ANNALI DI GEOFISICA, VOL. XL, N. 3, June 1997

Neogene-Quaternary magmatic activity and its geodynamic implications in the Central Mediterranean region

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Abstract
The petrogenesis and time/space distribution of the magmatism associated with the formation of the Northern and Southern Tyrrhenian basins, together with the directions and ages of lithospheric extension and/or spreading north and south of the 41°N discontinuity, show that the two arc/back-arc systems have undergone a different structural evolution at least since the middle Miocene (Langhian). The geochemical components involved in the genesis of the heterogeneities of the mantle sources of this magmatism require two separate, compositionally different slabs: 1) an old oceanic (Ionian) lithosphere still seismically active below the Calabrian arc and the Southern Tyrrhenian region; 2) an almost seismically inactive continental (Adriatic) lithosphere which carried large amounts of upper crustal materials within the upper mantle under the NW Roman Province/Tuscan/Northern Tyrrhenian region. The proposed geodynamic models require: 1) for the Northern Tyrrhenian/Northern Apenninic arc/back-arc system, the delamination and foundering of the Adriatic continental lithosphere as a consequence of the continental collision between the Corsica block and the Adriatic continental margin. This delamination process, which is still ongoing, probably started in the early-middle Miocene, but earlier than 15-14 Ma, as indicated by the age and petrogenesis of the first documented magmatic episode (the Sisco lamproite) of the Northern Apennine orogenesis; 2) for the Southern Tyrrhenian/Southern Apenninic-Calabrian arc/back-arc system, the roll-back subduction and back-arc extension driven by gravitational sinking of the Ionian oceanic subducted lithosphere. This process started after the end of the arc volcanism of Sardinia (about 13 Ma) but earlier than the first recorded episode of major rifting (about 9 Ma) in the Southern Tyrrhenian back-arc basin.

Key words *petrogenesis – geochemistry – magmatism – geodynamics –Italy*

1. Introduction

In the Central Mediterranean, Cenozoic magmatism is so widespread and shows such a variable petrogenetic affinity that it can be successfully used to put important constraints to the geodynamic evolution of the region.

In the early seventies, the study of the time/space distribution and serial affinity of the Italian volcanism made significant contribution to the geodynamics of the Central Mediterranean region (Barberi *et al.*, 1971, 1973, 1974a,b).

In the eighties, owing to the widescale use of sophisticated technological tools, there was an extraordinary increase in the output of high quality geochemical, isotopic and petrological data on igneous, metamorphic and sedimentary rocks, peridotitic massifs and mantle- and lower crust-derived nodules. Consequently, a much more detailed characterization of the earth reservoirs, which play a dominant role in the genesis and evolution of magmas (*i.e.*, up-

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per and lower crust as well as the mantle lithosphere and asthenosphere), has allowed a breakthrough in understanding the relation between magmatism and major geodynamic processes. The keypoint is the use of the petrogenesis of primitive (in the sense of least differentiated) magmas as a tool to infer the geochemical and isotopic composition of the magma sources, which in turn serves as a basis for understanding the nature and origin of the geochemical components involved in the genesis of the magma sources heterogeneities, and ultimately the reservoirs from which these components were derived. A comprehensive book on this topic has recently been published (Wilson, 1989).

2. Characterization of the magma sources in the Central Mediterranean region

In terms of serial affinity, the Oligocene to Quaternary magmatism of the Central Mediterranean region covers most of the known volcanic suites, *i.e.*: island arc tholeiite, calc-alkaline, high-K calc-alkaline (Sardinia Oligo-Miocene volcanism); these associations as well as shoshonite series and leucite tephrites (the Eolian volcanism); high-K calc-alkaline, shoshonite, leucite basanite and leucitite series as well as lamproites, kamafugites and carbonatites (the volcanism of the Italian peninsula from Tuscany to Campania); tholeiitic and Na-alkaline series (the Plio-Quaternary volcanism of Sardinia, Sicily channel and Southern Tyrrhenian basin) and the acid «anatectic» magmas of Northern Tyrrhenian basin, Tuscany and Latium (Serri, 1990 and reference therein; Stoppa and Lavecchia, 1992). About 50 different rock-types and 15 rock-series quoted in the literature complicate a problem which is already so complex by itself to make the reading of specific papers often difficult even for specialists. Evidently, the emplacement in about 30 Ma of such a wide range of magma-types in a relatively restricted area cannot be related to simple geodynamic processes as commonly hypothesized for magmatism produced during the interaction of major plates. Moreover, in the last decade it has become established that the identification of the magma-series does not give unambiguous information on the tectonic setting: magmas belonging to the tholeiite, K- and Na-alkaline series are erupted, although in different amounts, in intra-plate settings as well as in convergent and divergent plate margins; rocks of the calc-alkaline series are also found in some continental rifts and intra-plate provinces as a result of mixing between acid crust-derived and basaltic mantle-derived magmas (*e.g.*, Rio Grande rift; Wilson, 1989).

In general, rock-types and -series should not be used alone to identify their eruptive settings, in that the major element composition of primitive magmas is more dependent on the conditions and degrees of partial melting rather than the compositional variation of the mantle sources. Additional, important information can be obtained from the relative proportions of basic, intermediate and acid rocks, and the temporal and spatial relation between magma-series. Much more precise and detailed information on the relation between geodynamic processes and magmatism can be deduced from the interpretation of the incompatible trace element pattern combined with isotopes. In fact, incompatible trace element ratios of mantle-derived magmas are more affected by the compositional variation of the mantle sources than the conditions and extent of partial melting; trace elements coupled with isotopes give fundamental information on the nature and origin of geochemical components involved in the genesis of the magma-sources.

This rationale has been applied to the magmatism of the Central Mediterranean region giving priority to the characterization of the crustal and mantle sources of magmas in terms of major geochemical components and their origin rather than rock-types and serial affinities. Following this approach, it has been possible to recognize that a minimum of seven magma sources satisfactorily describes the genesis of this magmatism: 1) transitional Mid-Ocean Ridge Basalt (MORB)-type sources; 2) Ocean Island Basalt (OIB)-type sources and 3) Island Arc Basalt (IAB)-type sources; 4) upper crust-hybridized mantle sources and 5) Central Campania mantle sources; 6) continental litho-

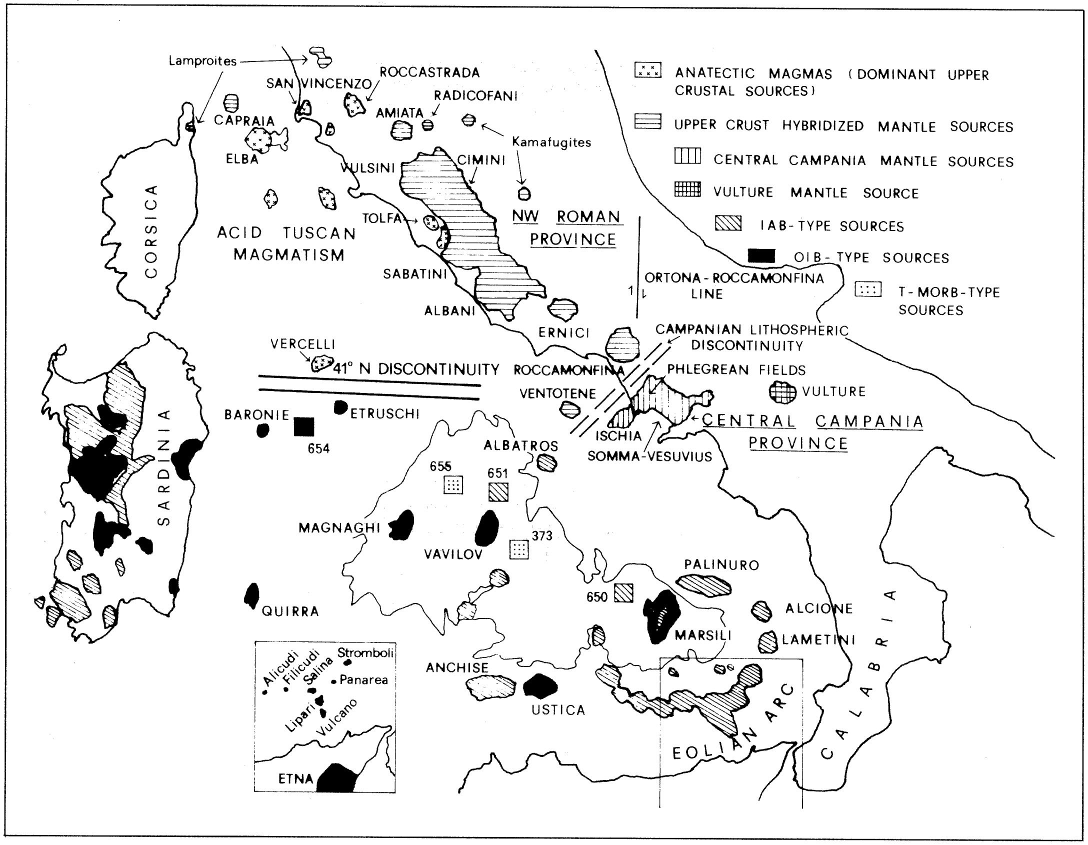


Fig. 1. Interpretation of the magmatism of the Tyrrhenian region in terms of major, dominant magma sources relevant for first order geodynamic processes (after Serri, 1990). The 41°N and Campanian Lithospheric Discontinuities are recognised on geochemical and petrological grounds. Inset: Etna, OIB-type mantle sources; Eolian arc, IAB-type mantle sources.

