53,83	1,46	18,06	4,60	2,75	0,16	3,06	7,05	5,47	2,21	0,71	0,17	0,47	100,00	47
DH4	Und.	52,89	1,18	20,00	2,50	3,98	0,15	3,06	8,14	5,11	1,73	0,62	0,06	0,59	100,01	50
NC2	Und.	51,66	1,26	18,96	3,22	4,10	0,15	3,85	9,22	4,76	1,60	0,63	0,20	0,39	100,00	53
NE2	Und.	53,31	1,49	18,11	3,46	4,12	0,18	3,16	7,47	5,16	2,07	0,70	0,14	0,65	100,02	47

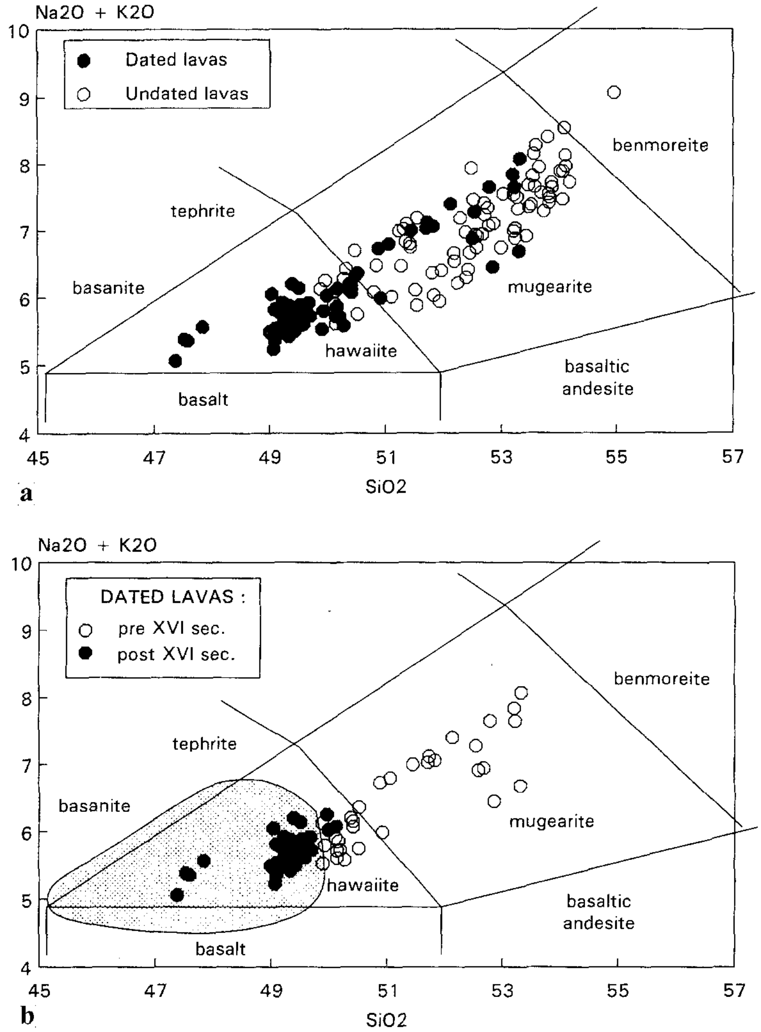

Fig. 1. TAS diagram (*Le Maitre*, 1989). **a** Dated lavas lavas are chiefly hawaiites grading into mugearites, whereas undated lavas are mostly mugearites to benmoreites. **b** Lavas earlier than 17th century are hawaiites-mugearites, whereas more recent lavas are clearly hawaiites. The field of lavas (hawaiites to alkalibasalts) erupted since 1974 to 1993 is also plotted (stippled area)

Civetta, 1977; *Condomines* et al., 1982). Typically, Ni and Cr contents are low with reference to typical WPB, even in the least differentiated of the R.M. lavas.

The chondrite-normalized (*Boynton*, 1983) REE patterns for the most mafic ($55 < \mathrm{Mg}^*_\mathrm{V} < 59$) of the analyzed lavas show strong LREE enrichment, and HREE depletion with $\mathrm{Ce}_\mathrm{N}/\mathrm{Yb}_\mathrm{N} = 16$–$18$ as in other mafic Etnean lavas of the alkalic series (*Carter* and *Civetta*, 1977; *Condomines* et al., 1982; *Cristofolini* et al. 1981a, 1984, 1987b; *Armienti* et al., 1989) and in the recent Na-alkalic volcanics from Ustica in the Tyrrhenian Sea (*Cinque* et al., 1988). This feature, typical of WPB, is however more pronounced than in typical alkalic OIB (*Clague* and *Frey*, 1982) and in Na-alkalic lavas from SE Sicily and the Sicily Channel (*Beccaluva* et al., 1981, 1982).

