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Genesis and evolution of Miocene-Quaternary intermediate-acid rocks from the Tuscan Magmatic Province

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ABSTRACT. — Occurrence of a large variety of rock types, intrusive and effusive, closely associated in space and time reveal a complex magmatic setting for the Tuscan Magmatic Province. Extensive petrological and geochemical investigations carried out over the later years indicate that main rock associations are represented by three groups of rocks at different degrees of evolution: i) mafic ultrapotassic rocks with lamproitic affinity, and high-potassium calc-alkaline and shoshonitic rocks; ii) intermediate-acid rocks bearing strong petrographic and geochemical evidence of magma interaction processes; iii) acid volcanics and intrusives showing petrological and geochemical characteristics of both extremely evolved and pure anatectic melts. Literature and new data suggest that a process of interaction between basic and acid end-members is responsible for the evolution of the Tuscan Magmatic Province magmatism. Major and trace elements and isotopic systematic help to recognize the basic end-members as compositionally akin to three basic-intermediate magmas belonging to Capraia shoshonites, Capraia high potassium calc-alkaline rocks rich in Sr, and lamproites from Tuscan area that acted together even in a single intrusive or effusive complex. The acid end-members in the interaction process are crustal anatectic melts derived by partial melting at ca 4-6 kbar of gneiss and garnet micaschists of the Tuscany basement having a sedimentary protolith. Residual assemblages of the partial melting process calculated by geochemical models agree with experimental petrological data, and help to reconstruct levels of melting and emplacement for intrusive complexes, and level of crystallization of phenocrysts for the effusive ones. The petrological model reported in this work fits well with geophysical data indicating a superposition of upper crust of both the European and Adriatic plates in westernmost Tuscany.

KEY WORDS: *Tuscan Magmatic Province, genesis, evolution, geochemistry, magma mixing, anatectic melts*

RIASSUNTO. — La Provincia Magmatica Toscana è caratterizzata da una grande varietà di rocce ignee, sia intrusive che effusive, che sono associate nello spazio e tempo e che rivelano un magmatismo estremamente complesso. Studi petrologici e geochimici effettuati nel corso degli ultimi anni indicano che le associazioni principali sono rappresentate da tre gruppi di rocce a differenti gradi di evoluzione: i) rocce mafiche ultrapotassiche con affinità lamproitica, e rocce calc-alcaline alte in potassio e shoshonitiche; ii) rocce intermedie-acide con forti evidenze petrografiche e geochimiche di processi di interazione fra magmi; iii) rocce acide che mostrano

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caratteristiche petrologiche e geochimiche sia di fusi anatettici sia di fusi estremamente evoluti. Nuovi dati e di letteratura suggeriscono che l'interazione fra magmi basici ed acidi è il processo di base che ha governato l'evoluzione del magmatismo della Provincia Magmatica Toscana. Elementi maggiori ed in traccia, e le composizioni isotopiche sono usati per riconoscere i termini estremi basici del mescolamento come composizionalmente analoghi a tre magmi basico-intermedi che appartengono alle rocce shoshonitiche e calc-alcaline alte in potassio e ricche in Sr di Capraia, e alle rocce lamproitiche dell'area toscana, che hanno agito insieme anche in un singolo complesso intrusivo o effusivo. I termini estremi acidi del processo di interazione sono fusi anatettici crostali, derivati dalla fusione parziale a ca. 4-6 kbar di micascisti a granato e gneiss aventi protoliti sedimentari e ritrovati nel basamento della Provincia Magmatica Toscana. Gli assemblaggi residuali del processo di fusione parziale calcolati attraverso modelli geochimici sono in accordo con i dati di petrologia sperimentale, e contribuiscono a ricostruire la profondità dove è avvenuta la fusione e la messa in posto per i complessi intrusivi, e la profondità di cristallizzazione dei fenocristalli per quelli effusivi. Il modello petrologico proposto in questo lavoro è in accordo con i dati geofisici che indicano una superimposizione di crosta superiore sia della placca europea che adriatica nella Toscana occidentale.

PAROLE CHIAVE: *Provincia Magmatica Toscana, genesi, evoluzione, geochimica, mescolamento fra magmi, anatessi*

INTRODUCTION

An important magmatic activity can be found on large areas of the Italian Peninsula and the Tyrrhenian Sea during the late Miocene-Quaternary post-tectonic phase of the Apennine orogeny. This magmatism makes up a number of magmatic provinces, which show distinct petrological and/or geochemical characteristics and testifies to the complexity of the Recent volcanism in the Italian peninsula (Peccerillo *et al.*, 2001). In Central Italy crustal anatectic acidic magmas and mantle-derived magmas, with affinities from calc-alkaline to ultrapotassic, were emplaced and often interacted at shallow crustal levels, making up plutonic bodies, subvolcanic masses, and volcanic complexes (e.g. Poli, 1992; Innocenti *et al.*, 1992; Peccerillo, 1999). This magmatism is commonly divided in two main provinces overlapping on space and time: the Roman Magmatic Province and the Tuscan Magmatic Province (TMP). The term «magmatic province» is used here to indicate a relatively restricted area in which igneous rocks have been emplaced over a relatively short period of time, of a few Ma or less, and where rocks are not necessarily comagmatic, i.e. do not necessarily derive from a single source or magma type, although in some cases they do. Further discussion can be found in Peccerillo and Turco (this issue). Main differences between TMP and Roman Province regard saturation in silica, presence of plutonism, and amount and affinitiy of mafic rocks. In particular, TMP rocks range from slightly saturated to strongly oversaturated in contrast with the rocks from the Roman Province which are saturated to strongly undersaturated in silica (e.g. Serri *et al.*, 1993; Peccerillo, 1999). Plutonic rocks are lacking in the Roman Province, mafic rocks are relatively scarce in TMP, and they belong to the high potassium calc-alkaline and shoshonite series, whereas mafic rocks of Roman Province range from shoshonite to strongly potassic alkaline series (Poli *et al.*, 2003; Peccerillo and Turco, this issue).

Magmatic complexes examined in this paper belong only to the Tuscan Magmatic Province. In spite of the widespread occurrence of acid peraluminous volcanic and intrusive bodies, a large number of magmatic complexes with a mafic composition also occur in Tuscany indicating that mantle derived magmas had a significant importance in the origin of TMP (e.g. Peccerillo *et al.*, 2001). In addition, most of acid extrusive and intrusive bodies of TMP show the presence of mafic magmas represented by mafic enclaves, lava flows, and dikes (e.g. Poli *et al.*, 2003) very variable in composition, indicating, hence, the occurrence of a compositionally heterogeneous upper mantle beneath Tuscany. The reasons of this heterogeneity and the processes that generated the various magma types within the upper mantle are still matter of debate (e.g. Peccerillo *et al.*, 2001; Conticelli *et al.*, 2002). Genesis of anatectic magmas is also debated mainly because of their quite peraluminous characters requiring an upper crustal source (e.g. Dini *et al.*, 2002; Poli *et al.*, 2002) which contrast with geological and geophysical data (e.g. Barchi *et al.*, 1998; Poli *et al.*, 2003) .

The aims of this contribution are manifold; in particular: i) we summarize the main petrological and geochemical characteristics of the intermediate-acid rocks in all the complexes of the TMP; ii) we discuss importance of mixing processes in the genesis of intermediate-acid rocks and we identify the possible end-members; iii) we study the partial melting processes that produced the acid end-members starting from crustal material, with a detailed and complete identification of the sources and of the residual assemblages, together with a tentative reconstruction of pressure and temperature for the anatectic process and for emplacement level for intrusive complexes, and level of crystallization of phenocrysts for the effusive ones; iv) we give some clues on the genesis of mafic magmas; v) we explore geodynamic implications of petrological and geochemical data.

GENERALS

The Tuscan Magmatic Province consists of a series of igneous complexes with small (<1 Km^2) to moderate (max 100 Km^2) size scattered through southern Tuscany, the Tuscan archipelago, and Northern Latium. Figure 1 gives an overview of locations, ages and main compositional characteristics of the Tuscan magmatic Province. The complexes are mafic to acid intrusive, subvolcanic, and volcanic; occurrences consist of stocks, dykes, necks, lava flows and domes, and of the large volcanic edifices of Monte Amiata, Monti Cimini and Capraia Island (Fig. 1). Numerous traces of igneous activity have been found also in boreholes drilled for geothermal ore mineral exploration mainly in the famous Larderello geothermal field and to the south. In Poli *et al.* (2003), and references therein, a detailed overview of igneous rocks of the TMP is reported.

Age ranges from 14 Ma to 0.2 Ma (Serri *et al.*, 2001). Ages show a tendency to decrease from west to east and four age zones can be roughly recognized at about 7.6, 5, 3, 0.9 Ma (Fig. 1).

Tuscan magmatism occurs in a region characterized by crustal thinning (maximum 25 km; Panza, 1984), accompanied by thinning of the lithosphere, and by upwelling of hot asthenosphere, indicating a mantle doming beneath southern Tuscany (Serri *et al.*, 1993). The well known geothermal fields at Larderello testifies a high heat flow (e.g. Zito *et al.*, 2003). Geophysical data report a layer of low seismic velocities within the upper mantle (Barchi *et al.*, 1998). This has been interpreted as due to the occurrence of a layer with a crustal-type density. Meaning of the physical nature of this layer is debated between two main interpretations (e.g. Morelli, 1982; Locardi, 1988; Peccerillo and Panza, 1999): i) an upper crustal slice within the upper mantle indicating a crustal doubling; ii) partially molten mantle material (e.g., metasomatic veins). In addition, Peccerillo and Panza (1999) interpreted the presence of deep-seated lithospheric roots as something missing relict of an undergoing lithospheric slab, below a depth of about 70 km.

The basement rocks in the Tuscan Magmatic Province consist of metamorphic terranes (Orlando *et al.*, 1994 and reference therein) overlain by various allochthonous and autochthonous sequences (e.g. Abbate *et al.*, 1970). Plutonic rocks have field relationships, such as the sharp and mainly discordant intrusive contacts, the internal isotropic fabric, and the metamorphic aureoles developed along contacts with wall-rocks, indicating that the plutons were emplaced at high crustal levels (e.g. Rocchi *et al.*, 2002). Skarn processes, as well as pervasive hydrothermal alteration, have intensely affected country rocks, e.g. at Campiglia, Gavorrano, and boreholes. Ore bodies, mainly pyrite and cassiterite, are widespread and well developed at the contacts with the country rocks and within the plutons themselves (e.g. Dini *et al.*, 2003).

