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THE CAINOZOIC CALCALKALINE MAGMATISM OF THE WESTERN MEDITERRANEAN AND ITS GEODYNAMIC SIGNIFICANCE

Abstract. Space-time distribution and petrogenetic affinity of the Cainozoic calcalkaline orogenic magmatism from the western Mediterranean (from Provence to Campania) has been reassessed, on the basis of new petrochemical and Sr-Nd isotopic data, for a better understanding of the geodynamic evolution of the area. The calcalkaline magmatism may be subdivided in two main cycles: the older, Oligo-Miocene in age (34-20 Ma in Provence, and 32-13 Ma in Sardinia); and the younger, Pliocene-Quaternary in age (Eolian area <2 Ma, Campania ca. 2 Ma, and part of the Tyrrhenian oceanic crust 4-1.6 Ma). The tholeiitic/calcalkaline serial affinity of the early magmatism both in Provence and Sardinia and its zonation in Sardinia for the period 21-18 Ma (tholeiitic/calcalkaline in the south, high-K calcalkaline/shoshonitic in the north) imply subduction of N-NW dipping oceanic lithosphere, at least from Upper Eocene to Lower Miocene. The existence at that time of subducting oceanic lithosphere, tentatively assigned to the Sicilide-Canetolo basin, is also required by the chronologically correlated oceanic opening of the Ligure-Balearic basin and anticlockwise rotation of the Sardinia-Corsica microplate. After a period of quiescence, coinciding approximately with the last main compressional phases in the northern Apennines, the second calcalkaline cycle developed during Pliocene-Quaternary times along the eastern peri-Tyrrhenian margin, from the Eolian area to Campania, in relation to a rifting phase affecting the Alpine-Apennine chain, east of Sardinia. This orogenic magmatism - as well as che diachronous oceanization of the Tyrrhenian basin and the southeastward migration of the Calabrian arc - can be satisfactorily interpreted in the framework of island arc - back-arc basin systems where, during the early stages of back-arc opening, arc- related volcanism is absent on both the remnant arc (Sardinia) and the migrating fore-arc plate (Eolian-Calabrian area) above a seismically active subduction zone (Ionian oceanic lithosphere). Geochemical and isotopic characteristics of the peri-Tyrrhenian orogenic magmas indicate that their mantle sources were hybridized by continental crust material (mainly upper crust- derived sediments) dragged down during subduction processes to a limited extent in the Eolian area (Stromboli), and more extensively further north in the Campanian and Roman provinces. This confirms the existence of a major lithospheric discontinuity (Ortona-Roccamonfina line and 41N° transform fault) separating a continental subducted slab (Adriatic) under the Central Apennines, and an old oceanic, still seismically active, subducting slab (Ionian) under the Calabrian-Eolian area.

INTRODUCTION

The Cainozoic magmatic activity extending from the European margin to the Tyrrhenian area (Fig. 1) is characterized by a wide compositional range, which covers most of the known volcanic suites: orogenic calcalkaline l.s. (Provence, Sardinia, Tyrrhenian oceanic crust p.p., Eolian Arc, and Campania), orogenic K-alkaline (Roman Province), anorogenic Na-and K-alkaline (French and Spanish coasts, Sardinia, and Tyrrhenian volcanic seamounts), and MORB-type (Tyrrhenian oceanic crust p.p.) (Beccaluva et al., 1987). Among the above associations, the orogenic calcalkaline suites which developed from Provence and Sardinia (Oligocene-Miocene) to the Eolian area and Campania (Quaternary) are of particular interest, since they represent a first-order geodynamic marker of the converging plate setting between the European and African

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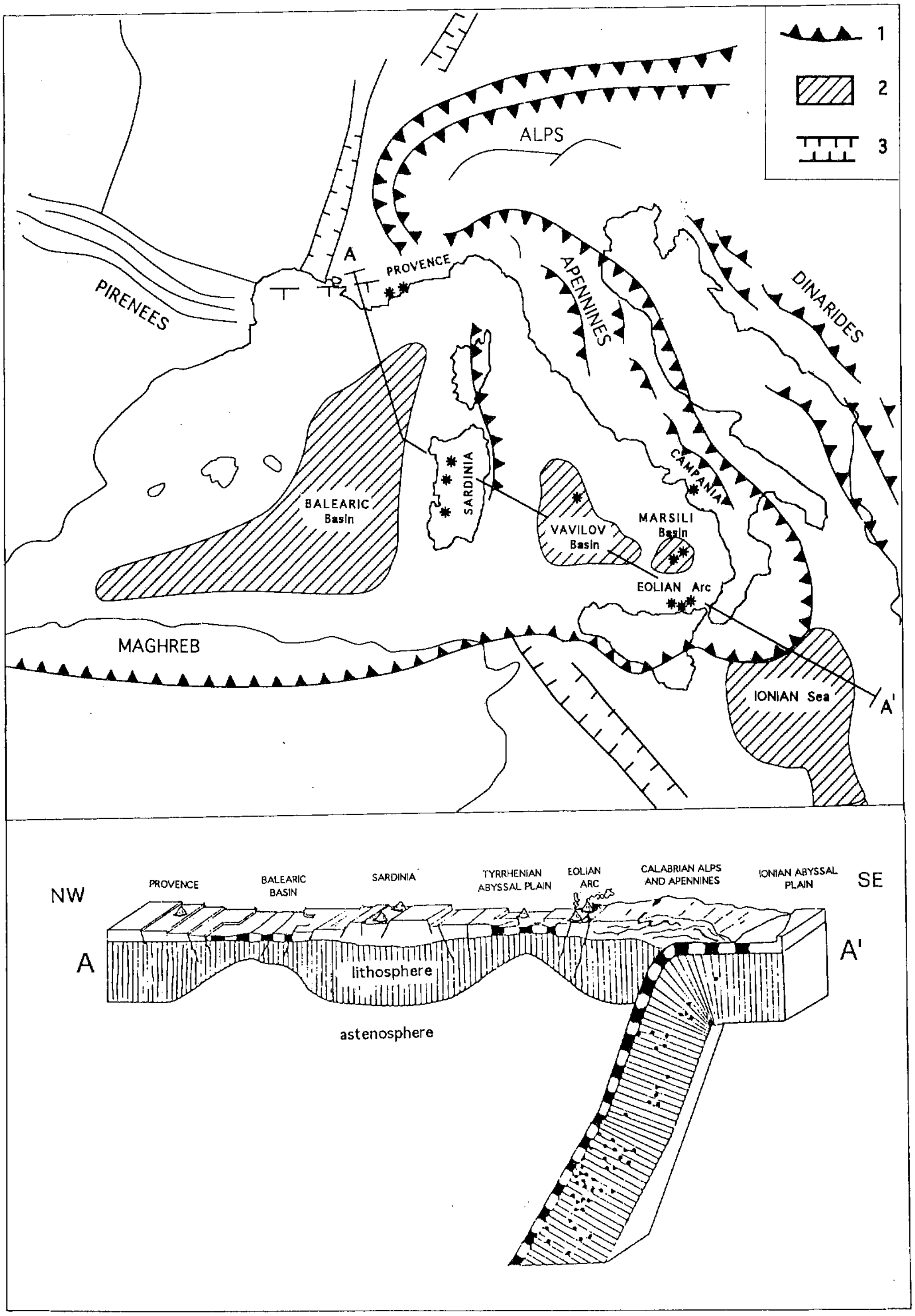

Fig. 1 - Structural sketch map of the Western Mediterranean area. Symbols: 1 = compressional front of the Alpine and Apennine-Maghrebian chains; 2 = areas with oceanic crust; 3 = main graben structures; stars = calcalkaline magma occurences. AA^{1} = cross-section between provence and Ionian Sea; dots indicate intermediate and deep hypocenters (after Gasparini et al., 1982); black and white stripes denote oceanic-type crust.