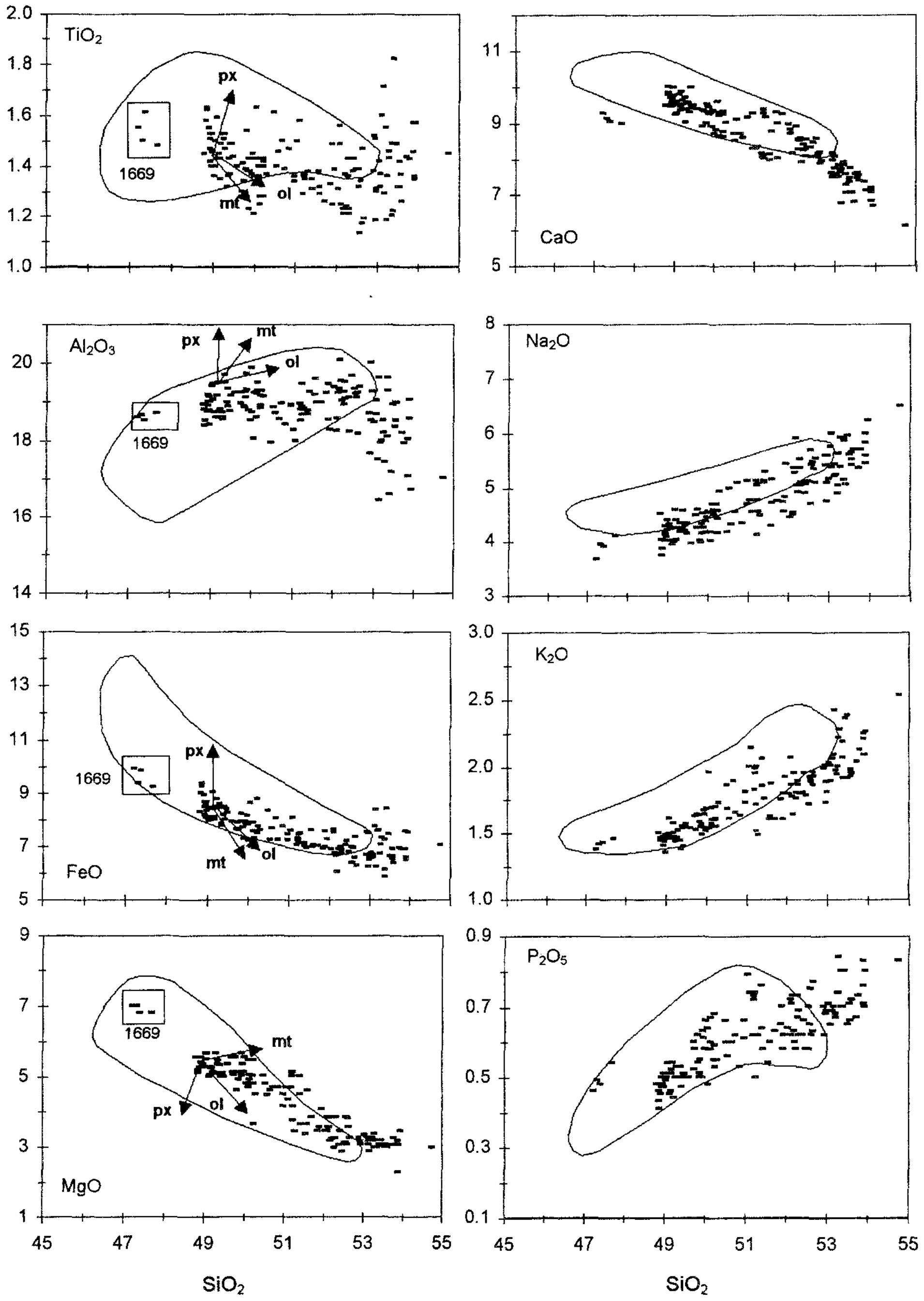

Fig. 2. In Harker diagrams, patterns for most oxides are related in a broad sense to a crystal fractionation process involving ol, pl, cpx and mt. The scatter around the average trends may be due to accumulation of mafic mineral phases (ol + mt). Continuous line encloses the field of historic Mongibello lavas (1329–1886) from literature (for references cf. *Cristofolini* and *Romano*, 1982)

Table 2. *Selected trace element analyses (p.p.m.) of R.M. lavas. Dat. = Dated lavas; Undat. = Undated lavas. The whole set is found in Corsaro and Cristofolini (1993) and may be requested of the authors*