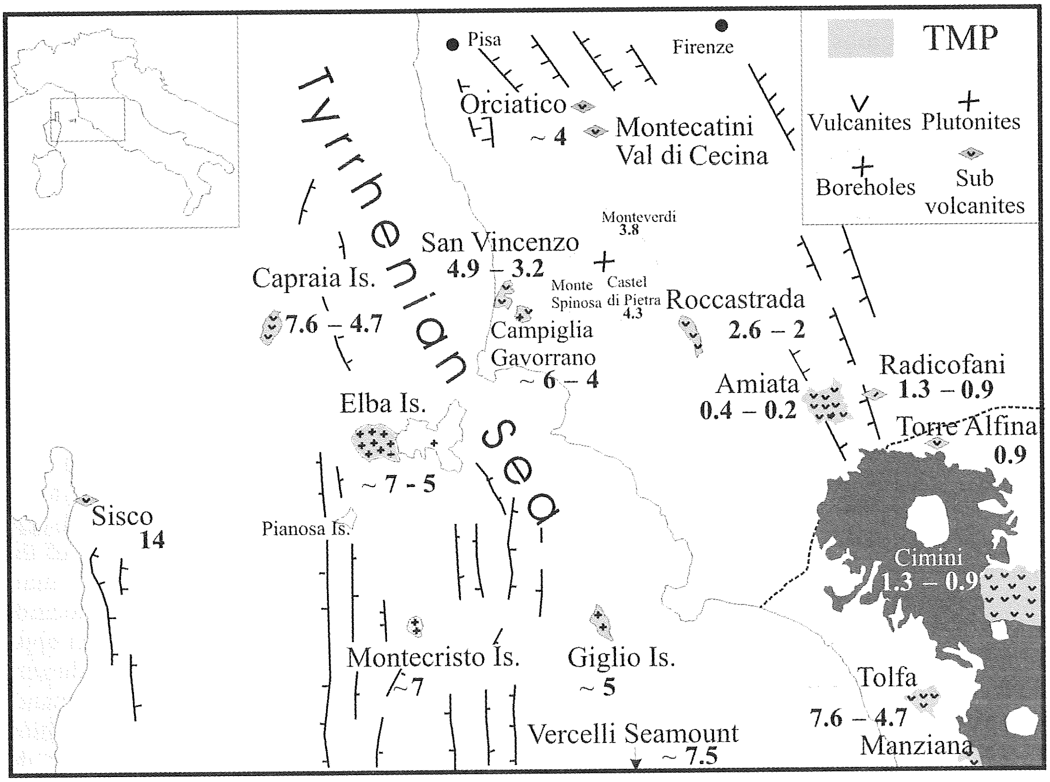


Fig. 1 – Location and age of intrusive, extrusive, and subvolcanic rocks of the Tuscan Magmatic Province. Dark gray areas - Roman Magmatic Province. The dashed line represents the border between Tuscany and Latium region. Note the younging of magmatism from west to east. Ages after the compilation of Serri *et al.* (2001).

The Tuscan magmatic province is very complex from a petrological point of view, mainly for two reasons: i) coexistence of several types of magmas and ii) extensive phenomena of magma mixing processes. Crustal anatectic acid peraluminous rhyolites and granites coexist with a wide range of mafic to intermediate magmas, including high-potassium calc-alkaline (HKCA), shoshonitic (SHO), potassic alkaline (KS) and ultrapotassic lamproitic rocks. Evidence of mingling and mixing with various types of mantle-derived calc-alkaline to potassic melts are both textural, e.g. mafic-intermediate enclaves and xenocrysts, and geochemical, e.g. extreme variability of isotopic compositions (e.g. Poli, 1992; Ferrari *et al.*, 1996; Dini *et al.*, 2002; Poli *et al.*, 2003).

Compositional characteristics of Tuscan Magmatism

A database has been built containing major, trace and Sr isotopic data for 549 samples from TMP and 41 samples of gneiss and garnet micaschists (hereafter GGM) with upper crust sedimentary protolith found in boreholes from the Southern Tuscany geothermal fields. Attention was paid to exclude samples that shown evidence of cumulus and alteration. Database contains literature and new data and can be requested to the author, whereas references are reported in the caption of Figure 2. In Table 1 selected samples of new data are reported. All the magmatic rocks have been divided into three main groups: mafic rocks

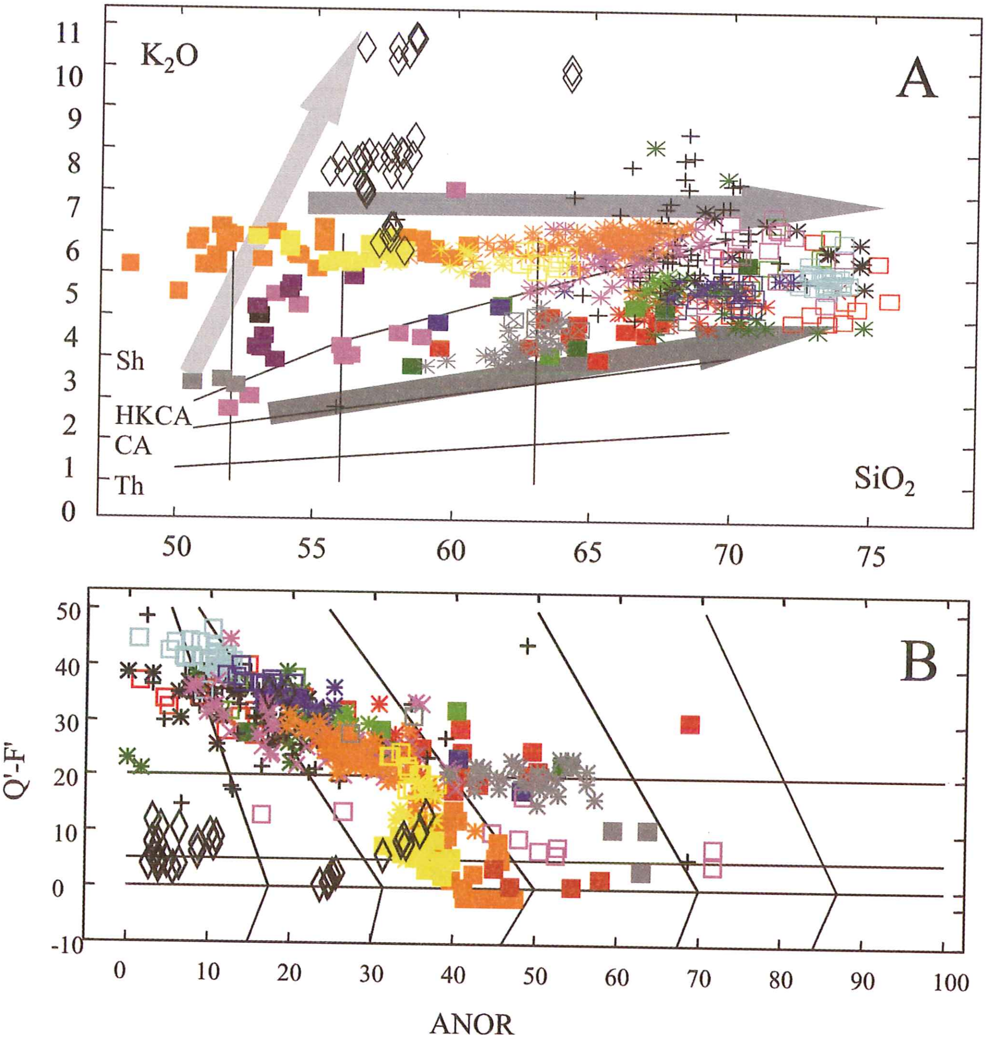


Fig. 2 – A: K_2O vs. SiO_2, alkalis vs. SiO_2 (Peccerillo and Taylor, 1976). B: Q'-ANOR classification diagram (Streckeisen and Le Maitre, 1979). Th = tholeiitic series; CA calc-alkaline series; HKCA = High potassium calc-alkaline series; Sh = shoshonite series. Symbols for mafic rocks, intermediate-acid rocks with evidence of magma mixing, and acid rocks without evidence of magma mixing processes are respectively: filled squares, stars, and open squares. Colors for different complexes as follows: red – Elba, green – Giglio, dark green – Montecristo, black – Gavorrano, cyan – Roccastrada, blue - San Vincenzo, magenta – Tolfa, orange – Amiata, brown – Radicofani, yellow – Cimini, dark gray – Capraia. Other symbols: black plus – boreholes samples, open diamonds – Lamproites. Gray color arrows in A show the main trend followed by the samples. Data from: Bagnoli *et al.*, 1979; Balducci *et al.*, 1981; Bertagnini *et al.*, 1995; Borsi *et al.*, 1965; Clausen and Holm, 1990; Conticelli *et al.*, 1992; Conticelli *et al.*, 1995; Conticelli *et al.*, 2002 ; Conticelli, 1998; De Rita *et al.*, 1994; Dini *et al.*, 2002; D'Orazio *et al.*, 1991; D'Orazio *et al.*, 1994; Faggioni *et al.*, 1998; Ferrara and Macera, 1976; Ferrara *et al.*, 1975; Ferrara *et al.*, 1976; Ferrara *et al.*, 1988; Ferrara *et al.*, 1989; Ferrari *et al.*, 1996; Giraud *et al.*, 1986; Gianelli and Puxeddu, 1979; Innocenti *et al.*, 1992; Innocenti *et al.*, 1997; Innocenti, 1967; Manetti *et al.*, 1979; Marianelli and Carletti, 1999; Mazzuoli and Pratesi, 1963; Mazzuoli, 1967; Peccerillo *et al.*, 1987; Peccerillo *et al.*, 1988; Peccerillo *et al.*, 2001; Perini *et al.*, 2003; Pinarelli *et al.*, 1989; Pinarelli, 1991; Poli *et al.*, 1984; Poli *et al.*, 1989; Poli, 1992; Poli *et al.*, 1995; Poli *et al.*, 2002; Poli *et al.*, 2003; Puxeddu, 1971; Rocchi *et al.*, 2002; Rombai *et al.*, 1995; Serri *et al.*, 1993; Serri *et al.*, 2001.; Westerman *et al.*, 1993.

TABLE 1

Chemical analyses of selected samples from TMP, divided according to the three groups reported in the text.