Table 1 — Major and trace element analyses of Oligo-Miocene lavas and gabbroic xenoliths from Villeneuve-Loubet and Agay (Provence).

	VILLENEUVE-LOUBET		AGAY							
	PR 1 Th/CA-A	PR 2 Th/CA-A	PR 3 Th/CA-D	PR 4 Th/CA-D	PR 5 Th/CA-D	PR 7 Th/CA-D	PR 8 Th/CA-D	PR 6 Th/CA hb-Gb	PR 7A Th/CA hb-Gb	PR 8A Th/CA hb-Gb
SiO2	60,10	58,80	64,12	64,67	64,46	64,56	64,62	48,01	46,59	52,16
TiO2	0,95	0,96	0,40	0,44	0,49	0,46	0,46	2,98	2,13	2,65
Al2O3	17,43	19,16	18,54	17,56	17,84	17,35	17,44	16,02	16,68	14,81
Fe2O3	0,96	0,72	0,49	0,50	0,53	0,53	0,54	1,61	1,61	1,55
FeO	5,79	4,32	2,96	2,99	3,16	3,18	3,19	9,65	9,63	9,31
MnO	0,11	0,28	0,13	0,11	0,17	0,13	0,11	0,27	0,29	0,29
MgO	1,39	2,28	1,82	2,12	1,93	2,23	2,11	7,34	9,19	6,32
CaO	7,04	7,98	5,95	5,06	6,04	5,53	4,88	9,41	10,69	7,79
Na2O	3,60	3,81	4,33	5,02	4,12	4,56	5,01	3,59	2,32	4,02
K2O	2,26	1,38	0,99	1,28	1,02	1,21	1,42	0,51	0,33	0,41
P2O5	0,36	0,29	0,27	0,24	0,26	0,25	0,23	0,62	0,53	0,69
LOI	1,51	1,41	4,41	1,81	3,41	1,91	1,10	1,11	2,53	2,83
V	141	167	63	70	74	77	66	316	244	285
Cr	32	21	24	33	16	19	20	200	243	85
Co	11	17	4	7	7	8	9	36	34	25
Ni	14	11	9	11	7	8	9	79	91	15
Rb	61	37	38	46	36	38	50	9	6	12
Sr	266	367	338	383	353	381	372	338	290	324
Ba	523	431	322	501	297	499	525	189	183	173
Zr	167	104	33	68	58	63	64	289	104	322
Nb	10	8	8	21	28	19	0	20	17	23
Th	7	5	2	5	4	4	3	3	2	6
La	17	10	10	12	17	16	10	32	18	25
Ce	25	24	26	40	30	37	17	65	37	55
Y	21	28	9	7	10	8	9	44	35	42

Abbreviations: Th = Tholeiites; CA = Calcalkaline; A = Andesites; D = Dacites; hb-Gb = hornblende Gabbros.

domains. Hence, the question arises whether and how these Cainozoic magmatic events may be interpreted in a unique framework: that is, if they can be referred to the spatio-temporal evolution of a common tectono-magmatic system.

In this paper we focus attention of the orogenic calcalkaline associations from Provence to Campania for a better definition of their magmatic affinity and spatio-temporal distribution, and an assessment of their geodynamic significance for the Cainozoic evolution of the Western Mediterranean area.

SPATIO-TEMPORAL DISTRIBUTION OF THE CALCALKALINE MAGMATISM

Provence

In Provence, the Cainozoic orogenic subvolcanic and volcanic rocks are mainly represented by the microdiorites, basalts, andesites and dacites of the Estèrel region (34-20 Ma: Bellon, 1981), and andesitic clasts in conglomerates near Nice. In Table 1, major and trace element analyses of representative samples from Agay (Estèrel region) and Villeneuve-Loubet (near Nice) are reported.

The whole compositional range varies from andesites to dacites, the latter including gabbroic cognate xenoliths. In Fig. 2, these rocks are transitional between the tholeiitic and calcalkaline series, disregarding the anomalous K-enrichment of the two andesites which is evidently due to the strong alteration in clay minerals, particularly celadonite, affecting these lava clasts. Petrographically, andesites contain clinopyroxene, plagioclase and magnetite phenocrysts, associated with brown amphibole in some samples. Plagioclase, amphibole, and magnetite mainly constitute the gabbroic xenoliths, most probably representing the cumulate assemblage, the removal of which determined the differentiation from andesitic to dacitic magmas. Dacites are the most evolved rocks of this suite and show the same phenocryst paragenesis, with plagiocla-

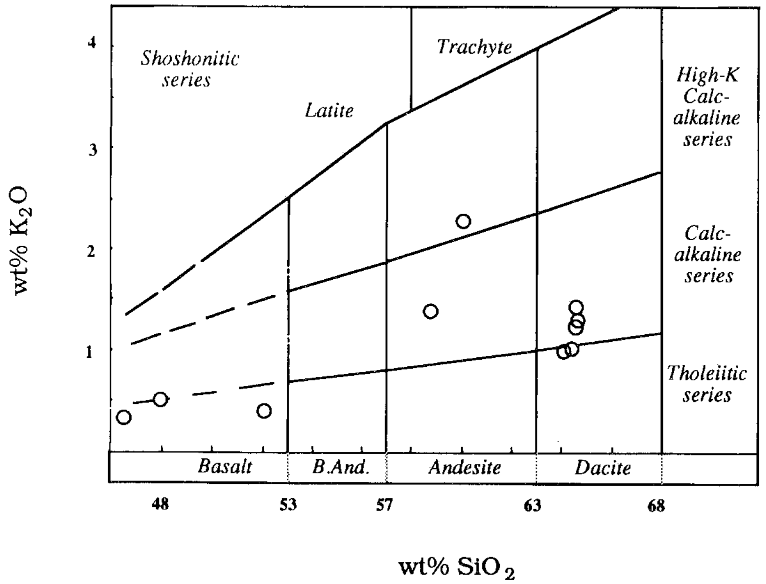

Fig. 2 - K_2O vs. SiO_2 diagram (after Peccerillo and Taylor 1976, modified) for Oligo-Miocene lavas and gabbroic xenoliths from Provence.

se prevailing over amphibole and magnetite. Accordingly, dacites and cumulate gabbros are depleted and enriched in Zr, Ti, and Y, respectively, owing to the favourable partitioning of these elements in amphibole and magnetite (Pearce and Norry, 1979).

Primordial mantle-normalized incompatible element distributions (Fig. 3) of the andesitic rocks reveal the usual characteristics of tholeiitic/calcalkaline orogenic suites: enrichment of Low Field Strength Elements (LFSE) such as Rb, Ba, Th and K and significant Ti and Nb negative anomalies. The enrichment of LFSE, coupled with the constantly low contents of High Field Strength Elements (HFSE) and Light-REE, suggests that the metasomatic enrichment of the mantle source mainly involved geochemical components mobilized in aqueous fluids driven off subducted oceanic crust (cf. Pearce, 1982).

On the whole, such a tholeiitic/calcalkaline affinity is typical of the initial stages of orogenic magmatism in active continental margins with subduction of oceanic lithosphere. Therefore, age and serial affinity of the magmatism consistently indicate that the paleo-European continental margin was affected by subduction of oceanic lithosphere at least from Upper Eocene to Lower Miocene.

Sardinia

The Oligo-Miocene volcanism in Sardinia has a calcalkaline l.s. character, and has usually been considered related to a N-NW dipping subduction zone along the paleo-European continental margin, which resulted in the Oligocene rifting between Sardinia and Provence (Cherchi and Montadert, 1982; Burrus, 1984). This ultimately led to the opening of the Balearic back-arc basin and anticlockwise rotation of the Sardinia-Corsica microplate (Montigny et al., 1981; Beccaluva et al., 1987).