sample		Cs	U	Ta	Zr	Hf	La	Nd	Sm	Eu	Tb	Lu	Y	Ni	V	Co	Cu
329M	Dat.	0,6	3,7	2,8	—	4,7	80,0	54	8,7	2,57	1,1	0,29	—	—	—	26	—
381C	Dat.	1,0	2,9	2,4	215	4,7	75,0	50	7,9	2,41	1,0	0,28	28	30	230	30	95
408D	Dat.	0,9	2,7	2,1	195	4,4	69,0	46	7,8	2,32	1,0	0,29	26	20	250	32	120
444C	Dat.	0,8	3,4	2,5	366	5,3	88,0	54	8,3	2,56	0,9	0,31	28	10	180	20	80
537C	Dat.	0,9	3,3	2,3	235	5,1	85,0	55	8,4	2,45	0,9	0,30	28	40	220	28	90
634G	Dat.	0,5	2,6	2,0	—	4,6	66,1	47	8,1	2,47	0,9	0,29	—	—	—	34	—
669D	Dat.	0,8	2,7	2,5	—	4,5	63,1	48	8,3	2,39	1,0	0,32	—	—	—	46	—
766A	Dat.	0,7	1,9	2,0	221	4,3	60,0	40	7,3	2,24	0,9	0,28	26	30	270	35	140
792L	Dat.	0,0	2,0	2,3	205	4,2	63,0	40	7,4	2,27	0,8	0,28	28	30	320	35	210
886A	Dat.	0,8	2,1	2,1	198	4,3	56,0	42	7,3	2,35	0,9	0,28	28	30	330	34	120
DC3	Und.	0,7	3,3	1,9	222	4,4	80,0	55	8,5	2,83	0,9	0,31	28	10	200	19	90
DE3	Und.	1,0	5,4	3,7	—	6,2	112,0	78	12,0	3,24	1,3	0,39	—	—	—	19	—
DH4	Und.	0,5	2,5	1,8	198	3,7	67,0	44	7,7	2,40	0,8	0,24	28	10	190	18	65
NC2	Und.	0,7	2,6	2,0	275	3,5	65,0	41	7,0	2,24	0,7	0,24	28	20	210	22	130
NI1	Und.	0,9	3,2	2,1	238	4,5	77,0	51	8,3	2,62	0,8	0,29	30	30	220	27	150
RB1	Und.	0,5	2,6	2,2	199	3,7	71,0	47	7,5	2,37	0,7	0,26	26	20	220	23	95
RF7	Und.	0,7	3,4	2,3	247	4,7	83,0	53	8,6	2,80	0,9	0,28	30	20	220	20	140
RF10	Und.	0,8	2,5	2,1	198	4,5	67,0	49	7,6	2,42	0,9	0,27	26	10	210	25	80
RH4	Und.	0,6	3,1	2,2	207	4,1	77,0	52	8,1	2,96	0,9	0,27	26	20	230	21	110

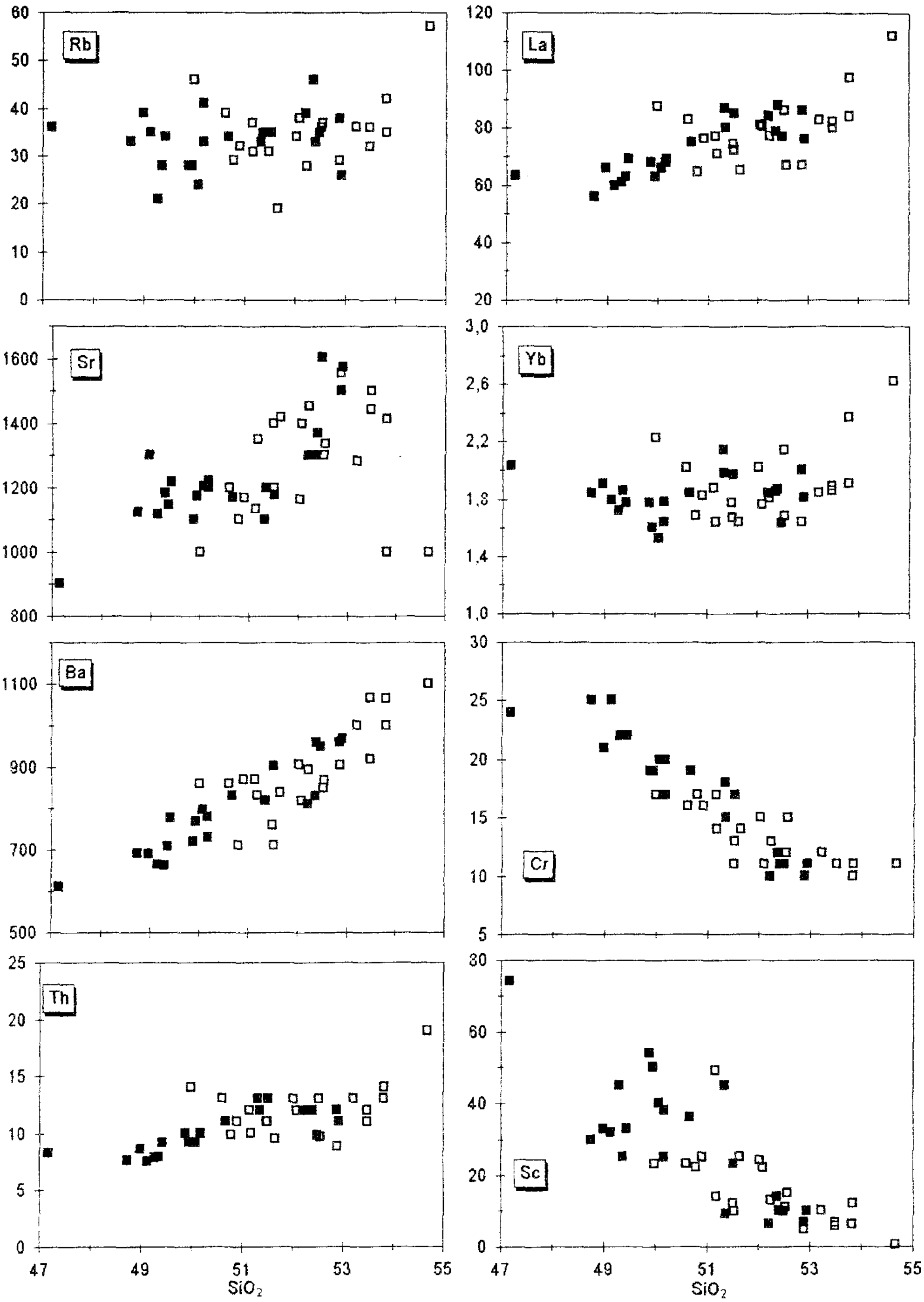

Fig. 3. Variation diagrams for the most significant trace elements. The observed distribution confirms that Undated Lavas (open squares) are more differentiated than Dated Lavas (full squares)