Group	Mafic				Intermediate - Acid			
Complex	Capraia	Cimini	Cimini	Cimini	Cimini	Capraia	Capraia	Capraia
Affinity	SH	SH	SH	SH	SH	HKCA	HKCA	HKCA
Sample	CP54	CIM204	CIM162	CIM172	CIM203	CP73	CP62	CP22
SiO_2	52.21	54.11	56.31	57.29	59.49	61.18	62.61	62.99
TiO_2	1.68	1.00	1.01	0.99	0.77	0.89	0.75	0.67
Al_2O_3	17.12	15.91	16.02	14.81	17.46	16.52	15.75	15.99
Fe_2O_3	10.73	0.91	1.56	1.44	2.42	2.30	2.91	3.62
FeO	0.15	4.50	3.80	3.68	2.44	2.96	2.34	0.88
MnO	0.15	0.08	0.11	0.10	0.07	0.09	0.06	0.07
MgO	3.58	8.82	6.73	7.59	3.32	3.33	3.27	3.38
CaO	6.55	6.18	6.03	5.85	4.32	4.85	5.11	4.32
Na_2O	3.15	1.42	1.70	1.51	2.29	3.52	2.93	3.17
K_2O	2.33	5.84	5.28	5.60	5.65	3.07	2.98	3.75
P_2O_5	0.39	0.28	0.34	0.29	0.23	0.27	0.22	0.29
LOI	1.95	0.91	1.08	0.81	1.49	1.02	1.08	0.88
Cr	375	490	379	460	81	105	126	123
Sc	-	20	-	-	14.1	-	-	-
Co	36	29	29	27	15	11.4	15	14
V	135	115	121	140	87	93	106	88
Ni	70	243	131	161	41	24	18	26
Cu	30	37	37	35	29	17	15	16
Zn	98	64	75	68	68	67	65	62
Rb	133	353	343	409	202	172	142	153
Sr	388	506	704	491	617	493	674	1042
Ba	556	918	1268	898	951	658	728	1367
Th	24	46	78	55	49	35	27	46
Zr	241	415	371	394	275	242	197	223
Y	29	29	25	28	26	22	23	20
Ta	-	2.1	-	-	2.3	-	-	-
Hf	-	11.2	-	-	8.1	-	-	-
Nb	22	26	17.5	20	15	17.9	12	13
Pb	16	54	89	52	97	36	39	59
La	30	86	127	92	84	55	56	128
Ce	66	197	250	178	171	113	106	246
Nd	-	88	-	-	71	-	-	-
Sm	-	17.7	-	-	15.2	-	-	-
Eu	-	2.4	-	-	2.14	-	-	-
Tb	-	0.97	-	-	1.3	-	-	-
Yb	-	2.1	-	-	2.6	-	-	-
Lu	-	0.35	-	-	0.43	-	-	-

SH = shoshonite; HKCA = High potassium calc-alkaline; - = not detrmined.

Major elements (exclusive of FeO, MgO and LOI determined by wet chemical analyses) analyzed by X-ray fluorescence spectrometry (XRF) with full matrix correction «after Franzini and Leoni, 1972; Cr, V, Ni, Rb, Sr, Y, Zr, Nb, Ba, La and

CONTINUED: *Table 1*

Intermediate - Acid		Acid			Basement		
Cimini	Bor.le S3	Capraia	Bor.le MS1	Gavorrano			
SH	HKCA	HKCA	HKCA	HKCA	Gneiss	Gneiss	Micaschist
CIM191	S3-11	CP7	MS1-7	GAV-3	SS2076	SD75	SD73
64.07	65.19	67.64	70.59	74.77	61.4	64.1	58.85
0.74	0.96	0.51	0.29	0.13	0.85	0.93	1.13
15.94	15.28	13.61	15.43	13.86	20.00	16.7	16.25
1.77	1.28	2.35	0.01	0.78	0.94	6.38	8.91
2.34	4.20	0.82	0.22	0.26	4.53	–	-
0.05	0.08	0.06	0.04	0.02	0.05	0.05	0.09
1.99	1.42	1.36	0.72	0.13	1.95	1.91	4.38
3.78	3.42	2.42	2.38	0.74	0.63	1.93	3.94
2.21	2.64	3.82	2.77	3.68	1.35	2.00	2.87
5.55	4.10	3.86	6.12	4.79	4.10	3.96	1.76
0.14	0.26	0.14	0.15	0.22	0.13	0.10	-
1.36	1.16	3.41	1.28	0.62	3.47	1.91	1.82
55	-	20	-	-	142	130	133
10.8	-	6.8	-	-	17.8	14.7	-
13	-	8	-	-	18.9	16	28
71	-	24	-	-	125	-	171
41	17.32	8	15.3	7	36	42	57
21	-	7	-	-	-	-	31
64	-	46	-	-	-	-	122
336	190	182	383	400	150	133	67
522	255	341	318	61	149	177	221
878	875	563	453	219	714	632	486
45	-	34	-	-	16.7	13.9	8
244	295	170	123	57	241	251	199
33	43	18	10	6	35	42	31
1.8	-	1.5	-	-	1.6	1.11	-
6.8	-	5.9	-	-	5.8	6.4	-
13	21	10	4	15	20	19	15
81	-	51	-	-	-	-	9
93	50	44	22	10	51	41	27
150	97	89	35	-	102	80	53
60	-	34	-	-	44	37	-
12.8	-	6.7	-	-	8.3	7.2	-
1.85	-	1.05	-	-	1.6	1.25	-
0.95	-	0.57	-	-	1.1	0.87	-
2.6	-	1.8	-	-	3.5	3.7	-
0.39	-	0.28	-	-	0.5	0.4	-

Ce (when other REE are not present) by XRF after Kaye (1965); Co, Ta, Hf and REE» by instrumental activation analysis after Poli *et al.*, 1977.

comprising dikes and mafic-intermediate enclaves, intermediate-acid rocks with field, petrographic, and geochemical evidence of magma mixing, and acid rocks without any evidence of magma mixing processes.

Together with a diagram of K_2O vs. SiO_2, the normative diagram Q'-ANOR (Fig. 2) is preferred to show the compositional variability and degree of silica saturation of Tuscan rocks, because of intrusive vs. effusive occurrence, and because of large variability in the crystallinity. It is to note that in the acid group the Alumina Saturation index (ASI) varies between 0.91 to 1.55, showing that some of these rocks are strongly peraluminous.

A detailed survey of the field, petrographic, and geochemical characteristics of the TMP can be found in Poli *et al.* (2003) and reference therein, and here only essentials are given.

Mafic group (MG). Mafic rocks are saturated to slightly oversaturated in silica and have different petrological affinities: ultrapotassic, mainly lamproites, shoshonitic, and high potassium calc-alkaline (HCKA). Lamproitic rocks crop out at Montecatini Val di Cecina, Orciatico, Campiglia, and Torre Alfina (e.g. Peccerillo *et al.*, 1988; Conticelli *et al.*, 1992; Conticelli, 1998). Mantle normalized incompatible element patterns closely resemble those of some upper crustal rocks such as shales, gneiss and granitoids (Peccerillo, 1999). The same conclusion can be drawn for Sr, Nd, and Pb isotopic compositions. The Sisco lamproite in Corsica (~14 Ma) has composition similar to the Tuscan lamproites but shows higher contents of HFSE and lower Sr isotope ratio. However, since many authors recognized that magmatism in the TMP change with age of emplacement becoming younger from West to East (for a review see Poli *et al.*, 2003), Sisco lamproites will not be further discussed as related to genesis and evolution of the TMP rocks.

Shoshonitic rocks crop out at Radicofani, Capraia, Cimini and Amiata, and are represented also by some enclaves found at Tolfa and Amiata (e.g. Poli *et al.*, 1984; D'Orazio *et al.*, 1994; Conticelli *et al.*, 1995; Ferrari *et al.*, 1996; Peccerillo, 1999). The Radicofani trachybasalts can be defined as shoshonitic on the basis of silica-potassium contents, and resemble the latest erupted rocks of Capraia (Punta dello Zenobito), even if the latter are closer to the boundary between shoshonitic and HKCA fields. On the same basis, last erupted products of Cimini (olivine-latite lava flows) resemble those of Amiata (trachytic lava flows). Enclaves from Amiata have the same K_2O as the final lava flows of this volcano but minor amounts of SiO_2, whereas Tolfa enclaves are quite scattered on the shoshonitic field. HKCA rocks are represented only by some of the enclaves occurring at Tolfa, San Vincenzo, and at Elba, Giglio, Montecristo, and by mafic dykes present in Elba.

Intermediate group (IG). Intermediate-acid rocks are from oversaturated to strongly oversaturated in silica and have different petrological affinities: shoshonitic and high potassium calc-alkaline. Shoshonitic rocks are present at Cimini and Tolfa, even if rocks belonging to the last complex are mainly between the two fields. Typical HKCA rocks are present in the old Capraia outcrops, at San Vincenzo, and in the plutons of Elba, Giglio, and Montecristo. Plutonic rocks drilled in boreholes seem not contain enclaves and according to the adopted classification they could not belong to the second group. However it seem reasonable to suppose that the least evolved rocks (e.g. $SiO_2 <$ wt. 66%) could be classified in this group. Accordingly such rocks plot in between shoshonitic and HKCA fields resembling those outcropping at Tolfa.

Acid group (AG). Acid rocks are strongly oversaturated in silica and have HCKA petrological affinities. They are present both in volcanic and intrusive complexes: at Cimini, Amiata, San Vincenzo and Roccastrada, and at Elba, Giglio, Gavorrano, and boreholes. Some of the acid rocks exhibit some characteristics typical of crustal derived melts: the high values of normative corundum (up to 5%), relatively low Na_2O contents (about 2.5 wt %), high and restricted SiO_2 contents (about 71-74 wt %), presence of cordierite and metasedimentary enclaves.