sphere mantle source (Vulture volcano) and 7) upper crust-type sources (fig. 1).

The geographical location of the magmatic centres is more relevant for first order geodynamic processes than the age of emplacement of magmas. The latter, coupled with structural field data, has great importance in inferring the variation with time of the prevailing stress regimes, but this is not the main aim of this review. The geographical distribution of the seven identified magma sources defines two crustal and mantle domains separated by two lithospheric discontinuities: 1) the Campanian Lithospheric Discontinuity which runs NE-SO across the Volturno plain and between Ischia and Ventotene; 2) the 41°N Lithospheric Discontinuity which divides the Tyrrhenian basin into a northern and southern sector that are characterized by different directions and rates of extension. The stage of oceanic crust formation was only reached in the Southern Tyrrhenian basin where two sub-basins Vavilov (to the west, 4.3-2.6 Ma) and Marsili (to the east, around 1.8-1.5 Ma) opened diachronously. In the Northern Tyrrhenian back-arc basin, rifting and crustal thinning developed entirely within a continental realm. The Northern and Southern Tyrrhenian back-arc basins are related to

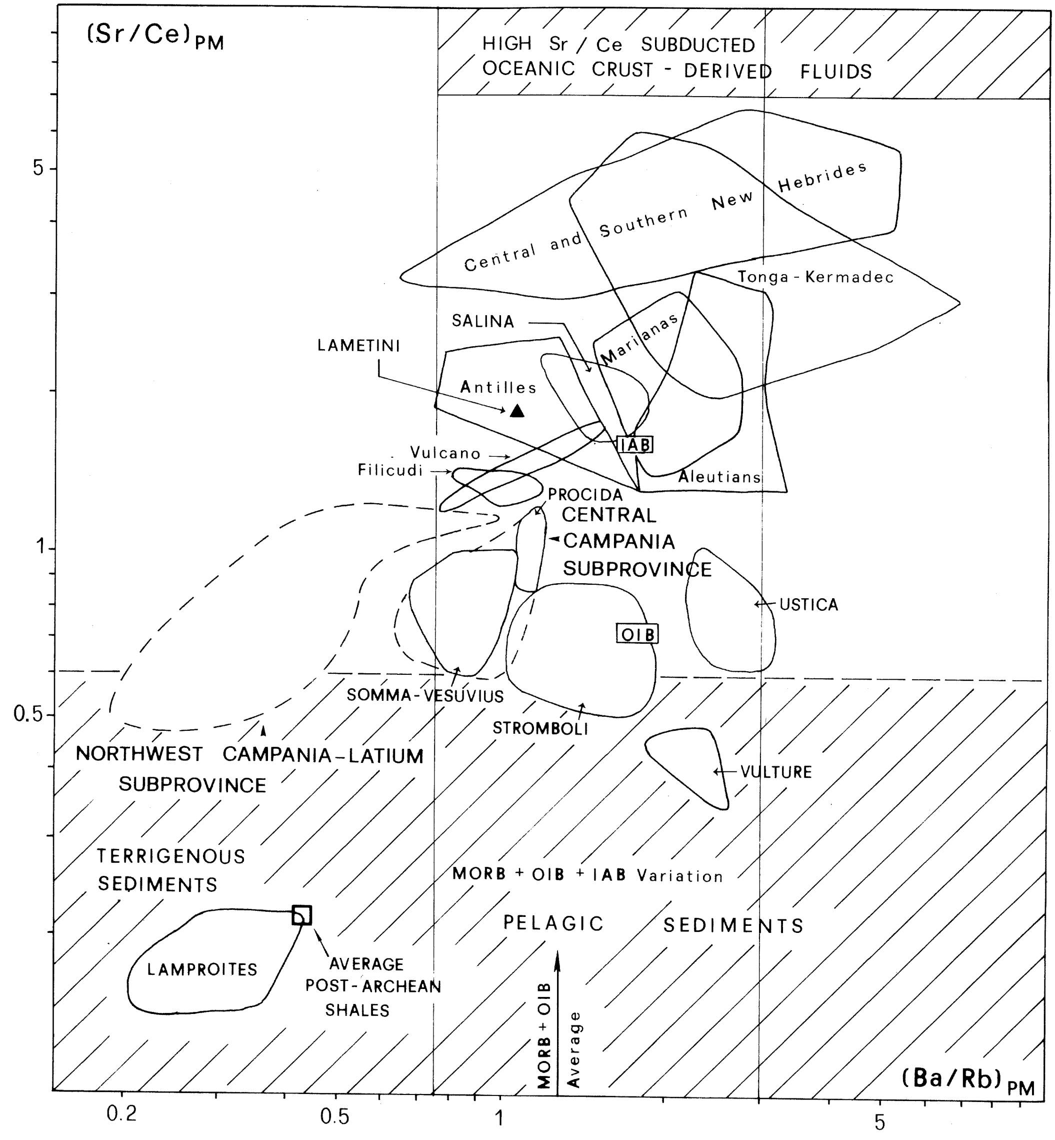


Fig. 2. Sr/Ce-Ba/Rb primordial mantle normalised diagram (modified after Beccaluva *et al.*, 1991). The composition of basalts and basaltic andesites from intra-oceanic arcs, data from BVSP (1981), Ewart and Hawkesworth (1987), allow extrapolation of the high Sr/Ce component derived from the subducted oceanic crust. Salina and Stromboli basaltic and basaltic andesite lavas (Ellam *et al.*, 1988; Francalanci *et al.*, 1989). Lametini and Ustica (Serri, 1990). Vulture (De Fino *et al.*, 1986). Somma-Vesuvius (Santacroce, 1987). Lamproites from Sisco, Montecatini Val di Cecina and Orciatico (Peccerillo *et al.*, 1988). Average post-Archean shales (Taylor and McLennan, 1985). Fields of carbonate-poor sediments from various authors: terrigenous and pelagic sediments commonly have low and high Ba/Rb respectively. References for other fields in Serri (1990). Note that the definitions North-West Campania-Latium subprovince (Beccaluva *et al.*, 1991), NW Roman Province (Serri, 1990) and NW Provincia Magmatica Romana (Serri *et al.*, 1991, 1993) are synonyms.

the formation of two main Apenninic arcs (the Northern Apenninic and Southern Apenninic-Calabrian arcs), separated by a first-order dextral strike-slip transfer, known as the Ortona-Roccamonfina line (Patacca *et al.*, 1992).

The 41°N and the Campanian Lithospheric Discontinuities separate not only two regions with different tectono-magmatic history, but also lithospheric sectors with different crustal and mantle evolution (fig. 1).

North of the 41°N and of the Campanian Lithospheric Discontinuities: 1) the genesis of the magmas is dominated by involvement of upper crust-derived rocks either as material incorporated within the uppermost mantle (Tuscan and Corsica lamproites: Montecatini Val di Cecina, Orciatico, Torre Alfina, Sisco and North-western Roman Province volcanism: Roccamonfina, Ventotene, Ernici, Albani, Sabatini, Vico, Vulsini, San Venanzo, Cupaello; figs. 2 and 3) or as «anatectic» melts (acid Tuscan magmatism largely derived from the upper crustal reservoir, either as partial melting at crustal levels and/or possibly from upper crustal material incorporated within the uppermost mantle); 2) OIB and MORB-type magmas are absent.