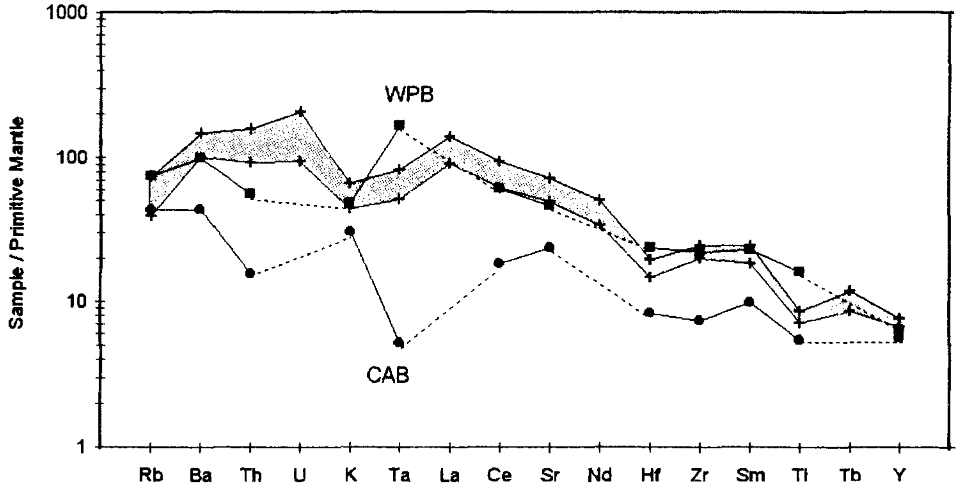

Fig. 4. Primitive Mantle (*Hofmann*, 1988) normalized pattern for trace elements in most mafic lavas ($55 < Mg_v^* < 59$). R. M. products (stippled area) are quite similar to WPB's with exceptions of lower Ta and Ti contents and higher Th. CAB pattern is also plotted for comparison

Primitive Mantle-normalized patterns (*Hofmann*, 1988) for trace elements from the least differentiated R. M. lavas ($55 < Mg_v^* < 59$) are quite similar to WPB (*Pearce*, 1982), except for lower Ta and Ti contents, and higher Th contents (Fig. 4). This character, already recognized for smaller sets of data, appears as a distinctive signature for the Etnean alkalic rocks (*Beccaluva* et al., 1982: *Cristofolini* et al., 1987a; *Armienti* et al., 1989) and may reflect an imprint of subduction related components on the mantle source of the Etnean alkalic magmas. This character is further confirmed for the most mafic of the analyzed R.M. lavas by several discriminant plots (Ti–Zr–3Y, *Pearce* and *Cann*, 1973; Th–Hf–Ta; *Wood, 1980; Pearce*, 1982), in which they plot close to or across the boundary between the CAB and WPB fields.

Sr-isotope distribution

$^{87}Sr/^{86}Sr$ values were measured for 35 lavas and range from 0.70332 to 0.70355, and match fairly well published data (*Carter* and *Civetta*, 1977; *Cristofolini* et al., 1987a; *Armienti* et al., 1989; *Barbieri* et al., 1993).

Significant differences appear well beyond the analytical uncertainty, even among samples from the same flow (1329, 1444, 1669). In the last 500 years the isotope ratio tends to increase with time (Fig. 5), but older lavas show values spanning almost the entire range, suggesting that $^{87}Sr/^{86}Sr$ values may have oscillated around 0.70344.

$^{87}Sr/^{86}Sr$ are little correlated to Sr, Rb and K_2O, as also reported by *Carter* and *Civetta* (1977) for R.M. products. This suggests that bulk assimilation of shallow crustal materials (poor in Sr and rich in Rb and K_2O) is not the main control of the observed isotopic variation.