The volcanic activity of the island started at about 32 Ma (Beccaluva et al., 1985), with basaltic-andesitic lavas outpoured sporadically along the western graben structure. From about 23 Ma, rhyodacitic ignimbrites outpoured over large sectors of the same area, in alternation with, and partly contemporary with, basaltic-andesitic lavas up to about 13 Ma, when the volcanic activity ended in Sardinia.

It is noteworthy that between 32 and 26 Ma, the magmatic activity in southern Sardinia (Mt. Arcuentu: Assorgia et al., 1985) had partly a tholeiitic/calcalkaline affinity as in Provence, whereas a significant spatial zonation of the volcanism took place between 21 and 18 Ma

Table 2 — Major and trace element analyses of representative Oligo-Miocene lavas from several localities of Sardinia.

	LOGUDORO-BOSANO										ANGLONA		ARCUENTU		MARMILLA			
	A503	A504	A540	A530	A567	A501	A519	A521	A577	A578	AL1	AL3	AR2B	AR4	A703	A713	A714	A853
	CA-BA	CA-BA	CA-A	CA-BA	HK-CA-A	CA-B	CA-B	CA-BA	CA-B	HK-CA-A	SHO-La	SHO-Tr	CA-BA	CA-BA	Th/CA-BA	Th/CA-B	Th/CA-B	Th/CA-B
SiO2	53,03	54,80	61,61	53,48	59,23	50,58	47,88	53,03	50,96	60,39	58,41	62,09	55,93	55,01	55,62	52,12	52,71	52,69
TiO2	0,96	1,18	0,74	0,84	0,65	1,03	0,90	1,07	0,86	0,90	0,78	0,79	0,73	0,88	0,86	0,76	0,74	0,81
Al2O3	20,42	18,68	16,29	20,18	17,16	17,90	17,56	17,75	19,09	17,74	18,37	18,25	16,95	17,40	16,10	17,14	13,57	14,67
Fe2O3	1,02	1,18	0,92	1,21	0,91	1,49	1,56	1,35	1,32	0,91	0,84	0,69	1,18	1,20	1,14	1,16	1,32	1,28
FeO	6,11	7,13	5,54	7,28	5,48	8,96	9,36	8,09	7,91	5,43	5,05	4,15	7,06	7,20	6,83	7,02	7,92	7,69
MnO	0,15	0,13	0,20	0,17	0,12	0,19	0,17	0,16	0,27	0,14	0,12	0,09	0,15	0,16	0,14	0,13	0,13	0,13
MgO	3,00	3,74	2,35	3,57	3,32	5,52	7,75	3,97	4,88	3,40	1,83	0,43	5,43	5,95	7,55	5,88	9,91	9,35
CaO	9,20	6,41	5,10	9,52	7,09	10,34	11,60	9,42	10,82	6,94	7,09	5,78	8,99	9,01	9,05	10,75	8,93	9,54
Na2O	3,01	3,00	2,43	3,05	2,66	2,07	1,88	2,34	2,00	2,91	3,09	3,05	2,09	2,16	2,05	1,79	1,57	1,47
K2O	1,79	0,68	3,12	1,07	2,10	0,80	0,67	1,11	0,72	2,05	3,73	4,26	1,34	1,30	1,07	0,26	1,03	0,31
P2O5	0,25	0,26	0,21	0,30	0,23	0,30	0,28	0,25	0,18	0,27	0,28	0,27	0,18	0,16	0,18	0,18	0,18	0,19
LOI	1,11	7,16	3,77	0,83	1,15	1,99	1,90	1,91	1,33	2,16	1,71	1,54	4,01	3,62	1,63	2,98	2,97	1,16
V	189	292	181	253	141	316	322	271	265	195	116	96	209	226	241	219	252	220
Cr	14	37	47	37	26	48	157	36	48	28	36	21	341	127	329	184	701	420
Co	22	20	15	25	15	30	43	25	37	17	14	10	30	29	25	29	40	38
Ni	10	10	16	14	14	15	58	19	31	14	15	11	81	30	72	78	220	124
Li	17	24	102	9	16	8	6	9	16	18	28	19	9	5	7	9	21	26
Rb	45	18	126	26	70	19	20	24	26	77	137	99	46	40	28	11	33	22
Sr	401	299	253	325	340	291	375	326	309	352	414	407	192	202	211	302	171	212
Ba	303	390	373	203	320	143	103	221	180	338	353	396	369	409	396	177	256	199
Zr	101	131	107	75	143	58	48	64	60	160	171	161	97	117	120	51	53	86
Nb	9	8	9	6	9	5	5	8	8	11	12	11	7	5	7	5	5	5
Th	3	4	5	2	8	3	4	4	3	8	13	16	6	8	6	2	6	4
La	18	23	23	11	24	nd	8	10	9	27	26	27	15	12	20	8	8	13
Ce	38	34	51	29	50	26	17	23	14	57	54	54	31	26	51	20	12	33
Y	27	31	26	20	33	20	19	32	24	32	23	18	26	25	26	17	17	25

Abbreviations: HK=High potassic; SHO=Shoshonitic; B=Basalts; BA=Basaltic andesites; La=Latites; Tr=Trachytes nd=not determined (other abbreviations as in Table 1).

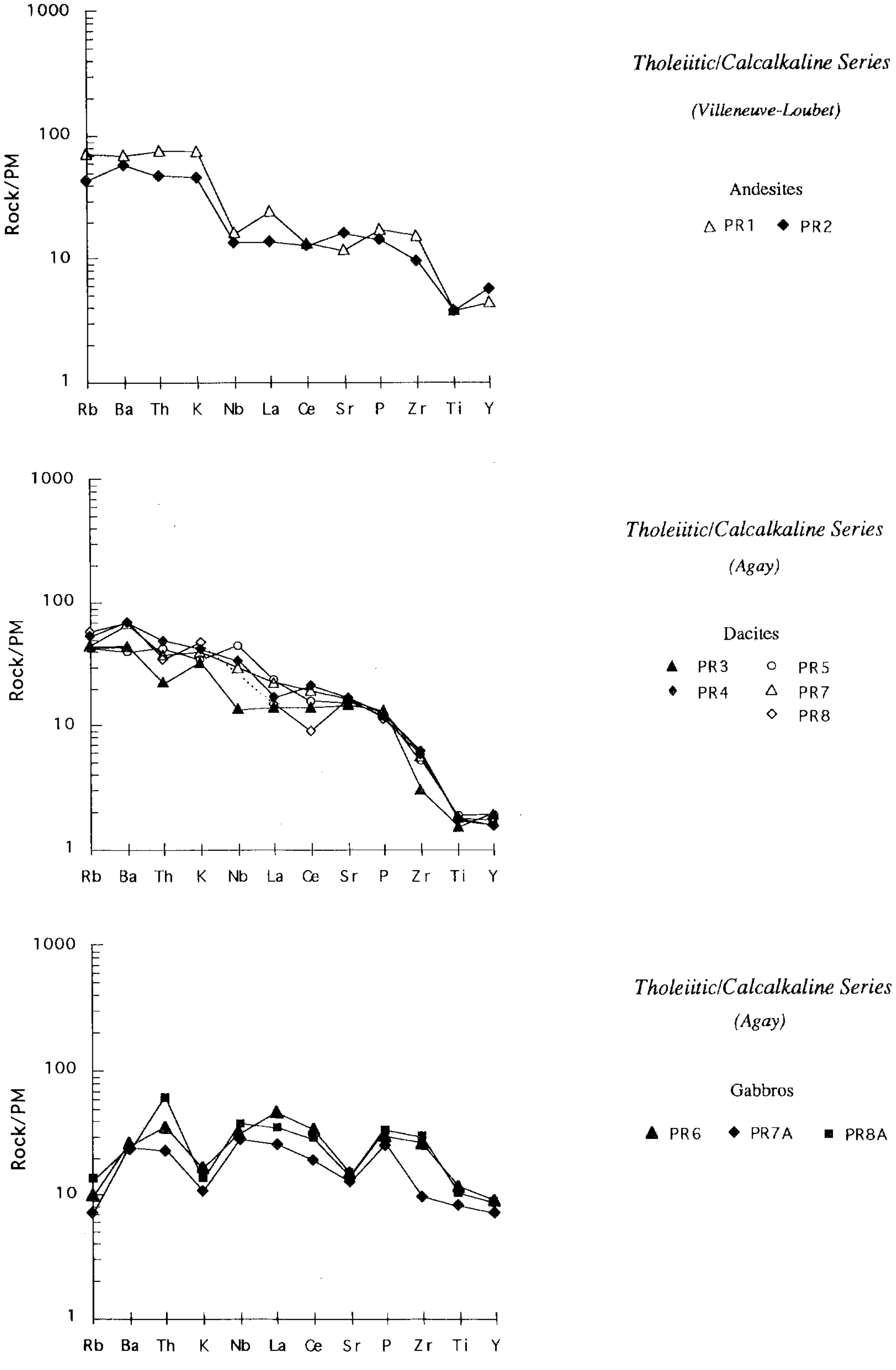

Fig. 3 - Primordial mantle-normalized spidergrams for lavas and gabbroic xenoliths from Provence. Normalizing factors from Wood (1979).