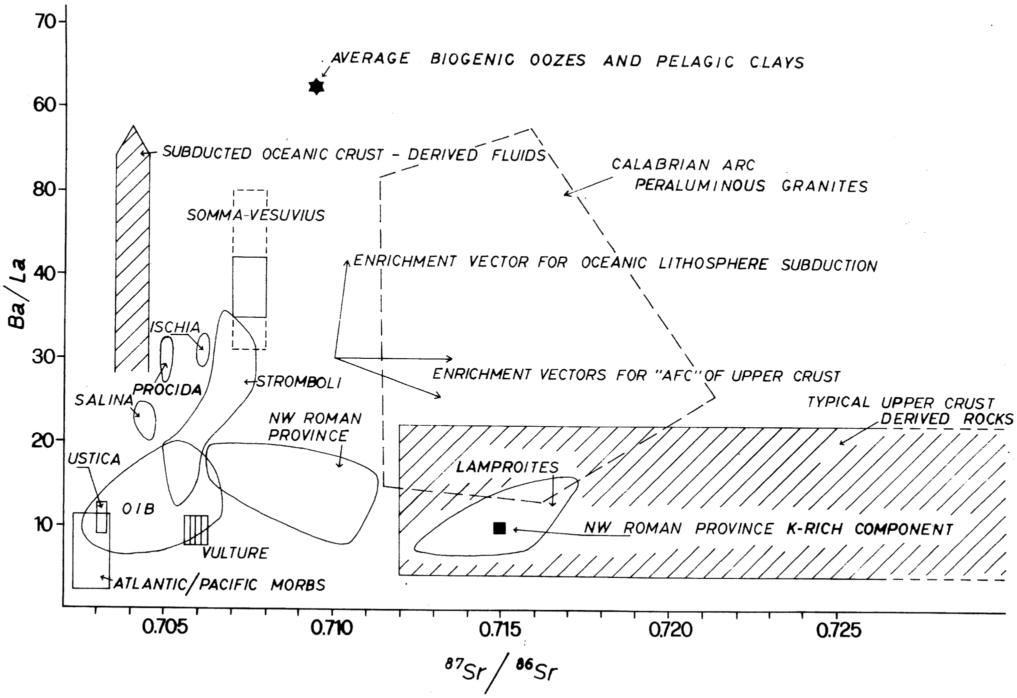


Fig. 3. Ba/La-$^{87}Sr/^{86}Sr$ diagram (after Serri, 1990). The filled square is the composition of the sediment-derived component used in the mantle hybridization modelling of the NW Roman Province (Beccaluva *et al.*, 1991). Sr isotopes from Somma-Vesuvius (Santacroce, personal communication). Ischia most basic rocks (Grotta di Terra dyke) and Procida volcanics: Sr isotopes from Orsi *et al.* (1990) and trace elements from Beccaluva *et al.* (1991). Calabrian arc peraluminous granites from Rottura *et al.* (1989). The average of biogenic oozes and pelagic clays (Ben Othman *et al.*, 1990) is only indicative due to the large compositional variation of pelagic sediments. Field of typical upper crust-derived rocks and Atlantic/Pacific MORBs from various authors. Enrichment vectors and OIB field (Davidson, 1987). Subducted oceanic crust derived fluids deduced from BVSP (1981), Davidson (1987), Ewart and Hawkesworth (1987), Ellam and Hawkesworth (1988). References for other fields as in fig. 2.

South of the 41°N of the Campanian Lithospheric Discontinuities: 1) the genesis of magmas is dominated by the involvement of transitional-MORB/OIB sources (Pliocene-Quaternary OIB-type volcanism of Sardinia, Eastern Sardinia rifted margin, Vavilov basin and Ustica) and evidence of a significant amount of anatectic magmatism has not so far been found; 2) IAB-type volcanism is widespread (the Oligo-Miocene volcanism Sardinia, the Quaternary volcanism of the Eolian islands and seamounts, most of Marsili seamount, Site 650 in the basement of Marsili basin, Site 651 in the Vavilov basin, Anchise and Albatros seamounts). The petrogenesis of the IAB-type volcanism, such as Salina, Lipari, Panarea and Lametini, is dominated by the involvement of a transitional MORB to OIB-type mantle wedge, variably enriched by a component with high Sr/Ce and Ba/La ratios derived from dehydratation of subducted oceanic crust (figs. 2 and 3). The influence of a third component with high Ba/La and low Sr/Ce ratios, probably derived from subducted sediments, produces a strong geochemical signature only at Stromboli. The petrogenesis of potassic and ultrapotassic magmas of the Central Campania region (Somma-Vesuvius, Procida, Ischia, Phlegrean Fields) is consistent with the enrichment of OIB-type mantle sources with a component with high Ba/La and low Sr/Ce ratios, probably derived from subducted sediments (figs. 2 and 3).

In the Vavilov basin, the asthenospheric mantle uprise was so important as to produce a back-arc oceanic crust (sites 655 and 373) and huge seamounts (Vavilov and Magnaghi) entirely derived from transitional MORB-OIB sources.

In the Western Tyrrhenian or Eastern Sardinia passive margin, no evidence of magmatism associated with the rifting preceding the opening of the Vavilov basin has so far been found; Eastern Sardinia represents, therefore, a typical non-volcanic rifted margin in a back-arc setting. At four localities (Quirra and Baronie seamounts, Etruschi basin, and Site 654) sporadic volcanic activity has been documented. Those whose age is approximately known (Etruschi basin, about 0.1 Ma and Site 654, about 1.8 Ma) were emplaced after the opening of the Vavilov basin had been accomplished. Geochemical and isotopic data for the tholeiitic lavas from Site 654 are consistent with magma genesis by partial melting of the an OIB-type lithospheric mantle (Beccaluva *et al.*, 1990).

Ustica island (Quaternary) is the only subaerial Na-alkaline volcano of the Tyrrhenian back-arc basin; in a first approximation, owing to its structural location (fig. 1) between the arc-type volcanism of Anchise seamount (Pliocene) and of the Eolian islands and seamounts (Quaternary to Present) Ustica can be considered a Na-alkaline volcano in an arc-back-arc setting. Recently it has been interpreted as an intra-plate volcanism developed outside the present Southern Tyrrhenian subduction zone (Francalanci and Manetti, 1994). In the eighties, Beccaluva *et al.* (1982), Calanchi *et al.* (1984) and Cinque *et al.* (1988) suggested that the Ustica mantle source shows some geochemical peculiarities which can be interpreted as related to a slight addition of a subduction-related component to typical OIB mantle sources.

The African foreland (Sicily channel, Iblean plateau and Etna) is the site of Pliocene to present volcanic activity with Na-alkalic and tholeiitic affinity. The Sicily channel is a low-volcanicity continental rift (Calanchi *et al.*, 1989) whereas Etna volcanism is related to important extensional tectonics of the Eastern Sicilian margin, undergoing a collapse toward the Ionian basin. All this sodic volcanism is related to partial melting of transitional to enriched MORB- and OIB-types mantle sources (Armienti *et al.*, 1989; Calanchi *et al.*, 1989; D'Orazio, 1994).

In a first approximation, the temporal and spatial distribution of the upper Tortonian to present Tyrrhenian and peri-Tyrrhenian magmatism is consistent with the classic model of roll-back subduction and back-arc extension (Malinverno and Ryan, 1986). The geochemical components involved in the genesis of the heterogeneities of the mantle sources of the Tyrrhenian and peri-Tyrrhenian magmatism require two separate, compositionally different slabs: 1) an old oceanic (Ionian) lithosphere still seismically active below the Calabrian arc and the Southern Tyrrhenian region; 2) a continental (Adriatic) lithosphere (fig. 4) which carried large amounts of upper crustal materials within the upper mantle at depths of at least 50-100 km under the North-Western Roman Province and Tuscan (Northern Apenninic arc) region (Serri, 1990). However, if the petrogenesis, time/space distribution of the magmatism and geological data are evaluated all together, this simple geodynamic conclusion no longer holds for the Northern Apennine magmatism.