MAGMA MIXING PROCESSES AND BASIC-ACID END-MEMBERS

Major-, trace-, and REE trends defined by TMP rocks are not consistent with a simple fractional crystallization process as a whole and within individual complexes through the segregation of their major and accessory mineral phases (e.g. Peccerillo, 1999; Dini *et al.*, 2002; Poli *et al.*, 2002). In addition, the occurrence of Mafic Microgranular Enclaves (MME) in IG rocks, both intrusive and effusive, and petrographic features such as mechanical interaction phenomena between MME and host rocks, patchy zoning and partially resorbed surfaces of plagioclases, together with variable Sr and Nd isotopic data, claim for magma interaction processes in the evolution of these rocks. MME have basic-intermediate compositions; in general, a shift towards more mafic compositions of enclaves is matched by a shift towards more mafic composition for the relative host rocks, as commonly observed in other magmatic provinces, indicating a partial re-equilibration between enclaves and hosts (e.g. Didier and Barbarin, 1991). Enclave size ranges from centimeters to decimeters and their amount is variable although never exceeding ~3.0 vol. % of the whole complex, even if some local facies in the intrusive environment can reach 20-30 vol. % (e.g. San Andrea in Elba). Chemical and field features strongly suggest, hence, that there was interaction between two crystal-mush systems and that enclaves have underwent partial re-equilibration with the host rocks. Such a process need some clarifications because is a point of crucial importance in understanding the mixing process, and it ruled out the possibility that the enclaves might have been totally solid at the time of interaction as suggested by some authors (e.g. Chappell, 1996). Re-equilibration when a media is completely solid can occur only by chemical diffusion processes, but this process would require a geologically unreasonable period of time owing to the extremely high diffusion coefficients in solids. Therefore re-equilibration is possible only if the two systems are well above the Rheological Critical Melt Percentage (Arzi, 1978) and they have a Newtonian rheology (e.g. Poli *et al.*, 1996). The evidence above outlined supports the hypothesis that enclaves are blobs of basic or intermediate, high-temperature magma chilled within a cooler, more silicic host, as suggested for other plutonic and volcanic associations (e.g. Didier and Barbarin, 1991; Poli *et al.*, 1996; Perugini *et al.*, 2001).

However, a simple two end-member mixing would generate linear trends in bivariate diagrams, whereas more complex patterns characterize the evolution of TMP rocks (e.g. Pinarelli *et al.*, 1989; Rombai *et al.*, 1995; Poli, 1992; Innocenti *et al.*, 1997). Moreover, mass balance arguments prevents from taking into account an assimilation of solid material coupled with fractional crystallization (AFC) process starting from a single parental magma. In fact, this would require special pleading in order to satisfy the observed proportions of acid (> 98%) and basic (< 2%) compositions. Therefore, a process of mixing of different batches of magmas coupled with fractional crystallization (MFC) have been proposed for many of the TMP complexes both, effusives and intrusives (e.g. Poli *et al.* 2003).

The process stated, the next problem is to find possible basic and acid end member magmas. In Figure 2A all the rocks from TMP define three trends. In the first trend (light gray), defined by the complexes of Capraia Shoshonites, Radicofani, Torre Alfina, Orciatico and Montecatini Val di Cecina, SiO_2 and K_2O are positively correlated, but SiO_2 has a very limited increase (52 to 58%) with respect to K_2O, strongly increasing from 2 to 10 wt.%. In the second trend (dark gray), defined by Capraia Shoshonites, HKCA samples from Capraia, Tolfa, all the granitoids, samples from San Vincenzo containing enclaves, SiO_2 and K_2O are positively correlated, and SiO_2 have a huge increase from 52 to 74 wt. with K_2O increasing maximum to 5 wt. %. In the third trend (intermediate gray), defined by Amiata and Cimini complexes, SiO_2 is variable from 54 to 74 wt.% with K_2O remaining almost constant. Some of Tolfa MME and MME belonging to San Vincenzo and all the plutons plot on the second trend. Other Tolfa enclaves plot on the first trend, whereas Amiata enclaves plot on the low silica part of the third trend. Regarding the first trend, the very high and low variation in K_2O and SiO_2, respectively, and the very primitive character of the complexes plotting on it (e.g. Peccerillo *et al.*, 2001) excludes evolutive processes at low pressure, and hence it can be envisaged as a trend derived by partial melting of mantle sources differently enriched in K_2O. It is noticeable that the second and third trends finish almost in the same area of silica at about 72-74 and K_2O 4.5-6 wt.%. A detailed inspection to the diagram reveals that samples plotting in this area do not contain any evidence of magma interaction, such as MME or petrographic features, and can represent, hence, rocks derived by anatectic processes. On the contrary, rocks plotting on the two trends extending towards low silica values can be envisaged as derived by magma interaction processes.

In order to better constrain end-member(s) of interaction processes in the TMP a plot of $^{87}Sr/^{86}Sr$ vs. Rb/Sr is reported in figure 3. From the inset of figure 3 emerges that some leucogranitic samples and aplites from Elba pluton plot on a trend having almost constant $^{87}Sr/^{86}Sr$ and strongly variable Rb/Sr starting from the facies containing MME, indicating that a fractional crystallization (FC) process is reasonable for the genesis of the variation of these rocks. On the same trend some samples belonging to Tolfa complex also plot. In

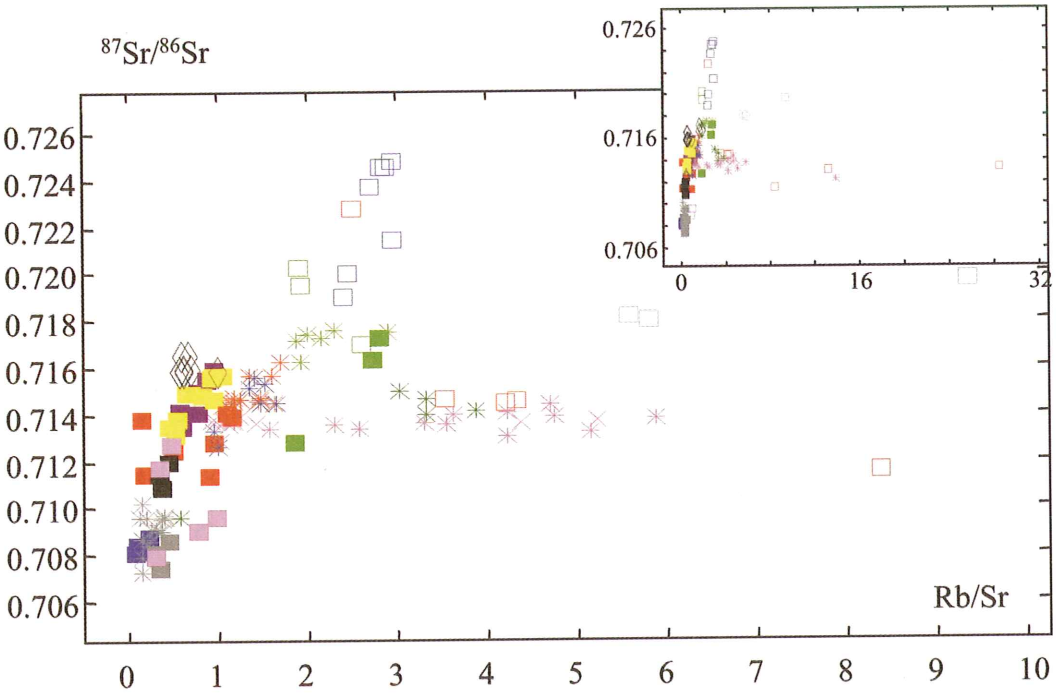


Fig. 3 – $^{87}Sr/^{86}Sr$ vs. Rb/Sr diagram for all the rocks of TMP. Note the abscissa scale in the insert. Data as in Figure 2.

particular, these samples are the high-silica rhyolitic rocks that do not containing enclaves outcropping on the Montagnola area; therefore also for those samples can be envisaged a process of FC. It is to note, however, that samples belonging to Montecristo pluton (Fig. 3), and surely contains magmatic enclaves, plot on the same trend.

A different trend is displayed by samples belonging to the Roccastrada volcanic complex and to Giglio rocks containing enclaves. A third trend with strong increase of $^{87}Sr/^{86}Sr$ and low increase of Rb/Sr is defined mainly by samples not containing enclaves of San Vincenzo. On the same trend plot also some leucocratic facies of Elba and Giglio. On the continuation versus lower $^{87}Sr/^{86}Sr$ and Rb/Sr contents plot many samples and in particular San Vincenzo rocks containing MME, most of the main facies (containing MME) of Elba, enclaves and basic dykes from Elba. This trend point to a group of rocks at very low $^{87}Sr/^{86}Sr$ and Rb/Sr and represented by Capraia volcanics, San Vincenzo enclaves and the HK enclaves belonging to Tolfa complex. Amiata, Radicofani and Cimini samples plot on a trend of increasing $^{87}Sr/^{86}Sr$ and Rb/Sr and pointing to the lamproitic rocks.

Because each complex has its own behavior detailed analyses have been performed on two complexes: San Vincenzo and Elba. In figure 4 are reported literature and new isotopic data on mineral separates and drilled minerals in effusive and intrusive environment. In figure 4A high purity separated and drilled minerals from the San Vincenzo complex (plagioclase; Feldstein *et al.*, 1994) are compared with host rocks. It is evidenced that plagioclase in all the three groups of rocks have three distinct isotopic compositions matching those of the three groups of rocks themselves. This clearly indicates lack of equilibrium between mineralogical phases and melts and argues in favor of the hypothesis that crystal transfer occurred among the three groups of rocks during a mixing process

In Figure 4B high purity mineral separates (plagioclase and K-feldspar) collected along a transect between an enclave and the host granite in the Elba island have been analyzed for Sr isotopic systematics (Table 2). Attention was paid during sampling and purification in order to avoid minerals belonging to the host. Morphology of isotopic variation among minerals grown both inside the enclave and host shows a typical diffusive pattern as that obtained using equation 3.13 of Crank (1975) for a semi-infinite plane sheet medium with initial concentration C_0 (enclave magma) and constant surface concentration C_1 (host magma). This strongly indicates that the isotopic variations is due to a diffusion process at the liquid state, with uphill and downhill phenomena (Crank, 1975).

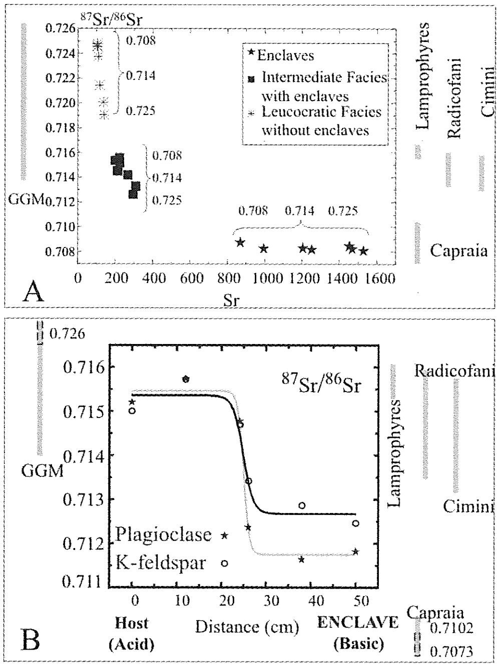


Fig. 4 – A: $^{87}Sr/^{86}Sr$ compositions against Sr of drilled and high purity separates plagioclase, and host rocks from San Vincenzo volcanic complex. Data are from Feldstein *et al.* (1994). B: Sr isotope ratios of high purity plagioclase and K-feldspars separates along a transect between enclave and host rock in Elba pluton. Isotope ratios for other complexes and basement rocks from Tuscan Magmatic Province are also reported. Data from Table 2. Dashed boxes indicate extension of the range to the values reported near by.