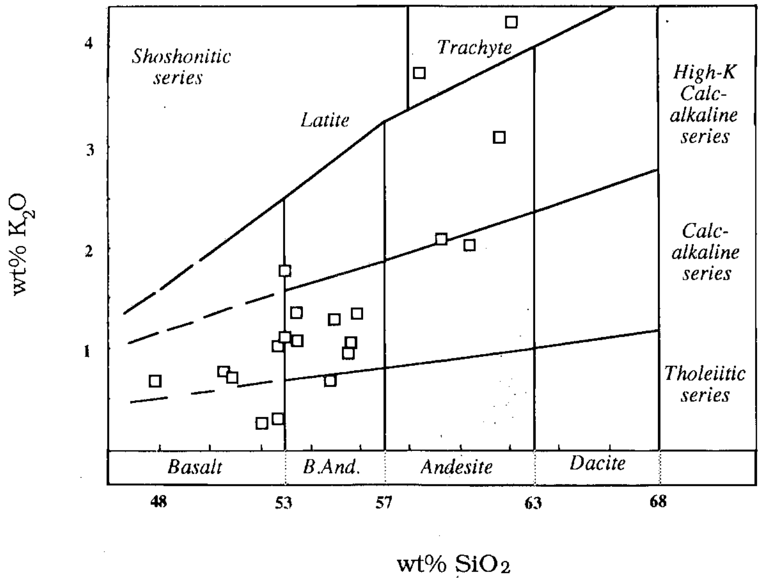

Fig. 4 - K_2O vs. SiO_2 diagram (after Peccerillo and Taylor 1976, modified) for Oligo-Miocene lavas from Sardinia.

with tholeiitic/calcalkaline and high-K calcalkaline/shoshonitic lavas in southern and northern Sardinia respectively (Beccaluva et al., 1987).

Table 2 reports representative analyses of the Oligo-Miocene lavas from Sardinia, and Fig. 4 shows their classification in the K_2O/SiO_2 diagram.

Petrographically, basaltic to andesitic lavas reveal the usual mineralogy of calcalkaline suites with the crystallization order: olivine, sometimes with reaction relationships with orthopyroxene, followed by clinopyroxene, plagioclase and magnetite. Brown amphibole is a sporadic additional liquidus phase in calcalkaline lavas, whereas it becomes more abundant in high-K calcalkaline andesites. Shoshonitic latites and trachytes from northern Sardinia (Anglona) consist of plagioclase, scarce clinopyroxene phenocrysts, and magnetite microphenocrysts set in a groundmass of the same minerals, plus alkali feldspar and interstitial biotite.

Primordial mantle-normalized spidergrams (Fig. 5) show geochemical peculiarities depending on the serial affinity: starting from tholeiitic/calcalkaline to high-K calcalkaline and shoshonitic lavas, there is an overall increase of incompatible elements, LREE/Y ratio, and the appearance of a marked Ba negative anomaly in the more potassic magmas.

The above characteristics suggest that, like Provence, the whole orogenic magmatism of Sardinia was also related to pure subduction of oceanic lithosphere. Moreover, the existence of a spatial zonation at 21-18 Ma with more potassic products in northern Sardinia may indicate a deepening of the subducted lithosphere northward in this period; significantly, this corresponds to the oceanic back-arc spreading in the Ligure-Balearic basin (Rehault et al., 1984), the anticlockwise rotation of the Sardinia block, the vanishing stage of the magmatism in Provence, and lastly, the southeastward migration of the overall tectono-magmatic system.

Eolian archipelago

The Eolian volcanic district is formed by a ring-like structure, consisting of seven islands and several seamounts, which extend to the western and northeastern sides of the emerged arc. All volcanic centres are underlain by a 250-300 Km wide and 550-650 Km long Benioff zone, dipping northwest from the Calabro-Peloritanian area to the Tyrrhenian abyssal plain. The volcanic activity, entirely Quaternary in age (Beccaluva et al., 1985), mainly consists of basaltic-andesitic to rhyolitic lavas, belonging to the calcalkaline and high-K calcalkaline se-