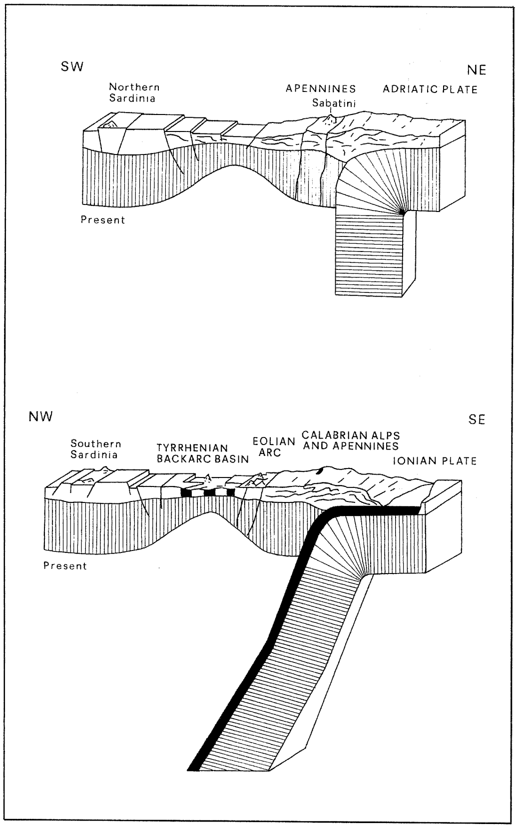


Fig. 4. Cartoon showing the roll-back subduction (below) of the Ionian oceanic lithosphere under the Calabrian arc and (above) of the Adriatic continental lithosphere under the Northern Apenninic arc (modified after Beccaluva *et al.*, 1991).

3. Petrogenetic and geodynamic models for the magmatism and orogenesis of the Northern Apennines

The petrogenetic models for the primitive mantle-derived magmas (Serri *et al.*, 1991, 1993) and Tuscan Magmatic Province (Innocenti *et al.*, 1992), the relation between magmatism, tectonics, sedimentation (fig. 5) and available geophysical data served as a basis for a new geodynamic model of the Northern Apennine orogenesis. *This model includes as a fundamental element the delamination (still ongoing) of the Adriatic lithosphere.*

3.1. *Classification*

The magmatism of the Tuscan and Roman Provinces has attracted the interest of generations of petrologists since the beginning of this century. Its genesis is controversial; the nomenclature is rather complicated and still debated (Marinelli, 1967; Barberi *et al.*, 1971; Peccerillo and Manetti, 1985; Civetta *et al.*, 1989; Peccerillo *et al.*, 1990; Beccaluva *et al.*, 1989, 1991; Serri *et al.*, 1991; Innocenti *et al.*, 1992; Conticelli and Peccerillo, 1992).

On the petrological and geochemical grounds, Serri *et al.* (1991, 1993) and Innocenti *et al.* (1992) proposed a new classification of the igneous rocks of the Northern Apennines into three groups (groups 1, 2 and 3: saturated, undersaturated trends, acidic and high-K calc-alkaline rocks of the Tuscan Province). Groups 1 and 2 consist of rocks with potassic and ultrapotassic affinity whereas the rocks of group 3 are sub-alkaline. To reduce the complexities due to differentiation and crustal assimilation processes, only the most primitive rocks of the region (Mg# > 65 and Mg# > 60 north and south of Rome, respectively) have been taken into account for the classification of mantle-derived potassic and ultrapotassic magmas. An outline of the mineralogy of primitive rocks is reported in table I: group 1 consists of rocks of the shoshonite (SH), ultrapotassic shoshonite (UKSH) and ultrapotassic latite (UKL) series, as well as lamproites, whereas group 2 is

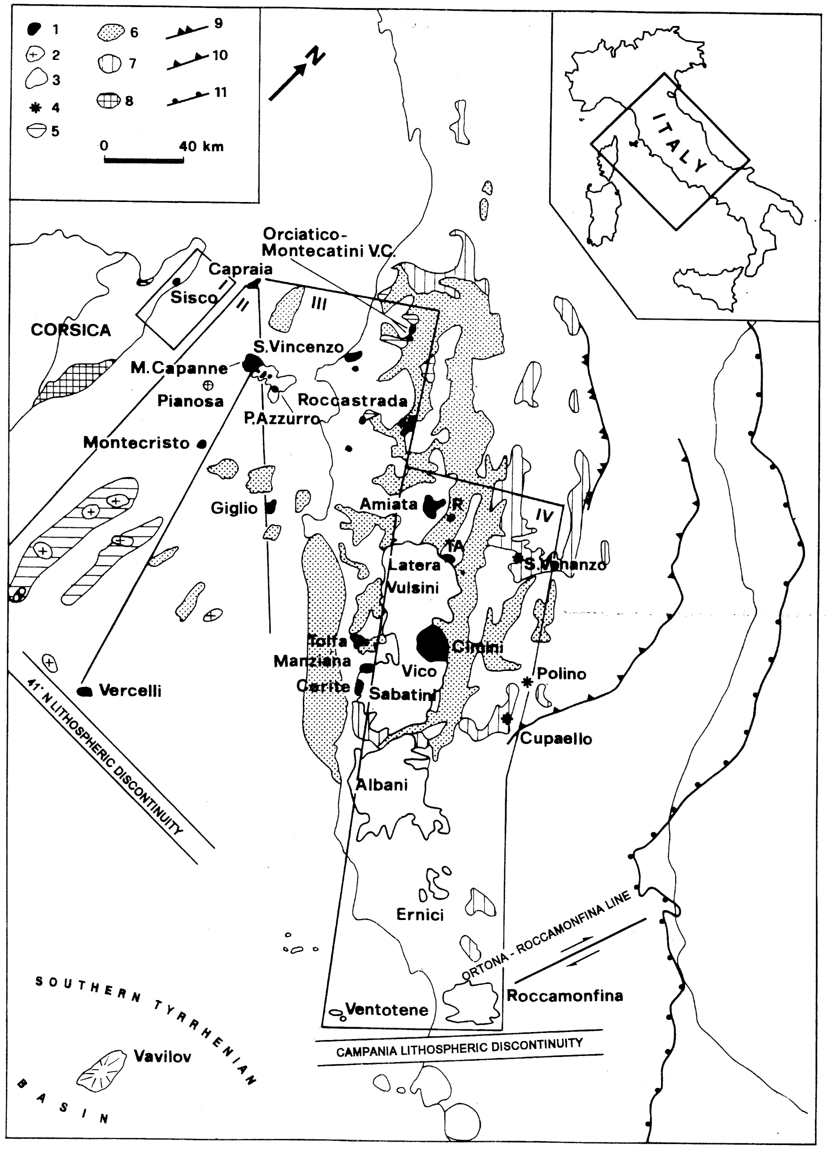


Fig. 5. Schematic map of the magmatic rocks of the Northern Apenninic arc and associated Neogene-Quaternary sedimentary deposit (after Serri *et al.*, 1991, 1993). 1) Plutonic and volcanic outcrops of the Provincia Magmatica Toscana (PMT); 2) buried plutons taken from «Synthetic structural-kinematics map of Italy; P. Scandone»; 3) volcanic complex of the North-Western Provincia Magmatica Romana (NW-PMR); 4) products with kamafugitic affinity (NW-PMR). 5,6,7,8) Sedimentary deposits which unconformably overlie the extensional collapsed Apenninic chain: 5) upper Tortonian-Messinian p.p. (about 10-6 Ma); 6) Messinian p.p.-Piacenzian p.p. (about 6-2.4 Ma); 7) Piacenzian p.p.-Pleistocene (about 2.4-0.1 Ma); 8) Burdigalian-Langhian. 9,10,11) Some active thrust front of various ages are reported: 9) Tortonian; 10) lower Pliocene; 11) upper Pliocene-Pleistocene. The sectors where the magmatism of the four phases was emplaced are separated by full lines and identified by I, II, III and IV. 41°N and Campanian Lithospheric Discontinuities; after Serri (1990).

Table I. Parageneses of the Northern Apennine primitive rocks.