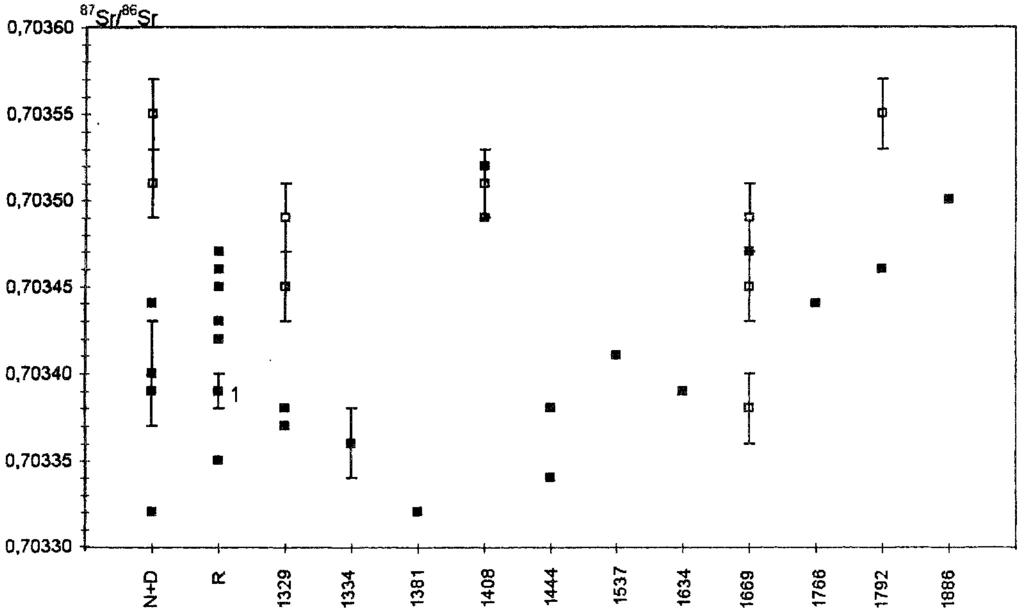

Fig. 5. $^{87}Sr/^{86}Sr$ values of analyzed lavas. Full squares: samples analyzed at the Dipartimento di Geofisica e Vulcanologia, Naples; Open squares: samples analyzed at the Dipartimento di Scienze della Terra, Rome. N + D: Lavas with "well" and "poorly" defined flow boundaries. R: Recent lavas. For data points with no marked analytical error, it is that of sample numbered "1"

The poor correlation of $^{87}Sr/^{86}Sr$ values with K_2O, Rb and Cs contents (a point also noted by *Armienti* et al., 1989), makes the assumption unlikely that isotopic variability is related to alkali enrichment due to selective diffusion (*Clochiatti* et al., 1988), also involving radiogenic ^{87}Sr removed by fluids from the clay fraction of sedimentary rocks (*Barbieri* et al., 1993).

Petrologic interpretation

For a petrologically consistent interpretation of the various data, features related to processes affecting magma compositions within the crust were distinguished from those dependent on the nature of the source region and the melting mechanism.

Processes within the crust

Whole rock chemical data suggest that the observed compositional variation is chiefly related to crystal fractionation from a common parental magma, as indicated by:

i) silica vs. major and trace elements;
ii) major elements mass balance;
iii) the incompatible element behaviour and comparison between computed mass balance and measured variation.

Table 3. *Mass balance calculations of major elements (Stormer and Nicholls, 1978). R = residua; S% = percent solid fractionated; ol = olivine; cpx = clinopyroxene; pl = plagioclase; mt = magnetite*

STEPS	R	S%	ol	cpx	pl	mt
A: 634G-329M	0,07	33	20	13	61	6
B: 329M-444D	0,13	12	18	17	63	2
C: 444D-RF7	0,08	21	—	13	79	8
D: RF7-DE3	0,07	19	6	15	74	5

i) The overall silica variation vs. other major element oxides and trace elements qualitatively matches trends related to fractionation of solid phases with compositions measured in the analyzed rocks. However, the scatter around the trends of variation, much larger than analytical accuracy, suggests an important role of selective subtraction or accumulation of crystals, confirmed by petrographic data, in controlling the observed pattern of variation, which cannot be regarded as a liquid line of descent. For example the most basic samples of the 1669 flow ($SiO_2 = 47.18\%$) may easily be related to the composition of the other lavas from the same flow by addition of olivine and opaque oxides (Fig. 2), as confirmed by petrographic data (P.I. = 30; $C.I._{phx} = 59$).

ii) For mass balance calculations we chose five of the less porphyritic rocks (634G, 444D, 329M, RF7, DE3) covering the R.M. compositional range. The overall chemical variation was then modelled using XLFRAC (*Stormer* and *Nicholls*, 1978) via four separate steps, with fractionating phase compositions (ol, cpx, pl, mt) obtained by microprobe analysis (unpublished data; *Corsaro* and *Cristofolini*, 1993). In contrast to petrographic data, the third step (Table 3) is clearly anomalous, as no olivine appears to be involved in fractionation. This again suggests that even in the most favourable cases, the observed variation does not strictly follow a liquid line of descent.

iii) The pattern of incompatible element variation (*Treuil* and *Joron*, 1975) does not match a simple crystal fractionation model, because either the binary correlation is low or the regression lines do not intercept the origin of the plots (*Corsaro* and *Cristofolini*, 1991); the latter observation suggests magma mixing as a possible mechanism of variation.

Also, trace element mass balance calculations using a Rayleigh crystallization model for the same four steps discussed above, with bulk distribution coefficients from *Villemant* et al. (1981), show little agreement between computed and measured enrichment (or depletion) factors, particularly for compatible elements (Fig. 6).

Overall, the foregoing data and observations appear to support processes other than simple crystal fractionation as responsible for the differentiation of the R.M. sequence. Taking into account the temporal variation patterns of major and trace elements, and the variable Sr-isotope ratios, magma mixing in RTF chamber/s (*O'Hara*, 1977; *O'Hara* and *Matthews*, 1981) with successive influxes of mafic melts having slightly different geochemical and isotopic features into variously differentiated magmas, might explain the overall observed data.