TABLE 2

Rb-Sr isotopic data for high purity separate minerals. All Sr isotopic analyses were normalized to 86/88Sr =0.1194. Uncertainties in measured isotopic ratios refer to least significant digits and represent +/- 2σ run precision. No correction for age have been performed. Data on plagioclase are from Poli et al. (2002)

		Plagioclase		K-feldspar	
Sample	Distance	$^{87}Sr/^{86}Sr$	2σ	$^{87}Sr/^{86}Sr$	2σ
TA24	0	0.711827	0.000020	0.712466	0.000017
TA25	12	0.711634	0.000020	0.71286	0.000015
TA26	24	0.712371	0.000015	0.713406	0.000010
TA31	26	0.714786	0.000015	0.7146	0.000010
TA29	38	0.715736	0.000015	0.715737	0.000010
TA30	50	0.715212	0.000017	0.715006	0.000011

In figure 4 possible basic end-members are also reported. It is evident that Capraia is the only feasible basic end-member for the volcanic environment (Fig. 4A), whereas no isotopic data of mafic material exist having isotopic ratios of the enclave core (Fig. 4B). It is to note, however, that in intrusive environment isotopes re-equilibrate rapidly because isotope diffusion coefficients are very high (Lesher, 1994; Baker, 1989), and because diffusion has much more time to act (Poli *et al.*, 1996). Then, Capraia magmas could be reasonable basic end-members also for intrusive magmatism of TMP.

In figure 5 SiO_2 vs. Sr is reported for enclaves and mafic dykes from effusive and intrusive environment compared with mafic rocks from Lamproites, Capraia, Amiata, Cimini and Radicofani complexes. Enclaves from Elba, Giglio and Montecristo, together with some dykes from Elba, plot in the field of intermediate and acid rocks, evidencing processes of re-equilibrium with host rocks, and at lower SiO_2 they point to the field of shoshonitic Capraia. Other samples from Elba dykes plot in the field of Capraia HK and in the field of some facies of Capraia having very high Sr contents together with enclaves from San Vincenzo. Tolfa enclaves plot in two different fields: those having HK affinity plot along the trend defined by the intrusive MME and pointing to the Capraia shoshonites, whereas those having shoshonitic affinity plot on Cimini, Amiata, Radicofani fields indicating an affinity with the lamproitic rocks of TMP.

In conclusion SiO_2 vs. K_2O and Sr diagrams, and Sr isotopic systematics indicate that three magmas can be considered as basic end-members for the magma interaction processes that acted in TMP rocks: Capraia shoshonites, Capraia HK rich in Sr, and lamproites from Tuscan area. Such magmas acted together even

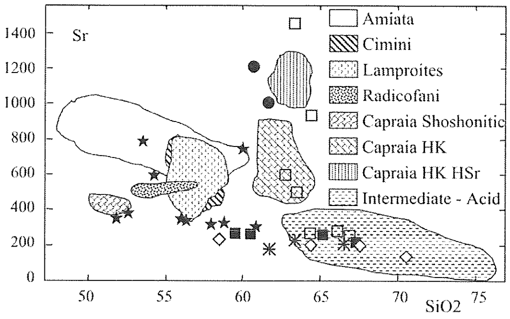


Fig. 5 – SiO_2 vs. Sr diagram for basic-intermediate, intermediate-acid rocks compared with MME and dykes from TMP. Symbols for MME: Elba – solid squares; Elba dykes – open squares; Giglio – asterisks; Montecristo – diamonds; San Vincenzo – solid circles; Tolfa – stars.

in a single complex as shown by the composition of Elba and Tolfa MME. On the other hand, mafic facies of Cimini, Amiata and Radicofani can be ruled out as viable basic end-members of the interaction processes.

Although it is not the goal of this paper (see Conticelli *et al.*, this issue), some constraints can be advanced for the genesis of the three basic end-members. The Capraia HK rich in Sr end-member is not primary having an intermediate composition and cannot be considered, hence, derived by direct partial melting of a mantle source. Genesis of these high Sr magmas is difficult to state, but it can be envisaged as the evolution products of mantle derived magmas differently metasomatized in element like Sr, Ba, Pb, but not K_2O and Rb. The other two end-members can be considered as primary on the basis of geochemical data and petrography (this paper and e.g. Peccerillo *et al.*, 2001). The coeval occurrence of lamproitic and shoshonitic mafic melts in the studied area suggests that a heterogeneous mantle showing these two extreme compositions existed below the TMP province. The first one showing clear fingerprints of high degrees of metasomatism, possibly with K-rich phases such as phlogopite playing a key role in the genesis of the lamproitic group of mafic rocks (Conticelli *et al.*, 2002). The relatively high silica content of this end-member suggests a genesis at moderate pressure (Foley, 1992), whereas the low Al, Na, Ca, and compatible elements require a restitic peridotitic source. Lamproitic mafic products are often associated with the existence of a metasomatized lithospheric mantle wedge above a subducting slab, the latter being the engine acting to produce the metasomatic process itself (Mitchell and Bergman, 1991). The second mantellic composition (Capraia shoshonites) shows higher Al, Na, Ca, and normal compatible elements suggesting a derivation from a fertile metasomatized lherzolitic mantle source. However, these two mantle compositions have to be considered just as two extreme end-members occurring in a mantle wedge potentially able to generate mafic melts spanning all the intermediate compositions ranging from ultra-potassic to calc-alkaline (Fig. 2A light gray arrow). Similar features have been observed in other Mediterranean areas geodynamically analogous (Perugini *et al.*, 2004)

The acid end-member can be envisaged as the most felsic granites and rhyolites. Most of these rocks have, indeed, compositional features matching those of both natural and experimental melts derived from metasedimentary crustal sources. These features are mainly represented by strong peraluminosity and high SiO_2 content, coupled with low concentrations of ferromagnesian elements (e.g. Patiño Douce and Beard, 1996). However as evidenced by Sr isotopic systematics (Fig. 3) some rocks of the AG must be considered as generated by FC processes, and the same holds using trace elements. Compositional characteristics of these rocks such as the strong depletion in elements stored in feldspar Sr, Ba, Eu (down to 30 ppm for Sr, 40 ppm for Ba, and 0.12 for Eu anomaly), and enrichment in incompatible elements (U, Th, Rb) indicate, in fact, that they cannot be produced by anatectic processes because the degree of melting required to produce such low Sr and Ba contents in the liquid would be too low (less than 1%) using partition coefficient reported in Appendix 1, and common crustal sources. Then isotopes and trace elements permit to distinguish between rocks derived directly by anatectic melt or by crystal fractionation processes able to deplete at very low values Sr and Ba by fractionation of feldspars. In Table 3 are reported ranges of compositions of TMP rocks considered derived by partial melting process of crustal sources.

GENESIS OF ANATECTIC MAGMAS

Compositions of envisaged true anatectic magmas (Table 3, hereafter AM) have been cross-compared with a large database compiled on experimental partial melts acquired from different starting crustal protoliths in the

TABLE 3

Range of values for rocks considered pure anatectic melts in all the examined complexes.
Values for the three rocks belonging to the GGM group used as sources for the partial melting model are reported in Table1.

Complex	Elba			Giglio				Gavorrano		Boreholes			
Type	Leucogranites		Cotoncello	Leucogranites		Scole				MS1 - Monte Spinosa		S2 - Castel di Pietra	
	min	max	PP-330	min	max	min	max	min	max	min	max	min	max
Rb	336	428	318	278	372	270	309	377	466	328	541	310	394
Sr	80	125	127	65	107	143	161	97	120	202	330	112	151
Ba	123	284	280	74	320	341	403	270	288	454	589	195	398
Th	12.9	18.2	14.4	8.5	18	-	-	-	-	-	-	-	-
Zr	66	139	116	53	157	146	202	145	150	104	126	78	208
Y	14.9	23.1	12.3	19	32	24	27	43	46	-	38	-	37
Ta	3.64	4.29	2.49	1.1	1.5	-	-	-	-	-	-	-	-
Hf	3.2	3.2	-	1.5	4.5	-	-	-	-	-	-	-	-
Nb	12.6	21	11.8	5	13	10	15	13	16	4	10	8.3	15.2
La	17.1	26	28.3	15.5	36	27	31	28	36	12.4	22	15.6	38
Ce	34.7	51.2	58.2	32	72	48	57	33	53	8.6	36	7.1	80
Nd	14.7	22.4	24.9	14.6	30	-	-	-	-	-	-	-	-
Sm	3.13	6.1	5.1	4.61	8.3	-	-	-	-	-	-	-	-
Eu	0.31	0.72	0.75	0.48	0.66	-	-	-	-	-	-	-	-
Tb	0.43	0.68	0.51	0.55	0.89	-	-	-	-	-	-	-	-
Yb	0.96	1.88	0.77	2.4	3.4	-	-	-	-	-	-	-	-
$^{87}Sr/^{86}Sr$	0.71447		0.7228	0.71699		0.71991		-		-		-	