Magma-series	SH/UKSH/UKL (ST)	Lamproite (ST)	K-series (UT)	HK-series (UT)	Kamafugites (UT)
Olivine	****	***	***	***	**
Monticellite					*
Melilite					****
Clinopyroxene	***	**	****	****	***
K-Richterite		*			
Phlogopite	**	****	*	*	**
Plagioclase	***		****	**	
Kalsilite					***
Leucite			**	****	**
Sanidine	***	****	**		
Nefeline				*	*
Ilmenite	*	*			
Magnetite	*	*	*	*	*
Perowskite					*
Apatite	*	*	*	*	*
Cr-Spinel	*	*	*	*	*

(ST) and (UT) = saturated and undersaturated trend rocks, respectively; SH = shoshonites; UKSH = ultrapotassic shoshonites; UKL = ultrapotassic latites. * Trace; ** minor; *** abundant; **** very abundant. Additional phases: Priderite and Rutile (Sisco lamproite); Pseudobrookite (Torre Alfina lamproite); Carbonate and Goetzenite (San Venanzo olivine-leucite-melilitite); Khibinskite and Goetzenite (Cupaello diopside kalsilite melilitite). (After Serri *et al.*, 1993).

formed by rocks of the K- and HK-series, as well as kamafugites.

1) *Group 1*, which contains silica-oversaturated and slightly undersaturated rocks, is named *saturated trend.* It consists of relatively primitive potassic to ultrapotassic alkaline rocks ranging from ol-hy-normative (Latera, Radicofani and Capraia shoshonites and Monti Cimini high-Mg UKL) to Q-normative (Sisco, Montecatini Val di Cecina, Orciatico and Torre Alfina lamproites). Radicofani ultrapotassic shoshonites and Vico olivin-latites also belong to this group.

2) *Group 2*, which mostly contains rocks strongly silica-undersaturated, is named *undersaturated trend*; all the relatively primitive potassic (KS) to ultrapotassic (HKS and kamafugites) alkaline rocks of the Northern Apennine, except Latera shoshonites and Vico latites, belong to this group. The ultrapotassic rocks range from ne-normative leucite-bearing trachybasalts (Vico), to lc-normative leucite-basanite, tephritic leucitite and leucitite (Vulsini, Sabatini, Albani, Ernici, Roccamonfina) up to larnite-normative kamafugites (San Venanzo, Cupaello); the potassic rocks (KS) varies from ol-hy normative shoshonite basalts (Roccamonfina, Ventotene) to ne-normative leucite-bearing basalts and trachybasalts (Ernici).

3) The third group rocks nearly coincides with the sub-alkaline rock of the Tuscan Province. Two sub-groups with different petrogenetic affinity can be distinguished: *acidic*

(Tuscan acidic granitoid and volcanic rocks) and *high-K calc-alkaline rocks* (Capraia). The data so far available on Capraia sub-alkaline rocks are too scarce to serve as a reliable basis for a thorough petrogenetic interpretation.

The best parameters which exemplify the geochemical diversity between the three groups of rocks are SiO_2, CaO, Al_2O_3, MgO, Mg#, CaO/Na_2O, Ce/Sr, $^{87}Sr/^{86}Sr(i)$ and $^{143}Nd/^{144}Nd$; only four diagrams are reported in this review (figs. 6a,b, 7a,b, 8 and 9).

3.2. *Petrogenetic model*

The Tuscan acidic plutonic and volcanic rocks derive dominantly from partial melting of the Adriatic continental crust which appears to have been extracted from the mantle in the late Proterozoic times (Juteau *et al.*, 1986). This magmatism is mostly found inside an ellipsoidal area (about 150×300 km) centred at Giglio Island (fig 5). Within this area, mantle-derived magmas unaffected by important mix-

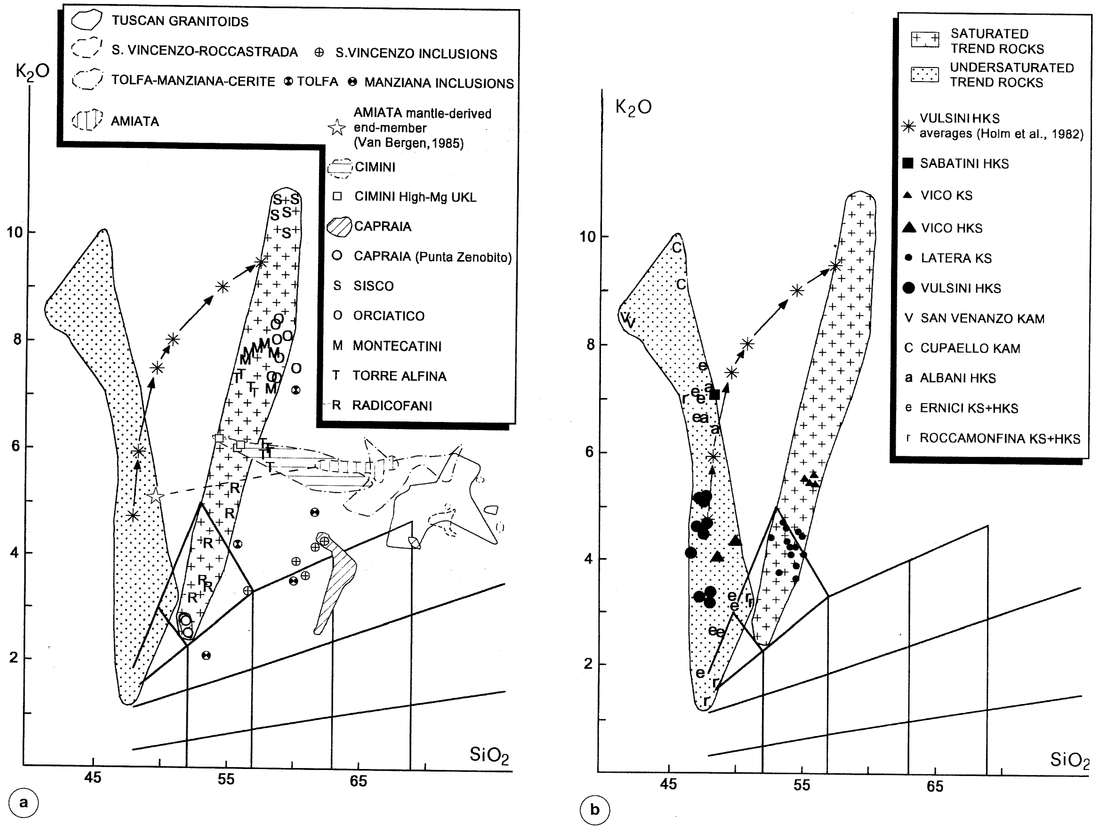


Fig. 6a,b. K_2O *vs* SiO_2 (wt %) diagram (anhydrous basis) for the PMT (a) North-Western PMR (b) rocks (after Serri *et al.*, 1993). a) All the available data on PMT are plotted. Sources of data in Serri *et al.* (1991), Innocenti *et al.* (1992), Conticelli and Peccerillo (1992) and Westerman *et al.* (1993). For Monte Amiata the calculated mantle-derived magmas is plotted (Van Bergen, 1985). Asterisks refer to average composition of different rock-types of Vulsini which exemplify the fractional crystallization-dominated trend of HKS (Holm and Munksgaard, 1982). b) Only primitive rocks with MgO > 7 and Mg# > 65 (north of Rome) and MgO > 6.5 and Mg# > 60 (south of Rome) are reported; MgO > 6.0 for Vico olivin-latites and for Ernici HKS.