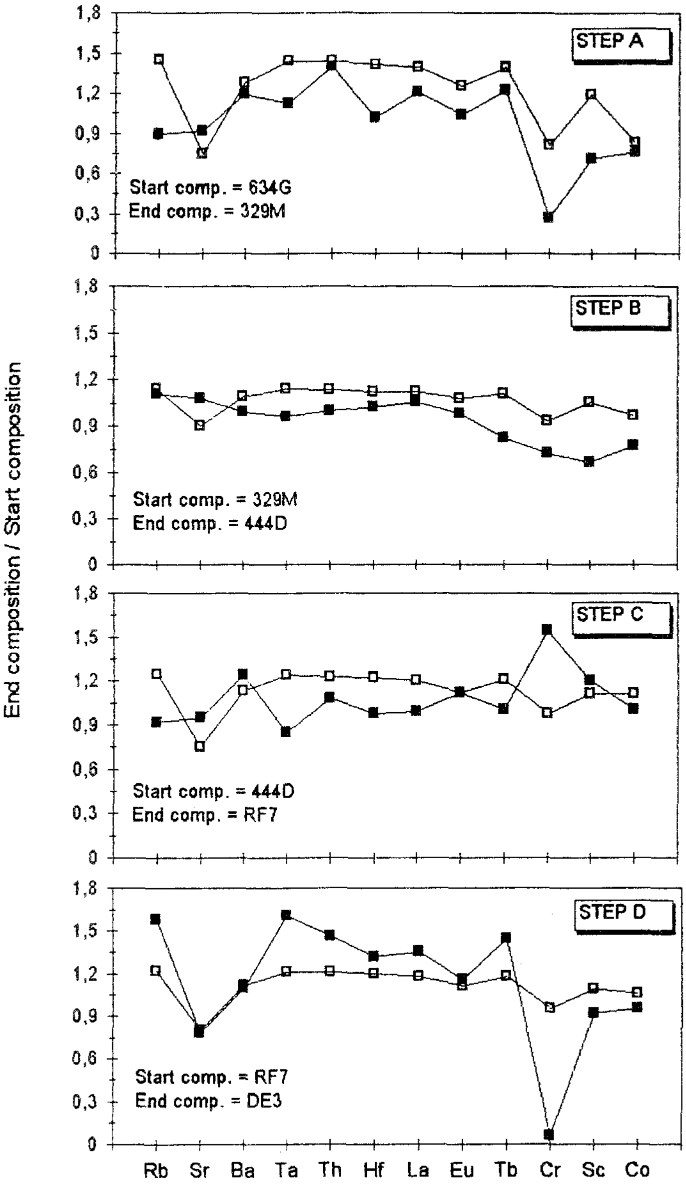

Fig. 6. Trace elements mass balance computed for steps A, B, C, D according to a Rayleigh crystallization model. Full squares: measured values; open squares: calculated values. See text for discussion

This model might at least qualitatively account for:

i) the major and trace element variation with time: the most recent lavas are on average more basic, being probably related to a larger proportion of magmas from an upper mantle source injected into reservoirs at intermediate depth, gradually substituting for earlier, more differentiated melts residing there;

ii) the difference between measured major and trace element contents and those computed according to a fractional crystallization model;

iii) the Sr-isotope variation, even within lavas from the same eruption, may be accounted for by one or several magma reservoirs open to the influx of mantle-derived melts and mixed in varying proportions with the residing differentiated magmas, imparting on them the imprint of an isotopically heterogeneous source region.

Contamination by shallow crustal material is ruled out by the lack of crustal xenoliths and xenocrysts, the overall limited variation range of isotope ratios and the very poor correlation between $^{87}Sr/^{86}Sr$ and any other chemical parameter that should be sensitive to mixing of shallow crustal materials and mantle-derived magma.

Source related characters

Sr-isotope ratios are consistent with a mantle source which is depleted in Rb with respect to Bulk Earth composition, as also shown by Etnean lava compositions compared to the Mantle Array (*Armienti* et al., 1989).

It seems very unlikely that the isotopic variability of analyzed lavas may be related to either assimilation of shallow crustal material or selective diffusion involving radiogenic ^{87}Sr (*Clocchiatti* et al., 1988). The most likely hypothesis is that the variation in Sr isotope distribution is related to a compositionally zoned source region, as shown by a study of upper mantle xenoliths chiefly from mafic alkalic lavas, which may be isotopically heterogeneous even at a centimetric scale (*Spera*, 1987).

Some indication for a recent event that increased $^{87}Sr/^{86}Sr$ appears for lavas erupted from 1329 to 1886, and is confirmed by data for more recent eruptions (1971–1986; *Armienti* et al., 1989). This might be accounted for by a higher proportion of magma from slightly Rb-enriched (possibly deeper) sources rising to the surface during the last 500 years.