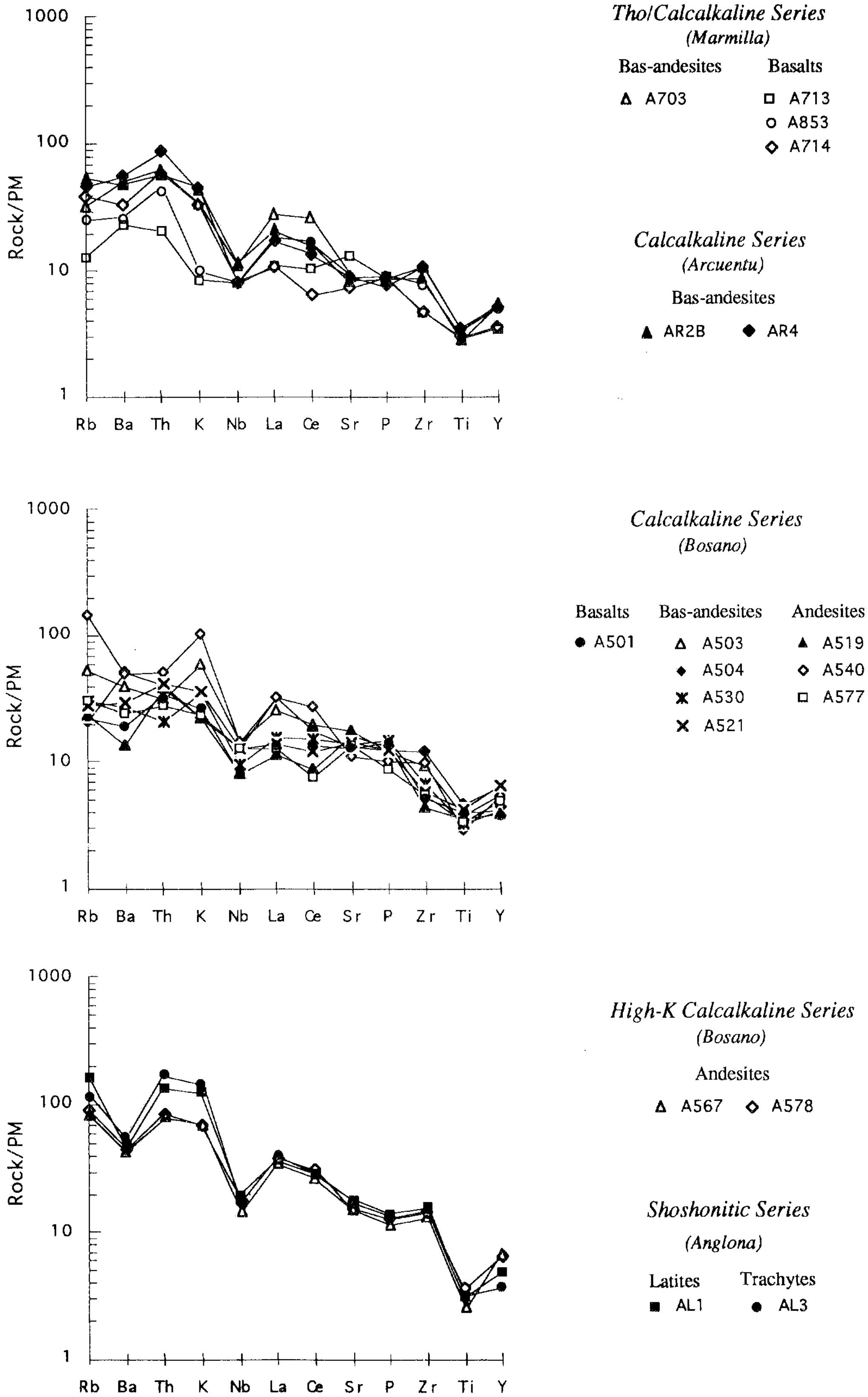

Fig. 5 - Primordial mantle-normalized spidergrams for Oligo-Miocene lavas from Sardinia. Normalizing factors from Wood (1979).

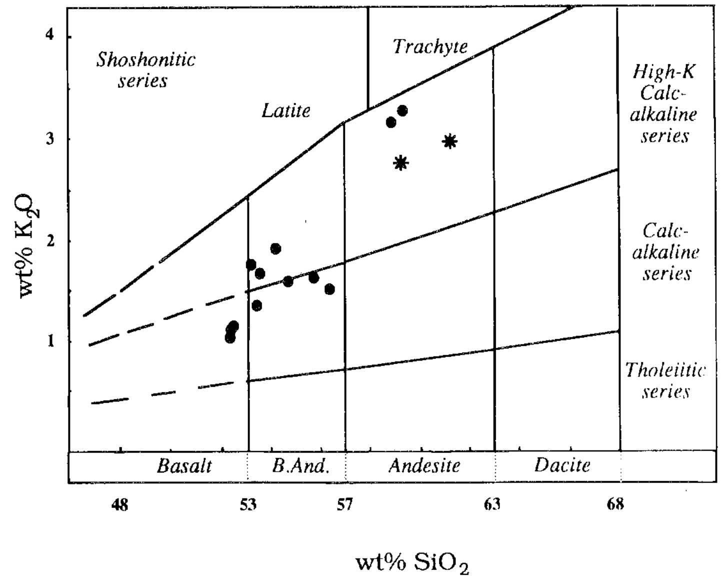

Fig. 6 - K_2O vs. SiO_2 diagram (after Peccerillo and Taylor 1976, modified) for lavas from several localities of Eolian Archipelago and Marsili Seamount. Symbols: full circles= lavas from Stromboli, Salina and Lipari; stars= lavas from Marsili Seamount.

ries, and subordinately shoshonite and leucite-tephrite products. A few arc tholeiite basalts have also been dredged from the submerged Eolian slope.

Representative analyses of calcalkaline and high-K calcalkaline lavas from Lipari (Galassi, 1990), Salina, and Stromboli (Ellam et al., 1988) are reported in Table 3 and in Fig. 6.

Petrographically, these lavas exhibit the same characteristics as those from Sardinia and Provence: olivine, followed by orthopyroxene and/or clinopyroxene, plagioclase and magnetite, joined by brown amphibole for andesitic compositions; biotite sporadically occurs in high-K andesites.

Compared with lavas from Sardinia, they show highly similar incompatible element spidergrams (Fig. 7), except for Sr, which is higher for the Eolian lavas in both calcalkaline and high-K calcalkaline series. This may be due to the peculiar composition of the fluids released from the subducted oceanic lithosphere. In any case, the petrological features of the Eolian calcalkaline magmatism perfectly fit its occurrence above an active Benioff zone.

Sr-Nd isotopic systematics reported in Fig. 8 show a substantial compositional analogy between Sardinia and Eolian calcalkaline lavas. However, it is interesting to note that some of the Eolian lavas (Stromboli shoshonites), unlike in Sardinia, have slightly lower Nd- and higher Sr- isotope ratios, probably due to subducted sediment contamination of their mantle sources (Ellam et al., 1988). This in turn suggests that the post-collisional subduction partly involved a continental crust component, particularly terrigenous sediments. Moreover, the rapid transition from calcalkaline to potassic lavas in the Eolian Archipelago, and their trace element and isotope characteristics (Ellam et al., 1988) are consistent with a progressive steepening of the subducted lithosphere at this stage, with metasomatic enrichments of magma sources by fluid components both from the oceanic crust and subducted terrigenous sediments (Beccaluva et al., 1985; Ellam et al., 1988; Ellam and Harmon, 1990).

Campania

The calcalkaline volcanism in Campania consists of the basaltic andesites and andesites drilled from the northwestern margin of the Phlegrean Fields, where they are buried under

Table 3 — Representative major and trace element analyses of lavas from the Eolian Archipelago and Marsili Seamount.

	STROMBOLI	SALINA	LIPARI											MARSILI Seamount	
	StB42	ESAL14	LP 63	LP 74	LP 5	LP 13	LP 85	LP 1	LP 20	LP 21	LP 23	LP 2	LP 37	CST68/13 2a	CST69/30 7b
	HK-CA-BA	CA-B	CA-B	CA-B	CA-BA	CA-BA	CA-B	CA-BA	HK-CA-BA	HK-CA-BA	HK-CA-BA	HK-CA-A	HK-CA-A	HK-CA-A	HK-CA-A
SiO2	53,49	52,45	52,45	52,35	54,62	55,79	52,36	53,33	54,23	56,36	53,20	58,98	59,46	59,77	61,32
TiO2	0,78	0,63	0,70	0,66	0,76	0,68	0,68	0,67	0,73	0,63	0,63	0,73	0,74	1,01	1,00
Al2O3	17,00	17,43	17,47	17,12	18,13	18,37	16,25	16,79	17,62	17,52	18,72	17,59	17,58	18,55	16,93
Fe2O3	8,07	9,46	1,20	1,13	1,13	1,01	1,10	1,18	1,16	1,05	1,14	0,89	0,91	1,43	0,86
FeO	nd	nd	7,20	6,80	6,78	6,08	6,60	7,05	6,95	6,28	6,83	5,35	5,43	4,03	4,70
MnO	0,14	0,15	0,16	0,14	0,14	0,13	0,15	0,15	0,15	0,13	0,14	0,12	0,12	0,15	0,14
MgO	5,55	5,67	6,30	6,14	3,61	3,96	7,18	5,88	4,95	4,46	4,48	2,45	2,47	2,09	1,89
CaO	9,81	10,33	10,80	10,24	9,82	8,83	11,69	10,64	9,09	8,80	9,20	6,66	6,67	4,58	4,30
Na2O	2,83	1,99	2,17	1,98	2,47	2,40	1,57	2,09	2,24	2,42	2,60	2,84	2,76	4.32	4,38
K2O	1,68	1,10	1,11	1,01	1,58	1,64	1,08	1,33	1,92	1,51	1,76	3,08	3,21	2,69	2,96
P2O5	0,27	0,13	0,17	0,18	0,23	0,23	0,22	0,22	0,23	0,22	0,24	0,27	0,26	0,28	0,32
LOI	0,11	0,18	0,26	2,24	0,73	0,87	1,13	0,67	0,73	0,62	1,07	1,05	0,38	1,47	1,40
V	237	265	274	269	306	285	276	319	276	286	297	178	175	119	132
Cr	121	64	148	132	75	73	314	157	80	107	31	28	38	12	13
Co	25	30	32	30	24	25	32	31	28	27	25	18	18	10	10
Ni	33	21	56	48	25	24	76	53	31	24	16	15	17	78	9
Rb	44	25	29	30	51	52	17	42	66	49	48	114	113	86	88
Sr	641	698	553	535	633	606	563	565	647	588	833	693	686	361	348
Ba	656	386	279	336	405	368	286	289	421	384	529	683	704	1002	996
Zr	121	58	91	83	131	148	107	112	90	162	96	134	134	208	204
Nb	12	5	3	3	6	5	5	4	7	6	6	12	12	27	30
Th	11	3	4	4	6	7	5	5	7	8	5	11	11	16	14
La	33	17	15	16	25	18	18	17	20	17	22	34	43	53	61
Ce	62	30	32	34	55	51	30	50	50	51	53	76	79	95	95
Y	23	16	15	16	21	17	17	19	19	25	18	23	23	41	39

Analyses of lavas from Salina and Stromboli (after Ellam et al., 1988); analyses of lavas from Lipari (after Galassi 1990); analyses of lavas from Marsili Seamount (after Selli et al., 1977); trace elements Ba, La, Ce, and Th (from Beccaluva et al., 1985; abbreviations as in Tables 1 and 2).