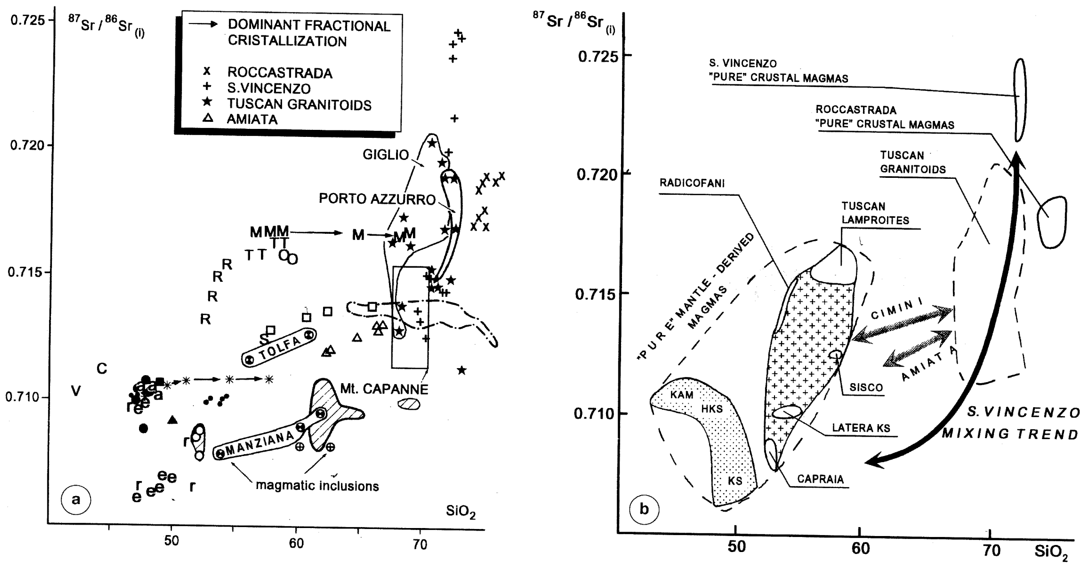


Fig. 7a,b. $^{87}Sr/^{86}Sr(i)$ *vs* SiO_2 (volatile-free basis) diagrams (after Serri *et al.*, 1993). a) Only primitive rocks with MgO > 6.5 and Mg# > 65 (north of Rome) and MgO > 6.0 and Mg# > 60 (south of Rome) are reported. Sources of data and symbols as in fig. 6a,b. b) Interpretative scheme for the genesis of the Northern Apenninic arc igneous rocks: San Vincenzo, Cimini and Amiata define mixing trends between acid crustal- and basic mantle-derived magmas; saturated trend rocks show a well definite positive correlation whereas undersaturated trend rocks exhibit the opposite.

ing processes with crustal anatectic melts have not so far been found, but all the Tuscan acid centres show evidence of mixing with potassic mantle-derived magmas. This is quite evident in all the acid volcanic centres of the Tuscan Province (exemplified by the San Vincenzo, Amiata and Cimini trends of fig. 7b) and also by the distribution of the Tuscan granitoids along the San Vincenzo mixing curve (figs. 7a,b and 9). Recently, Poli (1992) and Westermann *et al.* (1993) have shown that the petrogenesis of Monte Capanne, Porto Azzurro, Giglio and Montecristo plutons is characterized by mixing processes between acidic crust-derived magmas with various types of mantle-derived magmas. Pure crustal magmas are rare and have so far been found only among some of the San Vincenzo and Roccastrada rhyolites (fig. 7a,b).

The saturated and undersaturated trend rocks define two clearly distinct trends (figs. 6a,b, 7a,b, 8 and 9) which are consistent with an enrichment of their mantle sources by additions of two different K-rich components which metasomatized separated, compositionally diverse upper mantle sectors. In both cases the most remarkable mineralogical effect of these enrichment processes is the production of variable amounts of phlogopite through reaction between fluids and/or melts with the mantle.

The rocks of the *saturated trend* are ol-hy- and Q-normative mostly shoshonites, ultrapotassic shoshonites, ultrapotassic olivin-latites and lamproites. They are considered to be derived from partial melting at relatively low pressure (< 50 km) of strongly (lamproites) to moderately depleted phlogopite harzburgitic sources produced by reaction of residual peridotites with a K-Si-rich Ca-Sr-poor melt with high $^{87}Sr/^{86}Sr > 0.717$, Ce/Sr > 0.3 and K_2O/Na_2O > 6-7, and low $^{143}Nd/^{144}Nd \sim 0.5121$-$0.5120$ and Ba/La < 20 ratios, formed by partial melting of «subducted» carbonate-free material of the upper crustal reservoir

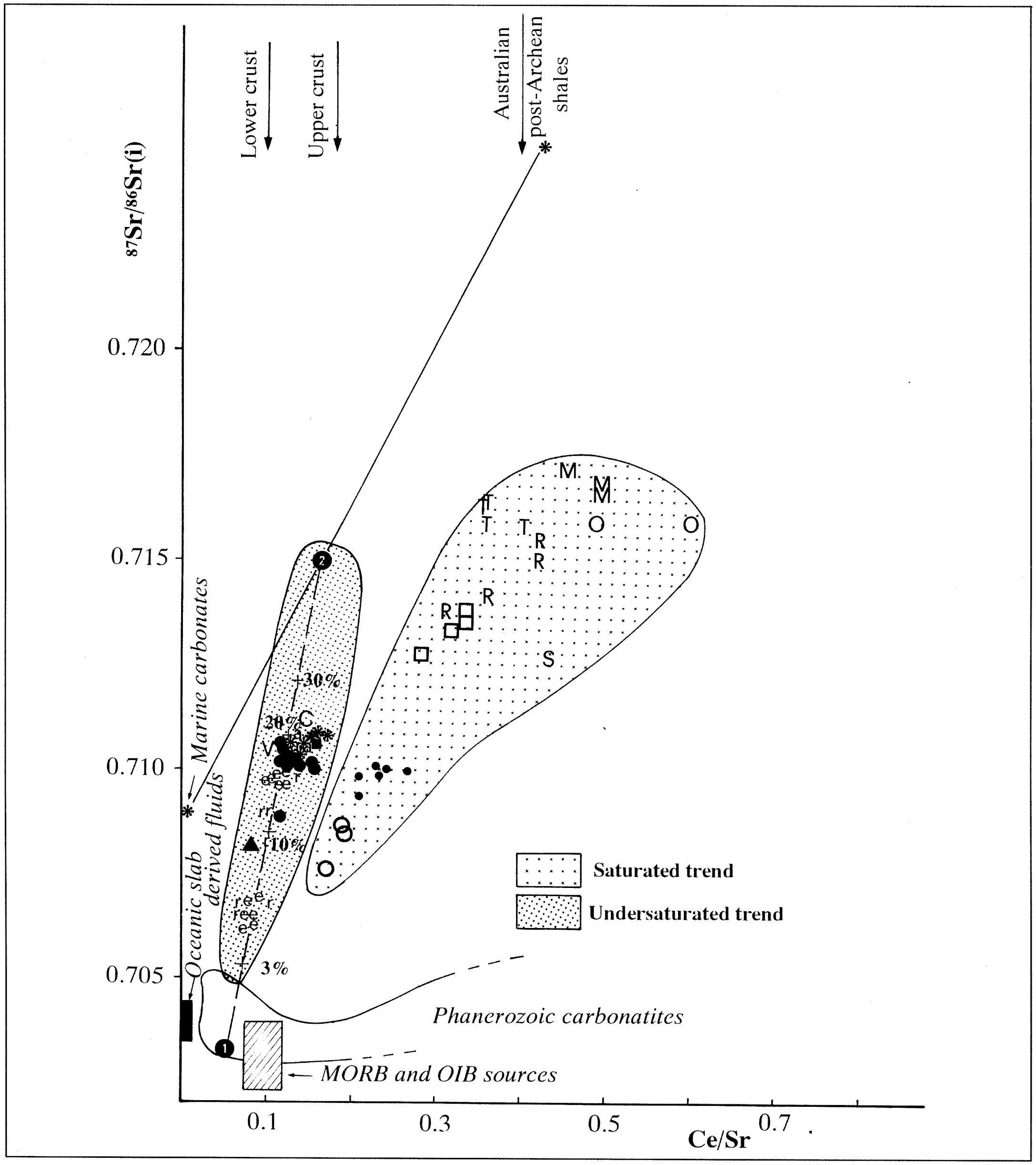


Fig. 8. $^{87}Sr/^{86}Sr(i)$ *vs* Ce/Sr diagram (after Serri *et al.*, 1991, 1993). Percentages along the dashed line represent mixing proportions (two end-member model) of the K-rich metasomatizing, sediment-derived component (2) in a Sr-enriched mantle source (1). Upper and lower crust compositions, as well as Post-Archean Australian Shales (PAAS) after Taylor and McLennan (1985). Marls, as binary mixing between a shale similar to PAAS and a marine carbonate, fall on the full line. Phanerozoic carbonatite field: data from Nelson *et al.* (1988) and Beccaluva *et al.* (1992). The field of fluids derived from a subducted basaltic oceanic crust is taken from Davidson (1987). Other sources of data and symbols as in figs. 6a,b and 7a,b.