Source melting mechanism

For the purpose of modelling the generation of R.M. magmas, we assumed a four-phase garnet lehrzolite mineralogy ($Ol_{57}Opx_{17}Cpx_{12}Gr_{14}$; *Yoder,* 1976) of the source which chemically matches Primitive Mantle composition (*Hofmann,* 1988). To prove the consistency of this indirect assumption, we recall that peridotite xenoliths in ancient Etnean lavas (*Aurisicchio* and *Scribano*, 1987) have been interpreted as residues of a garnet leherzolite melting event, and that the distinctive HREE depletion ($Ce_N/Yb_N = 15–18$) in analyzed lavas may be related to HREE retention by residual garnet.

We calculated melt compositions resulting from modal equilibrium partial melting of the source, and then compared those to measured compositions of the most mafic ($55 < Mg_v^* < 59$) of the analyzed lavas. Since these are not representative of primary magma compositions, the calculated and actual data were normalized to La values, and then their enrichment with respect to a La-normalized Primitive Mantle composition was computed.

Contents of most trace elements (computed with D's by *Frey* et al., 1978; *Henderson*, 1982) are consistent with melt fractions $F > 5\%$, larger than expected for the generation of alkalic melts (Fig. 7a). In contrast, the resulting patterns for actual

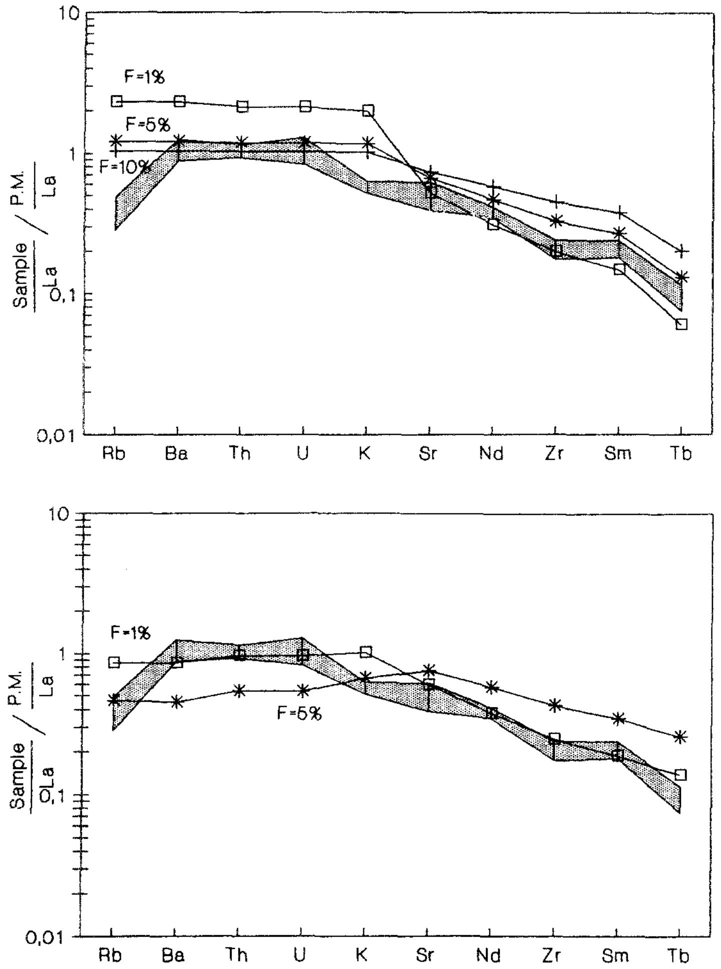

Fig. 7. Modelling of melting processes of source region. In order to circumvent crystal fractionation effects, model and actual data are normalized to La, and their enrichment to La normalized P.M. is computed. **a** The actual trace elements patterns in the least differentiated rocks (55 < Mg^*_v < 59; stippled areas) conform to the computed ones assuming modal melt fractions (F > 5%) larger than what is expected for the generation of alkalic melts. **b** Assuming low (F < 5%) modal partial melting degree of a source depleted by an earlier melting event (F = 1%), the actual and model compositions compare fairly well

and computed compositions compare fairly well for F < 5% of a source depleted by an earlier low degree (F = 1%) modal melting event (Fig. 7b). This is also confirmed by the Sm/Nd vs. Rb/Sr plot (Fig. 8), and matches observations on the grounds of isotope data, suggesting a source depleted by earlier melting events (*Armienti* et al., 1989).

Conclusions

New data on the whole R.M. sequence show that the most ancient lavas are mugearites and benmoreites (with petrographic features suggesting magmas having resided for long period of time at crustal levels), grading with time into hawaiite for

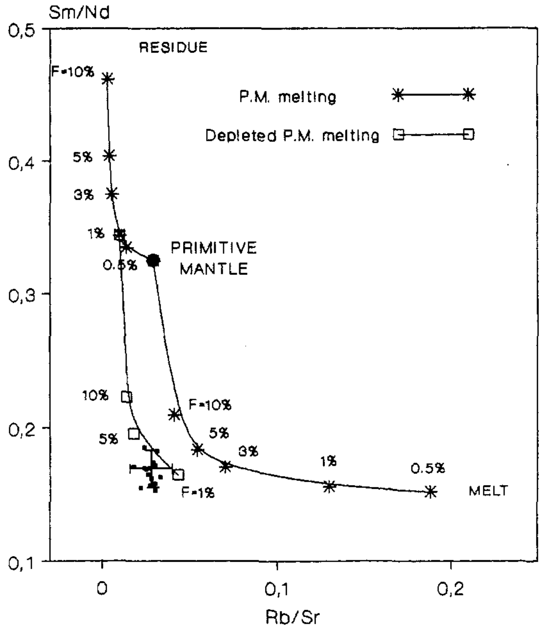

Fig. 8. Variation of Rb/Sr vs. Sm/Nd ratios in the melts and residues by different degrees of Primitive Mantle modal melting. Actual data match fairly well a model composition produced at low melting degrees ($F < 5\%$) of a source already depleted by earlier melting ($F = 1\%$)