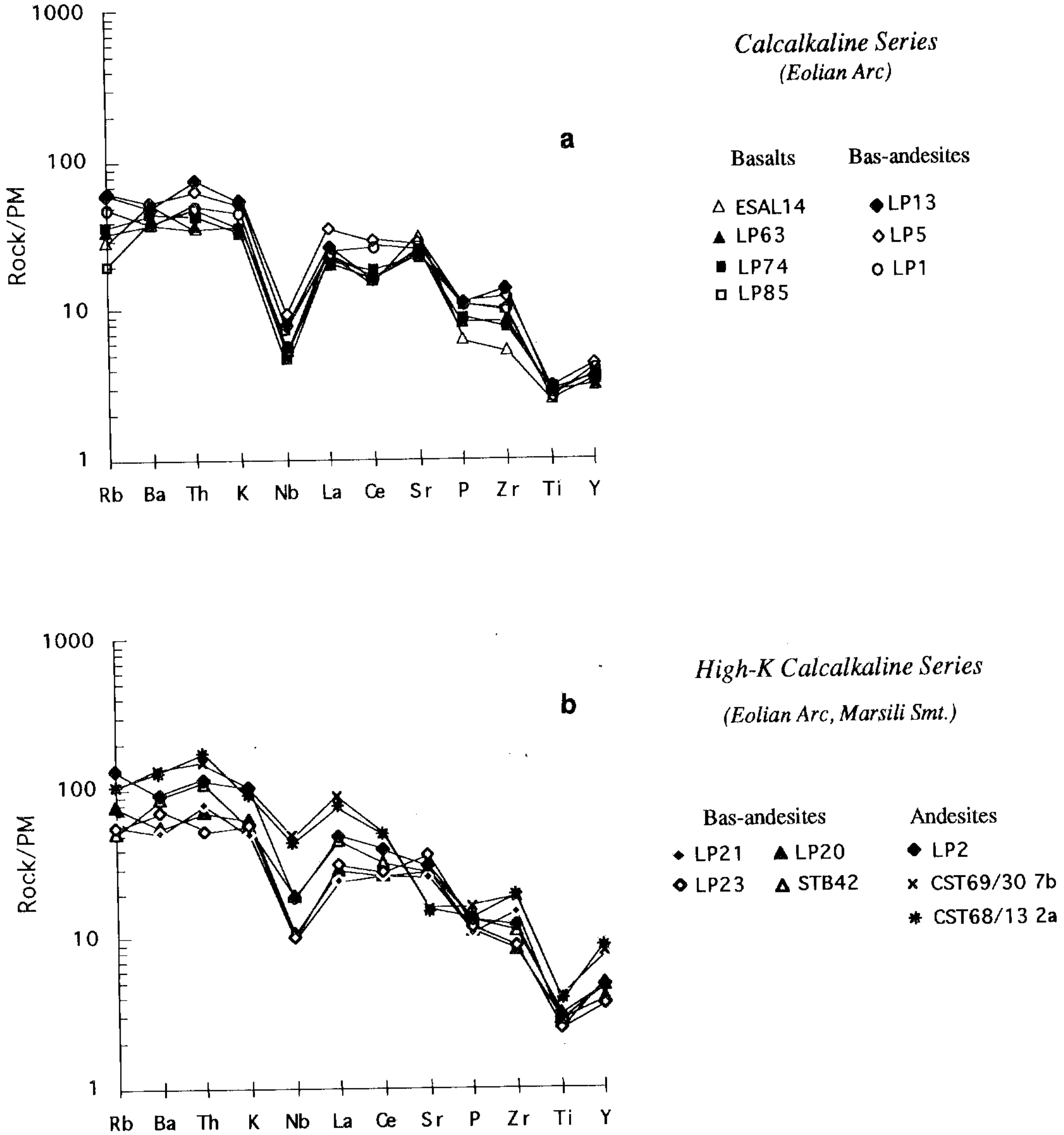

Fig. 7 - Primordial mantle-normalized spidergrams of lavas from Eolian Archipelago (a) and Marsili Seamount (b). Normalizing factors from Wood (1979).

the potassic alkaline volcanism (Di Girolamo, 1978). These lavas, with high-K affinity (Fig. 9; Tab. 4), were drilled for about 1550 m and are volumetrically as important as the later shoshonitic and leucite-bearing volcanics of the same area. A K/Ar age of 2 Ma was obtained for these lavas (Barbieri et al., 1979).

Petrographical features are quite similar to those of high-K calcalkaline lavas from Sardinia and the Eolian Archipelago: clinopyroxene, orthopyroxene, plagioclase and magnetite phenocrysts, with the occasional presence of biotite in andesites.

The primordial mantle-normalized spidergrams (Fig. 10) are substantially analogous to those of high-K calcalkaline series from the Eolian area and Sardinia, except for a significant negative P anomaly in Campania. Interestingly, the basaltic lavas drilled in the Vavilov and Marsili basins (Leg 107 in the Tyrrhenian Sea, Beccaluva et al., 1990) reveal comparable incompatible element distributions, except for their overall lower patterns in relation to their calcalkaline transitional characteristics. Such a transitional affinity has in fact been attributed to metasoma-

Table 4 — Representative major and trace element analyses of lavas from Campania (Volturno plain boreholes) and the Vavilov and Marsili basins.

	CAMPANIA				VAVILOV Basin		MARSILI Basin		
	P2-1800 HK-CA-BA	CV2-1440 HK-CA-BA	CV3-1889 HK-CA-BA	P3-297 HK-CA-A	651-49-2 79-81 CA-B	651-49-1 136-138 CA-B	651-53-2 120-122 HK-CA-B	650-67-2 114-116 CA-BA	650-69-CC 26-29 HK-CA-B
SiO2	52,91	55,02	55,05	60,33	52,75	49,04	52,56	55,53	52,88
TiO2	0,75	0,81	0,83	0,75	1,32	1,11	1,27	1,21	1,17
Al2O3	18,45	17,01	16,01	17,02	15,39	16,08	15,88	19,89	17,44
Fe2O3	2,66	5,47	0,94	1,94	8,53	4,98	7,75	7,08	8,99
FeO	5,45	1,31	4,70	3,20	nd	5,00	nd	nd	nd
MnO	0,16	0,13	0,12	0,12	0,12	0,15	0,13	0,04	0,08
MgO	4,88	4,21	3,10	2,80	7,10	8,22	7,34	1,93	3,93
CaO	8,64	9,12	8,30	5,60	7,06	9,47	7,11	5,37	6,58
Na2O	2,54	2,36	2,51	3,68	3,56	1,97	3,39	4,47	4,33
K2O	1,95	1,77	1,85	2,55	1,68	0,79	2,18	0,85	1,20
P2O5	0,11	0,11	0,10	0,16	0,20	0,25	0,26	0,13	0,23
LOI	1,50	2,59	6,49	1,85	2,29	2,95	2,13	3,50	3,16
V	200	212	199	152	238	233	235	218	246
Cr	40	83	20	19	79	153	213	380	228
Ni	20	13	7	14	52	156	71	164	97
Rb	83	70	86	144	29	17	35	9	19
Sr	555	458	465	481	244	248	355	342	398
Ba	344	347	363	540	172	137	255	160	216
Zr	100	108	130	190	118	93	133	78	92
Nb	10	10	12	17	7	6	10	4	4
Th	8	7	9	16	4	nd	9	5	5
La	23	22	25	36	12	9	17	8	14
Ce	48	45	50	73	26	nd	37	19	30
Y	22	21	24	30	26	24	24	14	20

Analyses of lavas from Campania (after Beccaluva et al., 1991); analyses of lavas from the Vavilov and Marsili Basins (after Beccaluva et al., 1990; abbreviations as in Tables 1 and 2).

tism of their mantle sources by subduction-related components, as already observed particularly in ensialic back-arc basins floored by oceanic crust (Beccaluva et al., 1990).