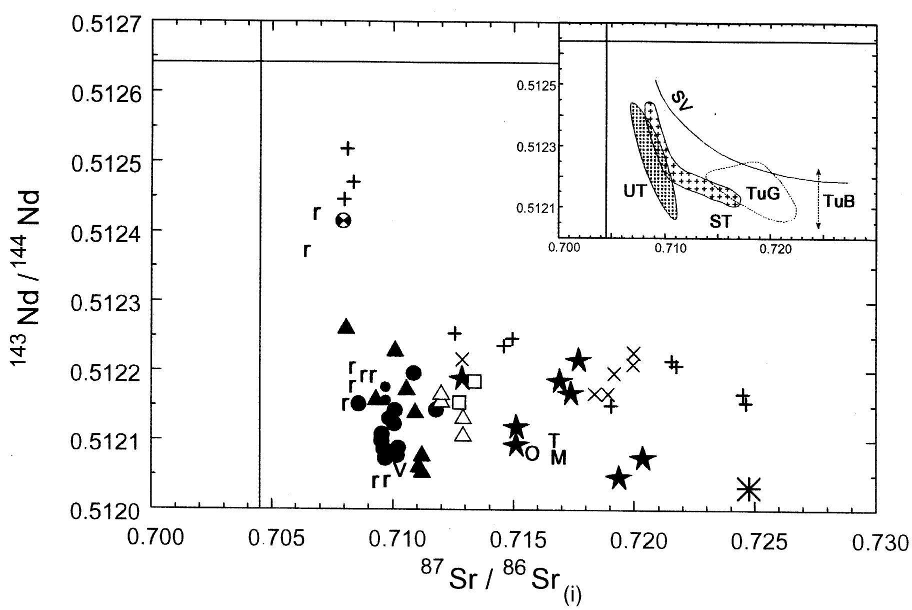


Fig. 9. $^{143}Nd/^{144}Nd$ *vs* initial $^{87}Sr/^{86}Sr(i)$ diagram for the NAM (after Serri *et al.*, 1993). Data sources: Vulsini, Vico and Sabatini (Roger *et al.*, 1985; Hawkesworth and Vollmer, 1979; Flehoc, 1991); Amiata and Roccastrada (Hawkesworth and Vollmer, 1979); San Vincenzo (Hawkesworth and Vollmer, 1979; Ferrara *et al.*, 1989); Elba (Juteau *et al.* 1986); San Venanzo (Conticelli, 1989); Orciatico, Montecatini Val di Cecina (Conticelli *et al.*, 1992); note that for Roccamonfina, $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr(i)$ are from Rogers *et al.* (1985) and Hawkesworth and Vollmer (1979) respectively; a shoshonite inclusion in the Manziana rhyolites (Ferrara *et al.*, 1990). Other symbols as in figs. 6a,b and 7a,b. In the inset: SV = San Vincenzo mixing trend; ST = field of the saturated trend rocks; UT = field of the undersaturated trend rocks; TuG = field of the Tuscan granitoids; TuB = inferred Nd isotopic range of crustal rocks of the Tuscan basement.

(*e.g.*, non-restitic felsic granulites). This component is very common in the Central Mediterranean region either as granitoid plutons/terrigenous sediments or as meta-sedimentary, non-restitic lower crust. The only available lower crustal material of the Northern Apennine basement is found as xenoliths in Torre Alfina lavas (Orlando *et al.*, 1994).

The primitive rocks of the *undersaturated trend* are critically undersaturated, mostly leucitites, tephritic leucitites, leucite basanites, melilitites. Experimental petrology suggests that these rocks were formed by partial melting of a variably enriched phlogopite clinopyroxene-rich mantle at higher pressure than group 1 primitive magmas. Trace element modelling indicates that three components (A,B,C) were involved in the genesis of their mantle source: A) a typical MORB-OIB-like mantle; B) a component with very high Sr, Ca and Sr/Ce values and very low silica and sodium content, probably carried by a carbonatite melt related to «subducted» marine carbonates; C) a recently added K-rich, Ca-Sr-poor crustal component, relatively well constrained to high $^{87}Sr/^{86}Sr > 0.712$ and $K_2O/Na_2O > 8$-9 values, and low $^{143}Nd/^{144}Nd < 0.51205$, Ba/La < 20 and Ce/Sr > 0.10 ratios. This constraint does not exclude a complete identity of component C with that which metasomatized the mantle sources of the *saturated trend* magmas.

Petrogenetic constraints indicate that the refractory-phologopite-rich harzburgitic mantle sources of the *saturated trend* magmas is the

Table II. Petrogenetic model of the primitive mantle-derived magmas of the Northern Apenninic arc.

Pre-enrichment sources	Metasomatic components	Magma sources	Primitive magmas	Localities
Saturated Trend (ST)				
Harzburgites with variable degree of residuality (MBL, mechanical boundary layer)	K-Si-rich, Na-Ca-poor melts with K20/Na20 > 6-7, Ce/Sr > 0.3 Ba/La < 20, $^{87}Sr/^{86}Sr > 0.717$ $^{143}Nd/^{144}Nd = 0.5121$-$0.5120$ (subducted low-Sr continental crust *i.e.*: terrigenous sediments and/or non-restitic acid granulites)	cpx-rich to cpx-poor phlogopite-rich harzburgites	Shoshonites Ultrapotassic shoshonites Ultrapotassic high-Mg latites Lamproites	Radicofani, Latera Radicofani Cimini Montecatini Val di Cecina, Orciatico, Torre Alfina, Sisco
Undersaturated Trend (UT) (rejected solution)				
1) *Two component hypothesis*				
lherzolites with variable degree of residuality (TBL, thermal boundary layer enriched in Sr and Ca through asthenospheric carbonatitic melts)	K-Ca-rich, Na-Si-poor melts with K20/Na20 > 8-9, Ce/Sr = 0.1-0.2, Ba/La < 20, $^{87}Sr/^{86}Sr = 0.712$-0.715 $^{143}Nd/^{144}Nd = 0.5120$-$0.5119$ (subducted high-Sr continental crust *i.e.*: marls with (10-20%) of carbonatic fraction)	Phlogopite-rich wehrlites/olivin- clinopyroxenites to Phlogopite- bearing lherzolites	Melilitites (kamafugites) Leucitites (HKS) Leucite-basanites (HKS) Tephritic leucitites (HKS) Leucite-bear ing basalts (KS) Shoshonitic basalts (KS)	San Venanzo Vulsini Vico, Vulsini Ernici, Roccamonfina Ernici Roccamonfina
2) *Three component hypothesis (preferred solution)*				
lherzolites with variable degree of residuality (typical MORB+OIB asthenosphere)	K-Si-rich, Na-Ca-poor melts with K20/Na20 > 8-9, Ce/Sr > 0.15 Ba/La < 20, $^{87}Sr/^{86}Sr > 0.712$ $^{143}Nd/^{144}Nd < 0.51205$ (subducted terrigenous sediments and/or non-restitic acid granulites) Ca-Sr-rich, Si-poor carbonatitic melt with $Sr/Ce \ll 0.1$ and $^{87}Sr/^{86}Sr \sim 0.709$ (subducted carbonate meta-sediments)	Phlogopite-rich wehrlites/olivin- clinopyroxenites to phlogopite- bearing lherzolites	Melilitites (kamafugites) Leucitites (HKS) Leucite-basanites (HKS) Tephritic leucitites (HKS) Leucite-bearing basalts (KS) Shoshonitic basalts (KS)	San Venanzo Vulsini Vico, Vulsini Ernici, Roccamonfina Ernici Roccamonfina

After Serri *et al.* (1993).

lithosphere mechanical boundary layer whereas the clinopyroxene-rich mantle source of the *undersaturated trend* magmas is probably an ephemerally and anomalously K-enriched asthenosphere.

The new petrogenetic model for the primitive rocks of the Northern Apennines is reported in schematic form in table II. Following the preferred solution of table II, it can be concluded that the huge geochemical and isotopic diversity of the *saturated trend* and *undersaturated trend* rocks would ultimately be due to different degrees of residuality (cpx-poor versus cpx-rich sources for the ST and UT rocks respectively) and to a low Ce/Sr, Ca-Sr-rich, Si-poor component with carbonatitic composition which was involved only in the metasomatism of the *undersaturated trend* mantle sources.

3.3. *Time-space distribution*

On the basis of several geochronological data obtained in the last decade (Innocenti *et al.*, 1992), it has been recognized that the magmatic activity of the Northern Apennines developed in four phases separated in space and time which become progressively younger from west to east (fig. 10) rather than, as suggested by Civetta *et al.* (1978) according to a continuous migration of the site of the magmatism toward the east.

Phase I: is documented only by one center, the Sisco sill (Corsica). Three published ages of this small lamproitic intrusion range from 13.5 and 15.0 Ma. The Sisco lamproitic sill represents the oldest activity related to the post-collisional lithospheric extension.