CONTINUED *Table 3*

Complex	Boreholes		San Vincenzo				Roccastrada				Tolfa	
Type	S3 - Castel di Pietra		High $^{87}Sr/^{86}Sr$		Low $^{87}Sr/^{86}Sr$		Rhiolites		Dome			
	min	max	min	max	min	max	min	max	min	max	min	max
Rb	280	330	327	403	318	363	390	449	400	486	305	403
Sr	168	208	135	206	112	113	48	70	54	67	29	225
Ba	367	452	294	380	263	280	110	172	130	163	39	473
Th	-	-	20.2	21	17.8	17.8	20	25	18.8	24.2	40	61
Zr	176	201	144	160	132	176	95	113	122	144	94	255
Y	38	80	18	24	18	21	26	33	26	28	21	38
Ta	-	-	1.5	1.6	2.1	2.1	-	-	1.9	2.3	-	-
Hf	-	-	3.4	3.7	3.9	3.9	3.8	3.9	3.4	4	-	-
Nb	14.6	16	11	15	9	11	14	15	13	13	9	20
La	32	44	34	39	37	37	30.5	34.1	26	31	50	77
Ce	30	75	70	74	71	71	68.1	71.2	34	51	104	141
Nd	-	-	30	33	35	35	28.8	34	20	27	38	50
Sm	-	-	6.8	7.1	8.3	8.3	6.8	7.19	5.2	5.9	4.6	7.9
Eu	-	-	0.83	0.86	0.88	0.88	0.53	0.55	0.36	0.43	0.68	1.3
Tb	-	-	0.59	0.63	0.79	0.79	1.12	1.23	0.61	0.87	0.92	0.92
Yb	-	-	1.4	1.6	1.5	1.5	3.09	3.25	2.1	2.2	2.5	2.7
$^{87}Sr/^{86}Sr$	-		0.72441		0.72017		0.71808		-		0.7134	

ternary graph of figure 6. Geobarometric data on fluid inclusions (Ruggieri and Lattanzi, 1992) indicate an emplacement pressure for the intrusive TMP rocks at about 2-3 kb with presence of contact aureoles, indicating that the source region for AM has to be surely placed at higher pressure. AM rocks range in SiO_2 between 69 and 74 wt.%. Accordingly, in figure 6 only experimental melts generated at pressure greater than 2-3 kb and with values of SiO_2 similar to those of AM rocks are plotted. AM rocks plot in a quite restricted area, indicating that the source rocks were quite homogeneous. Igneous protoliths with intermediate-basaltic compositions (amphibolites and basalts), and gneiss with igneous protoliths are not likely to be suitable sources rocks for the AM. On the contrary, gneiss with sedimentary protoliths and greywackes display a compatible major element geochemistry indicating that a possible source for AM samples can be represented by that kind of rocks. It is to note that pelitic sources are also not suitable to give magma similar to the AM. For instance, the CaO enrichment of AM rocks, relative to ferromagnesian components, is consistent with derivation from a biotite-plagioclase-rich source such as metagreywacke, rather than a simple biotite-rich metapelite (Patiño Douce, 1999). It is to note also that Poli *et al.* (2002) ruled out pelitic sources on the basis of modeling of trace elements by partial melting for the intrusive AM samples.

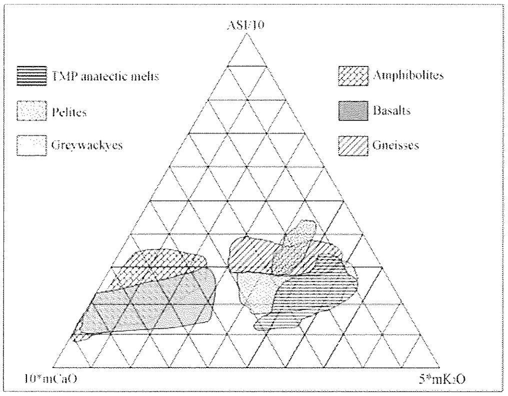


Fig. 6 – Triangular diagram [K_2O–CaO-$Al_2O_3/(Na_2O+K_2O+CaO)$ (ASI)] (molar) reporting the composition of AM rocks from Tuscan Magmatic Province Intrusives cross-compared with experimental petrology data of melt compositions from different crustal protoliths. The field of overlapping between gneiss and greywackes corresponds to gneiss having metasedimentary protoliths. Data from: MacRae and Nesbitt, (1980); Skjerlie *et al.*, (1993); Vielzeuf and Montel, (1994); Carrington and Watt, (1995); Gardien *et al.*, (1995); Patiño Douce and Beard, (1996); Montel and Vielzeuf, (1997); Pickering and Johnston, (1998); Castro *et al.*, (1999).

Greywackes as source rocks would require involvement of medium/upper crust in the genesis of acid Tuscan magmatism as suggested also by the very radiogenic Sr isotopic signatures. Many authors proposed gneiss and garnet micaschists having a metasedimentary protolith found in boreholes from the Southern Tuscan geothermal field (Bagnoli *et al.*, 1979; Gianelli and Puxeddu, 1979) as a possible source for the some of the AM rocks (e.g. Pinarelli, 1991; Poli *et al.*, 2002; Dini *et al.*, 2003). Such rocks have high variability of isotopic signature, which well compare with San Vincenzo and Elba AM rocks (Fig. 4). In figure 7 they have been cross-compared with all the AM rocks. It is to note that GGM encompass very well the isotopic variability of AM, but also that different complexes can be derived from different sources.

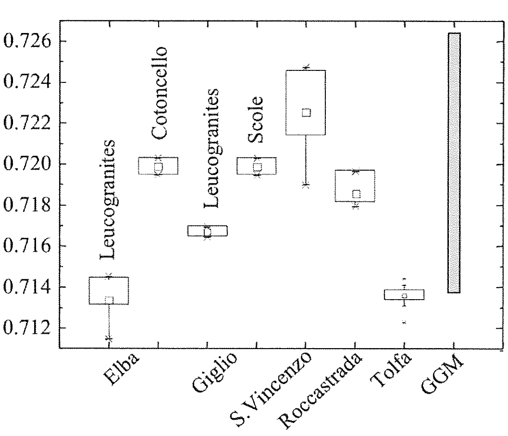


Fig. 7 – Sr isotopic compositions for AM and GGM rocks from TMP. Symbols: asterisks – minimum and maximum; open squares – mean; boxes – from 25 to 75 percentiles.

According to isotopic compositions we choose possible GGM samples for the different complexes (Tab. 1). Unfortunately no detailed isotopic systematic exists for Gavorrano and borehole samples and therefore they cannot be compared with GGM samples. Dini *et al.* (2003) report that very different isotopic composition exist for different facies from borehole granites: $^{87}Sr/^{86}Sr = 0.7165\text{-}0.7222$ and $^{87}Sr/^{86}Sr = 0.7145$. Accordingly the three sources envisaged for the other complexes have been used for borehole AM samples also.

A trace element model of batch partial melting starting from the compositions of the sources above envisaged has been applied, using equation

$$C_l = \frac{C_0}{D_r + F*(1-D_r)}$$

where C_0, C_l, F, and D_r represent composition of source, composition of melt, degree of partial melting, and bulk partition coefficient of the residuum, respectively. Successively the percentage of residual minerals has been calculated by linear programming minimizing the sum of squares of residuals as a constraint (SSR; e.g. Wright and Doherty, 1970) starting from the bulk partition coefficient modeled and using literature partition coefficients (Appendix 1). The SSR is used as a parameter indicating the effectiveness of the source used. Regarding models for Gavorrano and borehole AM samples, we performed models starting from three sources and we chose those with the lowest SSR.

In figure 8 the models for the different complexes are reported as spider diagrams and in Table 4 the bulk partition coefficients used in the models. Matching between modeled melts and AM is striking for all the complexes. In Table 5 are reported percentages of residual minerals with the best solution for each complex. Although calculated percentage of residual minerals must be regarded cautiously because the linear programming model is overestimated, that is we have more equations than unknowns, some insights can be advanced for each complex. AM samples from Elba, but Cotoncello sample, are well constrained using sample SD73 as source leaving a residuum made of mainly Opx, feldspars, and accessory minerals with no amount of biotite. Not very high amount of garnet is consistent with the low fractionation values of HREE. Cotoncello sample is well-constrained using sample SD75 as source leaving a residuum made of mainly Opx, Bt, feldspars, Q, and accessory mineral. Very high residual garnet is consistent with the strong fractionation of HREE in this sample. AM samples from Giglio behave similarly to those from Elba with less amount of Opx replaced by Q. The Scole samples have similar garnet in the residual assemblage to Giglio samples. Unfortunately REE analyses are unavailable for the Scole samples, but the similar ratio of La/Y in Scole samples with respect to the other Giglio samples corroborates the modelled residual assemblage. Regarding samples from Gavorrano and boreholes, lack of isotope and REE data does not permit detailed discussions. In general, Gavorrano samples are well constrained by both SD73 and SD75 sources whereas source SS2076 gives much higher SSR indicating that source of Gavorrano samples have to be envisaged in the lower isotopic signature samples. Regarding samples from boreholes all give very low values of SSR using as source the three GGM samples at different isotopic compositions. However the best results are gained using as sources SD75, and SS2076 for S2 and S3, and MS1, respectively. Important differences in the residual assemblages for the three boreholes samples regard Opx versus Q and garnet. In samples S2 and MS1 Opx is scarce whereas Q is high. The opposite holds for S3 samples. Garnet is higher in the MS1 samples, decreases in S2 and is nil in S3. The average increase of La/Y ratios from S3 to MS1 corroborates the modeled residual assemblage.

Regarding volcanic complexes, San Vincenzo samples are modelled using two sources with different $^{87}Sr/^{86}Sr$. Opx, Bt, Feldspar, Qtz, and accessory minerals are present in residual assemblage starting from source SS2076 for SV – High $^{87}Sr/^{86}Sr$