Sr and Nd isotopes of two Campania andesite samples plot in the Roccamonfina shoshonitic and leucititic series field (Fig. 8), being characterized by relatively low Nd- and high Sr-isotopes; this suggests that, as for some of the Eolian lavas, the magma sources of the Roman Region, irrespective of their K-enrichment, were significantly contaminated by terrigenous sediment components during subduction processes (Beccaluva et al., 1991).

TECTONO-MAGMATIC EVOLUTION AND GEODYNAMIC SIGNIFICANCE

In discussing the general evolutionary model of the western Mediterranean area, the space-time distribution of the calcalkaline orogenic magmatism plays a major role as first-order marker of the Cainozoic converging plate system along the southern palaeo-European continental margin.

The oldest magmatic events in Provence and Sardinia (34-26 Ma) developed along this continental margin, most probably in relation to N-NW dipping subduction of oceanic lithosphere. This is clearly indicated by the tholeiitic/calcalkaline serial affinity of the lavas, which is a characteristic of the initial stages of the orogenic magmatism related to oceanic subduction along island arc and active continental margins. Significantly, the later magmatic activity in Sardinia tended to have a pure calcalkaline affinity, more typical of a mature stage of subduction-related magmatism.

Between 21 and 18 Ma - that is, after the end of the magmatic activity in Provence - a significant spatial zonation of the magmatism occured in Sardinia with tholeiitic/calcalkaline, and high-K calcalkaline and shoshonitic lavas in the southern and northern areas of the island,

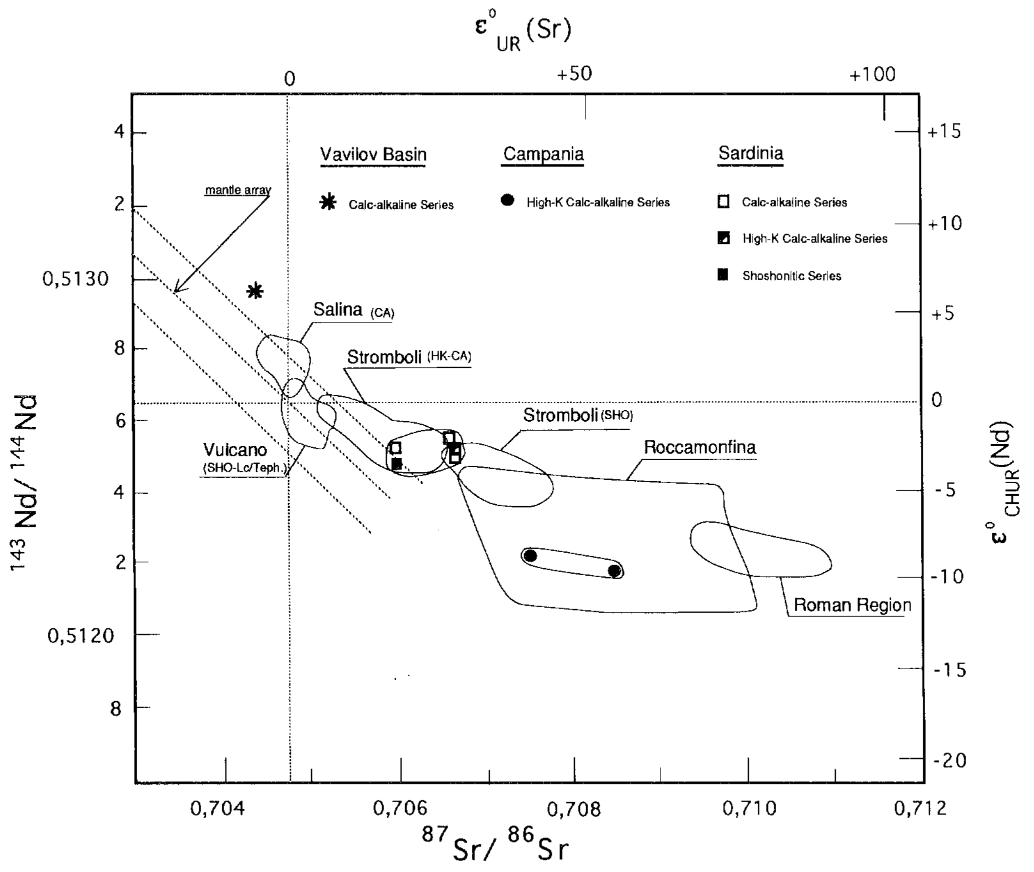

Fig. 8 - $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ diagram for calcalkaline lavas from Sardinia, Campania and Vavilov Basin. Also reported for comparison are the compositional fields of lavas from Roccamonfina (from Hawkesworth and Vollmer, 1979); Roman Province (from Carter et al., 1978); Stromboli, Vulcano, and Salina (from Ellam et al., 1988); Vavilov Basin (from Beccaluva et al., 1990).

respectively. Geochronological, paleomagnetic, and geological data indicate that such zonation is excellently time-correlated with the oceanic accretion and the formation of the Ligure-Balearic back-arc basin (Rehault et al., 1984), as well as with the anticlockwise rotation of the Sardinia-Corsica microplate (Montigny et al., 1981) relative to stable Europe.

Therefore, the above data consistently indicate that not only the orogenic magmatism, but also the formation of the Ligure-Balearic basin were induced by prolonged oceanic lithosphere subduction along the southern palaeo-European continental margin, which split in correspondence to its Oligocene-Aquitanian magmatic arc from Provence to Sardinia. This implies (Beccaluva et al., 1987): 1) the existence of oceanic lithosphere, which can be tentatively assigned to the basement of the Sicilide-Canetolo oceanic basin, east of the Sardinia-Calabria domain; 2) its N-NW dipping subduction below the palaeo-European continental margin, at least from Upper Eocene to Aquitanian; 3) the continent-continent collision between the Sardinian-Calabrian and Apulian-Apenninic domains as having taken place from Lower Miocene, rather than during Eocene (cf. Patacca and Scandone, 1987). With regard to this, quantitative palaeogeographic reconstructions are obviously unwarranted, since most of the oceanic lithosphere may completely disappear in subduction zones, without leaving any ophiolitic representative.