the youngest historically dated lavas. On a wider time scale, no chemical gap is apparent between the studied R.M. succession and, either the immediately preceding Ellittico centre products (mugearites-benmoreites-trachytes; *Cristofolini* et al., 1991), or the 20th century lavas (alkali basalts-hawaiites).

Petrochemical data, temporal variation patterns of major and trace elements and the variable Sr-isotope ratios, suggest that processes other than simple polybaric crystal fractionation are responsible for the differentiation of the R.M. sequence; similarly magma mixing in one or more RTF chamber/s (*O'Hara*, 1977; *O'Hara* and *Matthews*, 1981) seems unable to account for all available data.

To constrain the geometry of the Etnean plumbing system, we can consider indirect information from geophysical data, assuming that the present situation is unchanged since the start of its activity. We thus interpret (Fig. 9) the shallow low velocity domains around the axial region of the volcano (*Hirn* et al., 1991) as various magma batches in which differentiation processes, mainly involving plagioclase fractionation, are occurring.

A "low velocity layer" at about 17 km below sea level, suggested on the basis of seismological data (*Sharp* et al., 1980) beneath the Etnean summit region, occurs at a depth where magmas should cross compressional tectonic structures related to the overriding of a thinned Tyrrhenian lower crust onto a thick African crust. Magmas may slow down at this level, or reside there and fractionate significant amounts of near-liquidus mafic phases.

Since geophysical data show that underneath the Etnean summit region the Moho rises to a depth of 27 km (*Cristofolini* et al., 1979), it is suggested that dense magma "diapirs" may reside at the boundary between the visco-elastic upper mantle and the brittle lower crust and start fractionation before being capable of rising to shallower levels. This deeper long term storage might account for the absence of

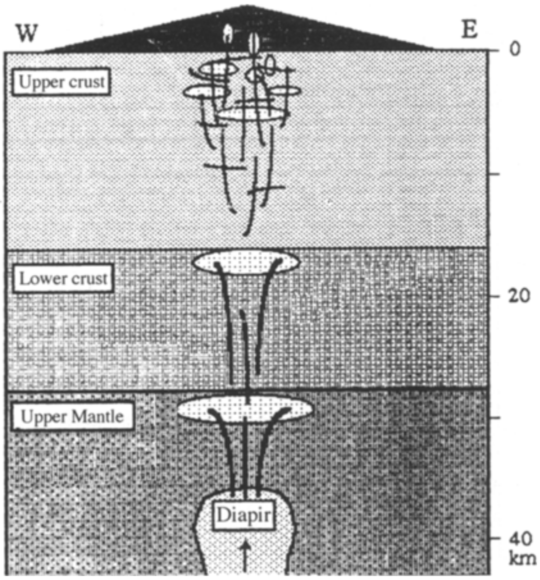

Fig. 9. Schematic W–E section of the lithosphere in the Etnean region showing spatial distribution of the plumbing system discussed in the text. The model is based on geophysical data from various authors (*Sharp* et al., 1980; *Cristofolini* et al., 1979)

primitive basalts among the Etnean alkalic lavas and may be indicated by petrological data: wehrlite nodules have been reported (*Scribano*, 1989; *Aurisicchio* and *Scribano*, 1987), showing poikilitic textures with Cr-diopside enclosing olivine and with Cr-spinel; these were interpreted as cumulates, equilibrated at high temperature and pressure in the field of spinel peridotites, extending at depths from about 25 to 50 km for temperatures below the basalt liquidus (1150–1250 °C; *Yoder*, 1976). Extensive fractionation of Ni- and Cr-enriched mafic phases might be a clue for interpreting the low contents of these elements even in the least differentiated of the Recent Mongibello lavas, relative to typical WPB.

Sr-isotope distribution in the analyzed lavas unequivocally indicates their origin from a mantle domain Rb-depleted with repect to the Bulk Earth, although some variation of $^{87}Sr/^{86}Sr$ ratio, even among lavas from the same eruption, might be referred to the presence of isotopically distinct magmas.

The actual trace elements pattern of analyzed rocks conforms fairly well to the calculated one assuming modal low degree melting ($F < 5\%$) of a garnet leherzolite source which has already been depleted by an earlier melting event ($F = 1\%$).

To explain the mild CAB signature commonly observed in the R. M. magmas, which otherwise show WPB features typical of a Na-alkali series, we note the location of Mt. Etna, against the trascurrent faults of the Mt. Kumeta-Alcantara system. This deep shear zone, along which the *African* and *Tyrrhenian* mantle-crust domains are in contact, might be a preferred path along which deeply generated components with CAB signature could have migrated into the magma source region, modifying its composition.

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