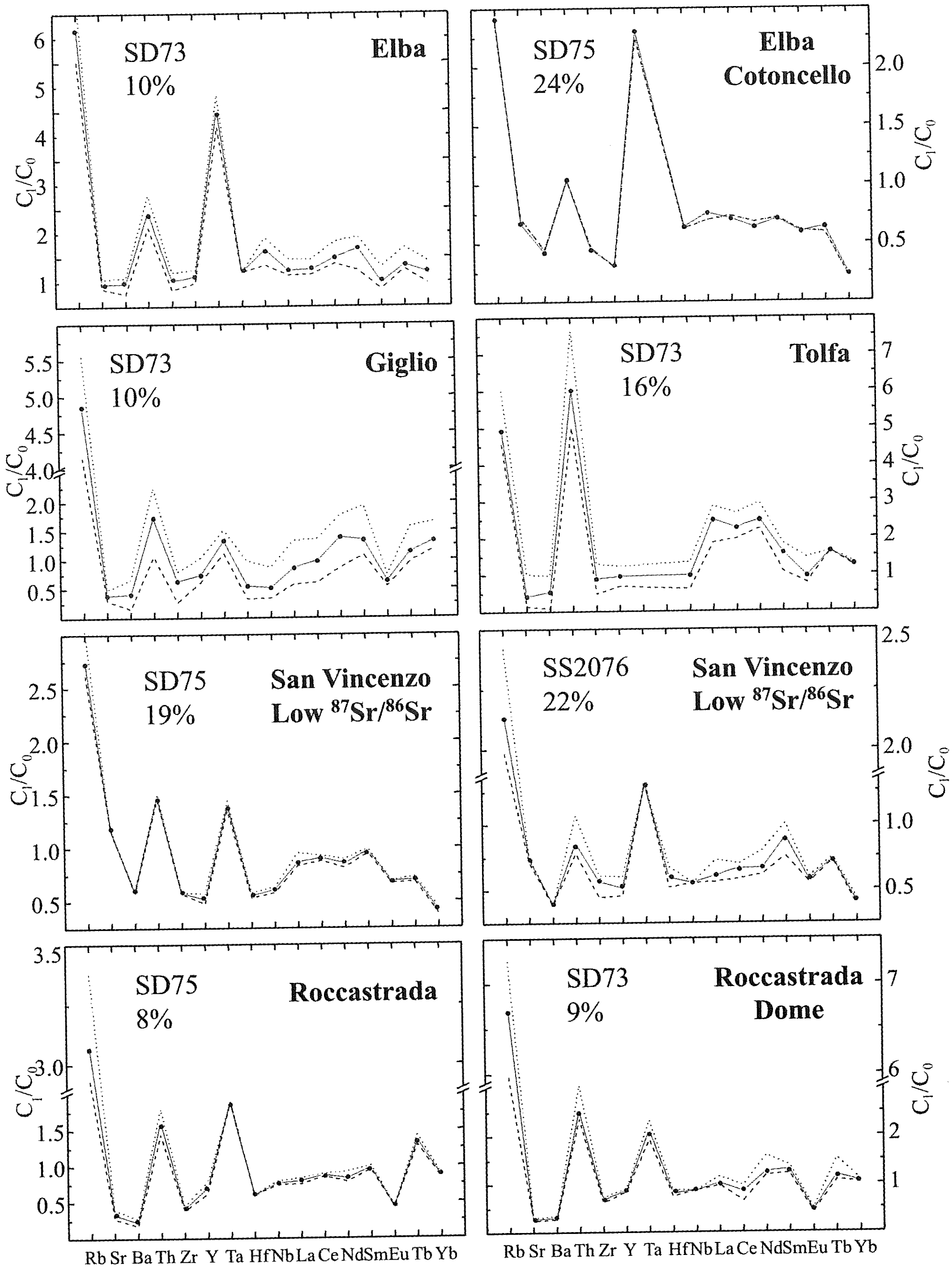
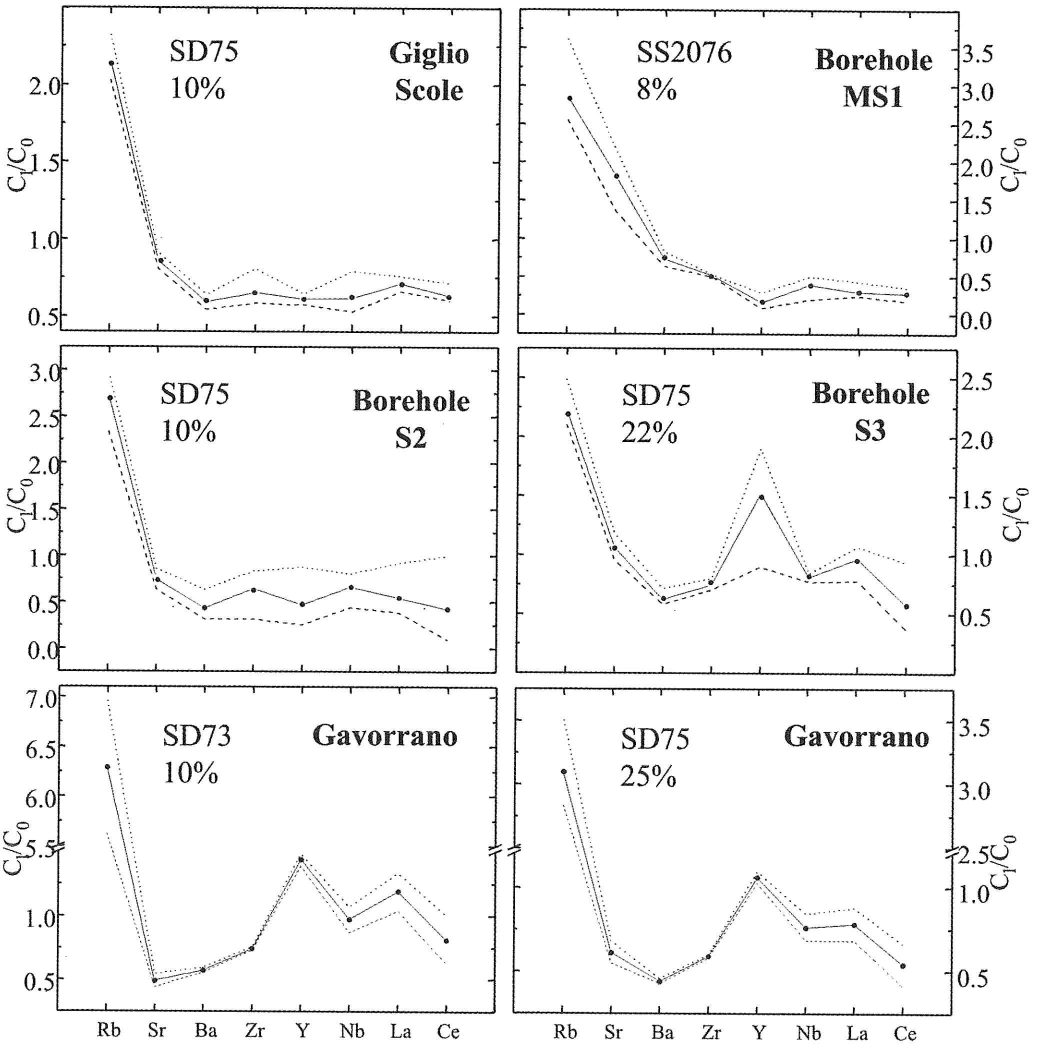


Fig. 8 – Spider diagram of minimum (dashed lines) and maximum (dotted lines) of AM rocks from Tuscan Magmatic Province and modelled melts normalized to the sources. Sources and degrees of melting are also reported.



samples, whereas Opx is absent in the model for SV – Low $^{87}Sr/^{86}Sr$ samples starting from source SD75 and high amount of residual Qtz is present. Garnet is higher in samples at high $^{87}Sr/^{86}Sr$ accordingly with the higher (Tb/Yb)n values of these samples. Roccastrada samples behave similarly to San Vincenzo but the fact that both Opx and Q are low. Low amount of garnet is consistent with the low (Tb/Yb)n values of these samples. Regarding samples from Roccastrada dome, all give very low values of SSR using as source the SD73 and SS2076 samples. As the two possible sources have the minimum and maximum values for $^{87}Sr/^{86}Sr$, results from the partial melting model do not give any constraint on the source of Roccastrada dome samples. However presence of restitic cordierite in the Roccastrada dome samples and high values of modeled residual cordierite (Table 3, 9.2%) can indicate that SD 73 can be a viable source for such samples.

It is to note that all San Vincenzo and

TABLE 4

Bulk partition coefficients used to model pure anatectic rocks for each complex.

Complex	Elba		Giglio		Gavorrano		Boreholes			San Vincenzo		Roccastrada		Tolfa
Type	Leuco-granites	Coton-cello	Leuco-granites	Scole	Source SD73	Source SD75	MS1	S2	S3	High $^{87}Sr/^{86}Sr$	Low $^{87}Sr/^{86}Sr$	Rhio-lites	Dome	
Rb	0.08	0.23	0.12	0.4	0.06	0.09	0.27	0.31	0.27	0.2	0.3	0.2	0.07	0.04
Sr	2.3	1.5	2.7	1.2	2.2	1.8	0.53	1.4	0.9	0.83	1.5	3.4	3.9	1.9
Ba	2.6	2.7	2.6	1.8	1.8	2.7	1.4	2.3	1.7	1.84	3	5	3.5	2.1
Th	0.46	0.95	0.6	-	-	-	-	-	-	0.6	1.1	0.55	0.31	0.05
Zr	2.1	2.5	2	1.5	1.4	1.9	2.1	1.8	1.43	1.9	2.2	2.7	1.54	1.16
Y	1.7	4.2	1.24	1.7	0.66	0.93	5.8	1.9	0.63	2.1	2.2	1.5	1.16	1.06
Ta	0.16	0.27	0.74	-	-	-	-	-	-	0.65	0.7	0.44	0.42	0.44
Hf	1.5	1.5	1.6	-	-	-	-	-	-	2	1.9	1.8	1.26	1.78
Nb	0.9	1.8	1.74	1.6	1.04	1.4	3	1.7	1.3	1.8	2.1	1.36	1.16	1.04
La	1.3	1.6	1.05	1.45	0.83	1.4	3.1	1.6	1.1	1.16	1.7	1.3	0.94	0.32
Ce	1.26	1.5	1.02	1.6	1.26	2.1	4	1.9	1.7	1.14	1.7	1.2	1.27	0.33
Nd	0.9	1.6	0.74	-	-	-	-	-	-	1.2	1.54	1.2	0.7	0.27
Sm	0.9	1.5	0.63	-	-	-	-	-	-	1.04	1.2	1.03	0.76	0.63
Eu	1.8	1.9	1.64	-	-	-	-	-	-	1.6	12	2.6	2.4	0.89
Tb	1.03	1.9	0.77	-	-	-	-	-	-	1.5	1.5	0.7	0.75	0.55
Yb	1.5	6	0.68	-	-	-	-	-	-	2.8	2.9	1.2	0.95	0.75

TABLE 5

Residuum assemblages calculated using linear programming (Wright and Doherty, 1970) minimizing the sum of squares of residuals as a constraint (SSR).

Complex	Source	Bt	Opx	Pl	Kfs	Qtz	Grt	Crd	Ap	Ttn	Zr	Spi	SSR
Elba	SD73	0	47	22	28	0	1.8	0	0.9	0	0.07	0	0.16
Cotoncl	SD75	14	28	37	0	10.6	10	0	0.7	0.11	0.1	0.2	0.12
Gig	SD73	0.02	21	32.3	30	13.9	0.45	0	0.5	0	0.09	1.4	0.1
Scole	SD75	14	10	29	0.06	34	0.22	7.5	3.8	0	0.06	1.4	0.09
GAV	SD73	0	21	29	28	20	0.04	0	1.8	0.04	0.01	0	0.13
GAV	SD75	0	44	4.8	46	0	0	0	3.6	0	0	1.2	0.22
MS1	SS2076	9.2	3	7.8	5.8	58	1.7	0	11.4	0	0.08	2.9	0.15
S3	SD75	5.5	66	6.9	18	0	0	0	2.2	≈ 0	0	1	0.1
S2	SD75	13.2	6	25	10.5	36	0.18	3.4	4.5	≈ 0	0.07	1.3	0.1
SVlow	SD75	8	0	24	4.7	58	3.5	0	0.9	0.1	0.08	1	0.21
SVhigh	SS2076	16.3	37	33	2.3	5.3	5	0	0.8	0.02	0.07	0.27	0.2
RCS	SD75	12.3	0.92	18	55	11.2	0.82	0	0.86	≈ 0	0.09	0.38	0.14
RCS dome	SD73	0.75	1.8	7.7	62	16.7	0.65	9.2	0.53	0.04	0.07	0.93	0.09
Tolfa	SD73	0.91	0	0	75	22	0.81	0	≈ 0	0	0.09	1.2	0.6

Mineral abbreviations are after Kretz (1983). SV low and high $^{87}Sr/^{86}Sr$.