After about 18 Ma, the calcalkaline activity strongly decreased in Sardinia, and finished around 13 Ma, clearly in relation to a marked decrease of the subduction rate concomitant with the continental collision. Later on, during Serravalian and Tortonian times, orogenic mag-

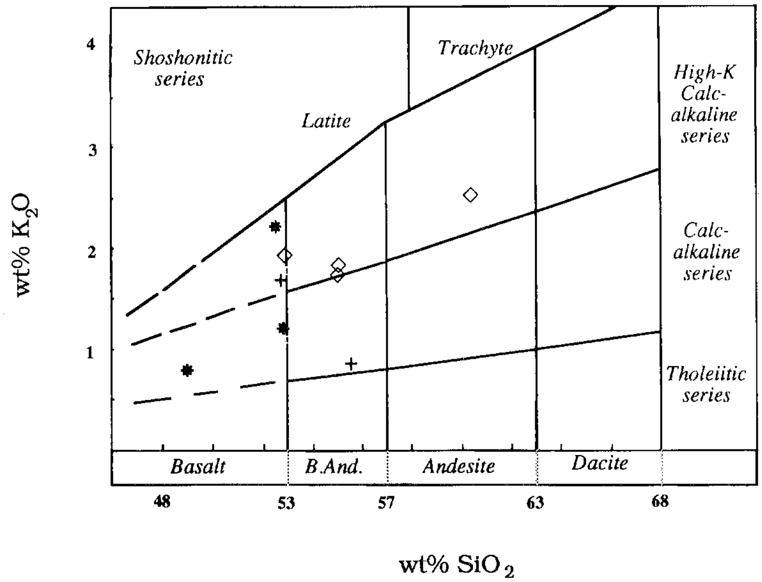

Fig. 9 - K_2O vs. SiO_2 diagram (after Peccerillo and Taylor 1976, modified) for lavas from Campania (Volturno Plain). Symbols: diamonds = lavas from Volturno Plain; stars = lavas from Vavilov basin; crosses = lavas from Marsili basin.

matism was substantially absent in the central Mediterranean area, coinciding with the last main compressional phase in the northern Apennines (Carmignani et al., 1978). In this sector, therefore, active subduction ceased completely, leaving a subducted slab plunging almost vertically under the Central Apennines (Panza et al., 1980), as recently confirmed by tomographic data (Spakman, 1990).

A new tectono-magmatic phase started around 7 Ma ago, with rifting in the Apennine and Calabrian Alps chain and production of the Tuscan Province magmatism, characterized by a complex interaction between mantle-derived potassic melts and crustal anatectic melts (Barberi et al., 1986; Ferrara et al., 1986). Southeastward migration of the rifting subsequently resulted in the opening of the Tyrrhenian basin, with the diachronous development of the Vavilov (4-3.5 Ma) and Marsili (1.9-1.6 Ma) oceanic crust, as demonstrated by the Leg 107 results (Kastens et al., 1986). Not surprisingly, basaltic rocks from the easternmost Vavilov basin and those from the Marsili basin revealed calcalkaline and high-K calcalkaline transitional affinity, like other back-arc basin basalts, particularly in ensialic basins, where oceanic crust accretion takes place in proximity to subduction zones (Beccaluva et al., 1990). This implies the existence in Upper Miocene-Pliocene times of a large subducted lithospheric segment, at least from Tuscany to the Tyrrhenian basin, responsible for metasomatic enrichments of the mantle sources, from which the "calcalkaline" magmas were generated.

A new arc magmatism with calcalkaline affinity developed during the Quaternary in the Eolian Archipelago and Campania, eastward of the Tyrrhenian basin, which therefore acts as an interarc basin between Sardinia and the eastern peri-Tyrrhenian margin, with a tectono-magmatic evolution substantially analogous to the Pacific arc - back-arc systems (Crawford et al., 1981). In our opinion, active mantle diapirism above the subduction zone not only supplied the basaltic magmas of the Tyrrhenian oceanic crust, but also favoured the counterclockwise rotation of the Italian peninsula and pushed the Calabrian arc into its present position. These tectono-magmatic features also imply subduction of oceanic lithosphere, which may be assigned to the Ionian lithosphere, plunging below the Calabrian-Eolian area with a still seismically active Benioff zone.

Accordingly, Sr- and Nd-isotopes (Fig. 8) indicate that a significant contribution of continental crust material (mainly terrigenous sediments) to the supra-subduction mantle sources

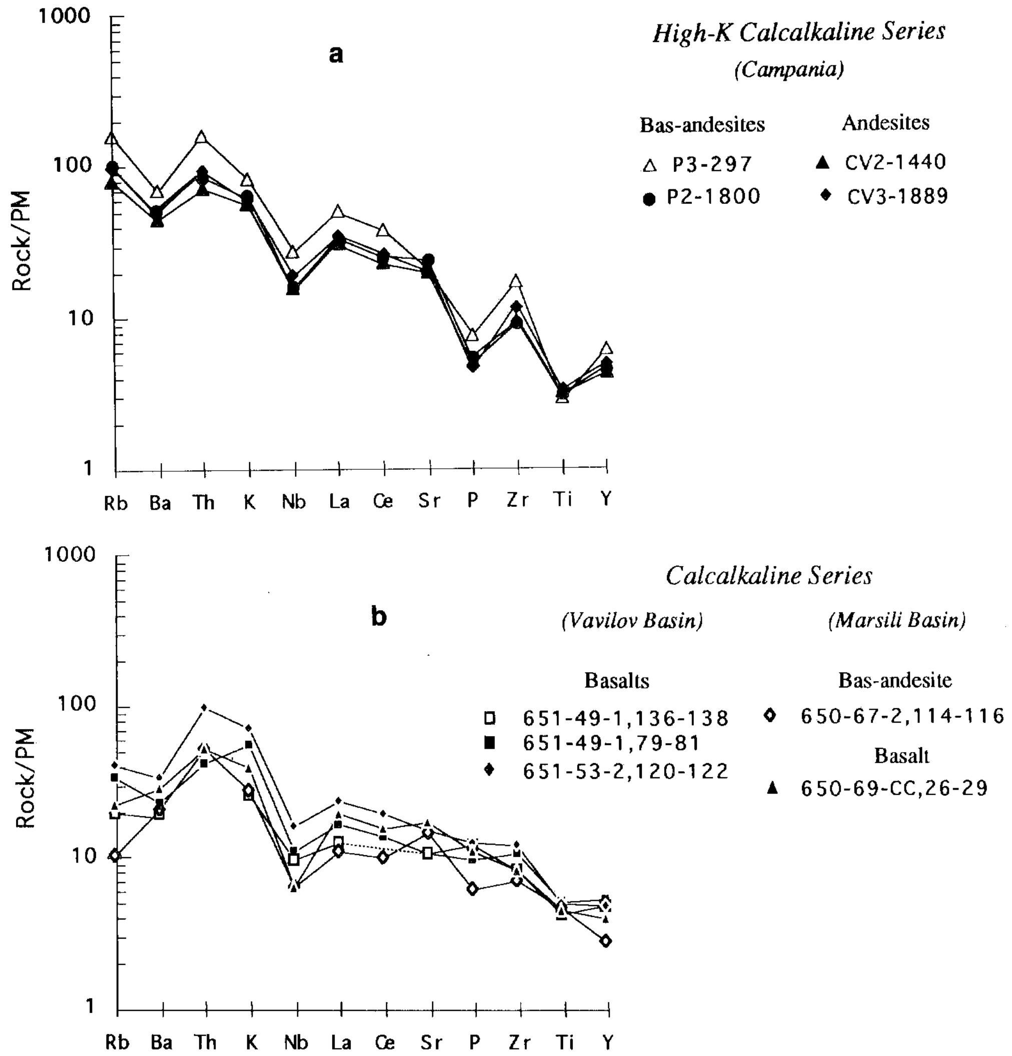

Fig. 10 - Primordial mantle-normalized spidergrams of lavas from Campania (a) and Vavilov and Marsili basins (b). Normalizing factors from Wood (1979).

of magmas is restricted to Stromboli for the Eolian area, whereas it is predominant in Campania and the whole Roman Province. In this respect, the Ortona-Roccamonfina line and the 41N° transform fault in the Tyrrhenian basin, already considered the boundary between two main magmatic sub-provinces (Serri, 1990; Beccaluva et al., 1991), could reflect a first-order lithospheric discontinuity between oceanic (Ionian) and continental (Adriatic) subducted lithospheric slabs, in the south and the north respectively.

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