Roccastrada AM rocks contain cordierite both magmatic (see below) and possibly restitic which occur as irregular turbid and altered fragments and a few have cores containing inclusions of sillimanite, spinel, and biotite. Only the last can be considered as refractory cordierites coming from the source region, whereas the former could derive from refractory garnet, owing the pressure decrease during the magma ascent, by the reaction: Grt = Bt + Crd + melt.

Tolfa samples are modelled using SD73 as source, accordingly to the $^{87}Sr/^{86}Sr$ values. However results are poor because residual assemblage formed only by feldspar and quartz and SSR relatively high (0.6), both indicate that source for Tolfa AM samples is not well constrained.

Several studies simulating crustal anatexis (e.g. Thompson and Connolly, 1995) show that crust can achieve wet-solidus melting temperatures but also that the amount of wet-solidus melt generated is less than 1 wt %. This can be caused by the rapid migration of free water relative to the rising of the isotherms through the crust and the high solubility of water in the melt. Accordingly, significant amounts of melt can occur only in association with muscovite and biotite dehydration-melting reactions. Then experimental works in fluid-absent conditions will be compared with modeled residual assemblages. The three GGM sources have major element compositions similar to the starting materials of the two experimental petrology works by Patiño Douce and Beard (1996) and Vielzeuf and Montel (1994), even if the second is a little richer in SiO_2.

Presence of Crd and Grt helps to envisage pressure at which the melting occurred. The two studies agree to state that Grt is stable at pressure higher than 5 kbar, whereas only the Vielzeuf and Montel (1994) work states that Crd is stable below 3 kbar. Then nothing can be said about Crd/Grt stability in between 3 and 5 kbar. The amount of Crd that can be considered having significance in the modelled residuum assemblages is above 4%, considering errors connected with the linear overestimated programming and with partition coefficients. Accordingly, only Giglio – Scole, and Roccastrada – dome can be considered to have left Crd in the residuum. This put the melting process for those complexes at pressure surely lower than 5 kbar. Although less constrained because Crd contents are about 3.5% only, also residuum for S2 complex claims for pressure between 3 and 5 kbar. All the other complexes contain garnet in the residuum indicating that the melting process occurred at pressure higher than 5kbar. Looking at residual assemblages for each sources, at higher degrees of modelled partial melting correspond higher amounts of Opx, although with some scatter. Then Opx can be used as a proxy for the degrees of melting. The low amount of Bt in some residua could be consistent both with the reaching of Bt out field during the partial melting, and/or with low amount of Bt in the source which would have been lowered (T) the Bt out line. Presence of Kfs in the residual assemblage seem to be in contrast with the lack of this phase in the experimental runs of both works at pressure lower than 10 kbar. However Patiño Douce and Beard (1996) state that plagioclase in the experiments contains large amount of orthoclase molecule, and hence the presence of Kfs in the residual assemblage could take into account for this feature, and reconciling the presence of Kfs in the modeled assemblage. A note needs to be given about Tolfa residual assemblage. The presence of large amount of Kfs would indicate a very high pressure of partial melting, higher than 10 kbar according to the experimental works. This is not in agreement with the thickness of the crust in the area (max 25 Km; e.g. Panza, 1984). This feature coupled with the peculiar lacking of Opx and Bt in the residual assemblage, may indicate that none of the envisaged crustal sources is responsible for the genesis of Tolfa AM. On the other hand Tolfa volcanic complex is southernmost located in the TMP and therefore different crustal sources could be possible.

Both San Vincenzo and Roccastrada AM rocks do not contain Opx, indicating that magmas crossed the stability of Opx and this is consistent with positive slope of Opx stability line in the P-T diagrams for both the experimental works. Both San Vincenzo and Roccastrada rocks contain, on the contrary, cordierite, considered magmatic on the basis of textures and chemistry, indicating that the melts crystallized in the field of cordierite that is at about 800-870°C. This temperature is only little higher (740-800°C) than that estimated by Pinarelli *et al.* (1989) and Feldstein *et al.* (1994) for San Vincenzo rocks, but much higher than that estimated by the former authors for Roccastrada rocks (670-700°C). It is to note, however, that the two-feldspar geothermometer used to evaluate crystallization temperatures of Roccastrada magmas, strongly depends on equilibrium conditions that often are difficult to asses.

Intrusive samples do not contain magmatic cordierite except some from boreholes, which, however, are much altered, and few occurrence in Elba and Giglio AM rocks. This seems to indicate an emplacement level at higher pressure than the cordierite stability. On the other hand emplacement level is well constrained by fluid inclusions studies at about 2-3 kbar (Ruggieri and Lattanzi, 1992), and hence an emplacement level at about 3kbar can be supposed. Further indications can be acquired by the absence of orthopyroxene in the intrusive AM samples, indicating that magmas crossed the stability of Opx and this is again consistent with positive slope of Opx stability line in the P-T diagrams for both the experimental works.

In conclusion, the modeled residuum assemblages indicate that the reaction Bt+Pl+Qtz = Opx + Grt +(Kfs) +M is an adequate model reaction for the fluid absent partial melting of the GGM sources. It is to note that presence of Grt in the source is not necessary because it is a reaction phase always present if melting occurs at pressure higher than 5kbar in biotite-plagioclase-rich sources such as meta-graywackes.

CONCLUSIONS AND GEODYNAMIC IMPLICATIONS

New and published data on the effusive and intrusive rocks belonging to the Tuscan Magmatic Province evidenced that magma interaction between basic and acid end-members is responsible for the evolution these rocks. Major and trace elements and isotopic systematic help to recognize different basic end-members, that acted together even in a single complex, and are akin to mafic Capraia shoshonitic, intermediate Capraia HK rich in Sr, and Lamproites from Tuscan area.

Petrological and geochemical data and trace element modeling suggest that the leucocratic facies found inside volcanic and plutonic complexes represents either products derived by Fractional Crystallization from a less evolved parent magmas and pure acid melts derived by partial melting of crustal sources. Experimental petrology and geochemical evidence suggest that such sources must have a metasedimentary character such as greywackes. Suitable sources have been recognized in the gneiss and garnet micaschists having a sedimentary protolith found in boreholes from the Southern Tuscany geothermal fields. Detailed partial melting models corroborate such hypothesis, and modeled residual assemblages agree with experimental petrology works. In particular, amounts of residual garnet and cordierite match very well the geochemical characteristics of the TMP pure anatectic rocks. Residual assemblages indicate also that such partial melting event should have occurred at pressure greater than 4-6 kbar for all the complexes. On the other hand, field evidence, such as contact aureoles found around the plutons, and pressure of emplacement estimated by fluid inclusions claim for an emplacement level at 2-3 kbar.

The gneiss and garnet micaschists have been found in boreholes at maximum depth of 4 km. Partial melting of such rocks at about 12-18 km put some problem on the structure of the crust below the TMP. This discrepancy can be resolved by taking into account geophysical data obtained by the project «CROsta

Profonda» and in particular by the CROP 03 profile (Barchi *et al.*, 1998), where superposition of upper crust of both the European and Adriatic plates has been seismically recorded in westernmost Tuscany. This feature implies that upper crustal rocks such as micaschists and gneiss may actually occur at great depths, i.e. they could represent the upper layers of the underlying crustal section. Melting of such a layer may provide an explanation for the need of having melting of upper crustal rocks at deep crustal levels.

Starting from the above data, a complex genesis for the lithosphere in this segment of Northern Apennines («Etruscan Belt») could be envisaged. During Late Oligocene-Early Miocene, a multiphase compressive regime built up the «Etruscan Belt» concurrent with the Corsica rotation. Starting in Middle Miocene, the Etruscan belt underwent a strong extension that was responsible for its collapse. Soon after, from Middle Pliocene onward, the western Tuscany underwent an almost generalized strong regional uplift, still presently active. During the extension-uplifting stage the active role was played by an asthenospheric intrusion that occurred beneath the Etruscan belt (e.g., Serri *et al.*, 1993). This thinned the crustal stack and, strongly interacted with it, completely restructuring the crust-mantle boundary so that, the present, Tuscan Moho is a brand new one. At this stage, in response to the asthenospheric intrusion, both asthenosphere and lithosphere melted producing basaltic magmas that were either extruded or pounded in the crust and mixed with anatectic melts. Anatectic melts formed at the contact between superimposed crustal sections. These contacts are likely to represent important mechanical discontinuity levels along which mafic magmas were preferentially stored, favoring anatexis and mixing between mantle- and crust-derived magmas.

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APPENDIX 1

	Bt	Opx	Pl	Kfs	Grt	Crd	Ap	Tit	Zr	Spi
Rb	2	0.02	0	0.4	0	0.08	0	0	0	0
Sr	0.1	0.04	4	3.6	0	0.12	0	0	0	0.4
Ba	11	0.013	0.8	6	0	0.02	0	0	0	0
Th	1.2	0	0	0	0	0.1	0	5	15	0.4
Zr	0	0.2	0	0	0	0	0.6	0	2000	5
Y	0.3	0.2	0	0	35	0.72	28	20	200	0.3
Ta	1.75	0	0	0	0	0.06	0	15	5	18
Hf	1.5	0	0.1	0	0.3	0	0.4	10	1190	0.65
Nb	3	0.15	0	0	0	0.01	0.1	6	55	100
La	0.4	0.01	0.38	0.08	0.2	0.06	25	60	3	1.31
Ce	0.3	0.02	0.27	0.04	0.35	0.07	35	90	2.4	1.19
Nd	0.3	0.03	0.2	0.035	0.53	0.09	57	103	3	0.96
Sm	0.26	0.03	0.17	0.025	2.6	0.1	63	340	3.7	0.684
Eu	0.24	0.05	5	4.5	1.5	0.01	30	157	3.4	0.4
Tb	0.28	0.09	0.1	0.025	11	0.95	56	326	26	0.36
Yb	0.44	0.34	0.1	0.03	40	1.77	24	231	225	0.55

Partition coefficients for Qtz are considered 0 for all minerals and elements.
Partition coefficients from compilation at GERM database available on-line at http://earthref.org.

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