Phase II: includes Montecristo, Vercelli and Monte Capanne acid plutons (7.3-6.2 Ma) and most of the activity of Capraia composite volcano (6.9-6.0 Ma).

Phase III: took place between 5.1 and 2.2 Ma. It includes the Porto Azzurro, Giglio, Campiglia, Gavorrano, Castel di Pietra and Monteverdi acid plutons, the San Vincenzo rhyolites and the Orciatico and Montecatini Val di Cecina lamproites. The second period of activity of Capraia (4.7 to 3.5 Ma) took place entirely within the age limit of this phase. Also the Roccastrada rhyolites (2.5-2.2 Ma, table I) and the volcanic products of the Tolfa district are considered to belong to this phase (fig. 2).

Phase IV: starts at 1.3 Ma and up to 0.8 Ma consists only of products of the *saturated trend* (Radicofani, 1.3 Ma; Monti Cimini, 1.3-0.9 Ma and Torre Alfina, 0.8 Ma). Most of the activity of this phase took place between 0.6 and 0.1 Ma and consists nearly entirely of potassic and ultrapotassic products of the *undersaturated trend*; the rocks of the *saturated trend* of Latera were erupted between 0.15 and 0.09 Ma; the Monte Amiata (0.30-0.28 Ma) is the sole volcanic center of the Tuscan Province which was active within the age range of Roman Province (0.63-0.08, Barberi *et al.*, 1994).

3.4. *A lithospheric delamination model for Northern Apennine orogenesis*

In the last decade, it has been recognized that various types of delamination processes may take place during continent-continent collision; some models are reported in Nelson (1992). In general, the distinctive character of delamination processes is the rapid mechanical thinning of a lithospheric root beneath a collisional orogen. By rapid thinning we intend a process which occurs in less than 15-20 Ma, much quicker than the time needed to establish the lithosphere by conductive cooling (about 60 Ma). The thinning takes place through mechanical decoupling that allows: 1) the lower part of the lithospheric mantle (Houseman *et al.*, 1981), or 2) the whole lithospheric mantle (Bird, 1979) or 3) the mantle lithosphere plus eclogitized continental and oceanic crust (Nelson, 1992) to founder within the asthenosphere.

The delamination process which we believe operated during Apennine orogenesis is at variance to that formulated on a theoretical basis by numerous authors (Bird and Baumgardner, 1981; Houseman *et al.*, 1981; Turcotte, 1983) and described for different geotectonic settings by Nelson (1992), in that the decoupling level occurred within the lower crust of the in-

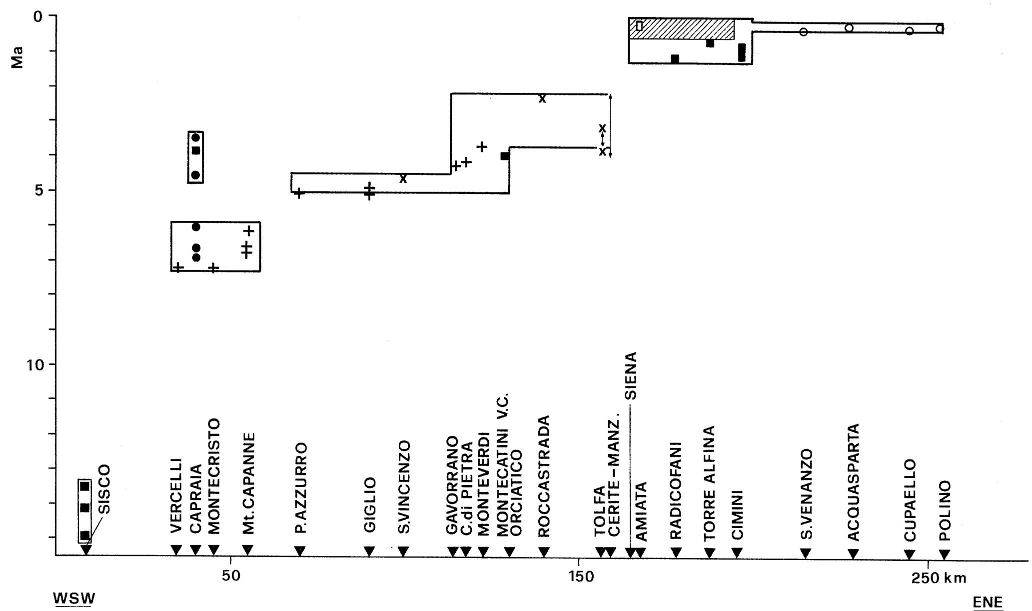


Fig. 10. Age (Ma) *vs.* distance (km) diagram of the igneous centres of Northern Apenninic arc north of Rome, projected along a section WSW-ENE from Corsica to Adriatic Sea crossing Bastia and Siena (after Serri *et al.*, 1991, 1993). Acid plutons (+); acid volcanics (×); ST centres (■); Capraia high-K calcaline series (●); North-Western Roman Province (hatched area); North-Western Roman Province kamafugites (o); Amiata (open square). Only Rb-Sr biotite-whole rock and U-Pb zircon ages for the plutonic rocks, and K-Ar and $^{40}Ar/^{39}Ar$ datings for volcanics are used. Lines with double arrows indicate the age range of Tolfa district. Sources of geochronological data in Innocenti *et al.* (1992).

coming (or lower) plate; *i.e.*, the Adriatic lithosphere (Serri *et al.*, 1991, 1993; Innocenti *et al.*, 1992). This new type of delamination model is strongly grounded on the time-space distribution and petrogenesis of Northern Apennine magmatism which requires, at least for the last 15 Ma, a continuous incorporation within the upper mantle of large amounts of lower crustal materials of the Adriatic lithosphere. This model is relevant to the problem of the origin of the continental crust (*i.e.*, why is the average continental crust so acid and why are outcrops of lower crust materials only rarely found in orogenic belts?), in that it provides an efficient, common mechanism to recycle lower continental crust into the mantle.

Numerous literature models of tectonic evolution of the Northern Apennine orogenesis from the lower Cretaceous to the present agree on the conclusion that: i) the final closure of a relict oceanic basin between the Corsica and Adriatic blocks took place through subduction towards the west under Corsica and ii) the beginning of the continental collision occurred in a time span which ranges between the upper Eocene and the lower Miocene (Reutter *et al.*, 1980; Keller and Pialli, 1990; Carmignani and Kligfield, 1990). Therefore the magmatism of the Northern Apennines (15-0.1 Ma) developed entirely in a intra-continental setting after the collision between the Adriatic and Corsican continental plates.

The proposed delamination model requires that in a time span between the continental collision and the Sisco lamproite magmatism (15-13.5 Ma) the Adriatic plate started to undergo a delamination process which allowed its Thermal Boundary Layer (TBL), Mechanical Boundary Layer (MBL) and a part of lower crust to be incorporated within the upper mantle (fig. 11a-c). This process, which is still ongoing, should not be mistaken for a continental subduction for various reasons.

1) Plate convergence, a major process during continental collision, is absent at a regional scale and minor at a local scale during delamination. This is because the driving mechanism of the proposed lithospheric delamination process is due to internally generated forces; *i.e.*, the gravitational instability of the lithospheric roots of the Apennine chain (essentially the Adriatic mantle lithosphere – mostly thermal boundary layer – but also lower crustal granulites, which increase their density through eclogitization) thickened during the continental collision between the Adriatic and Corsican plates. In this model the compression only occurs in a very limited, external sector of the orogenic belt and is synchronous with much more widespread lithospheric extension in the internal side of the chain; the minor, local convergence is due to the drag effect produced at upper crustal level by the sinking into the asthenosphere along an inclined plane of the delaminating part of the Adriatic plate.

2) At a regional scale the system is in extension (extensional collapse of the chain).

3) Most of the magmatism is emplaced onto the part of the Adriatic lithosphere which acted as lower plate before the onset of the collision and, then, of the delamination. In other words, the magmatism occurred mostly east of the suture zone.

The proposed model is based on the constraints imposed by:

i) The petrogenesis of the magmatic rocks on the structure and composition of the upper mantle under the North Apennine back-arc basin.

ii) The discontinuous migration of the locus of the lithospheric extension in each of the four phases on the position of the Adriatic lithosphere undergoing delamination.

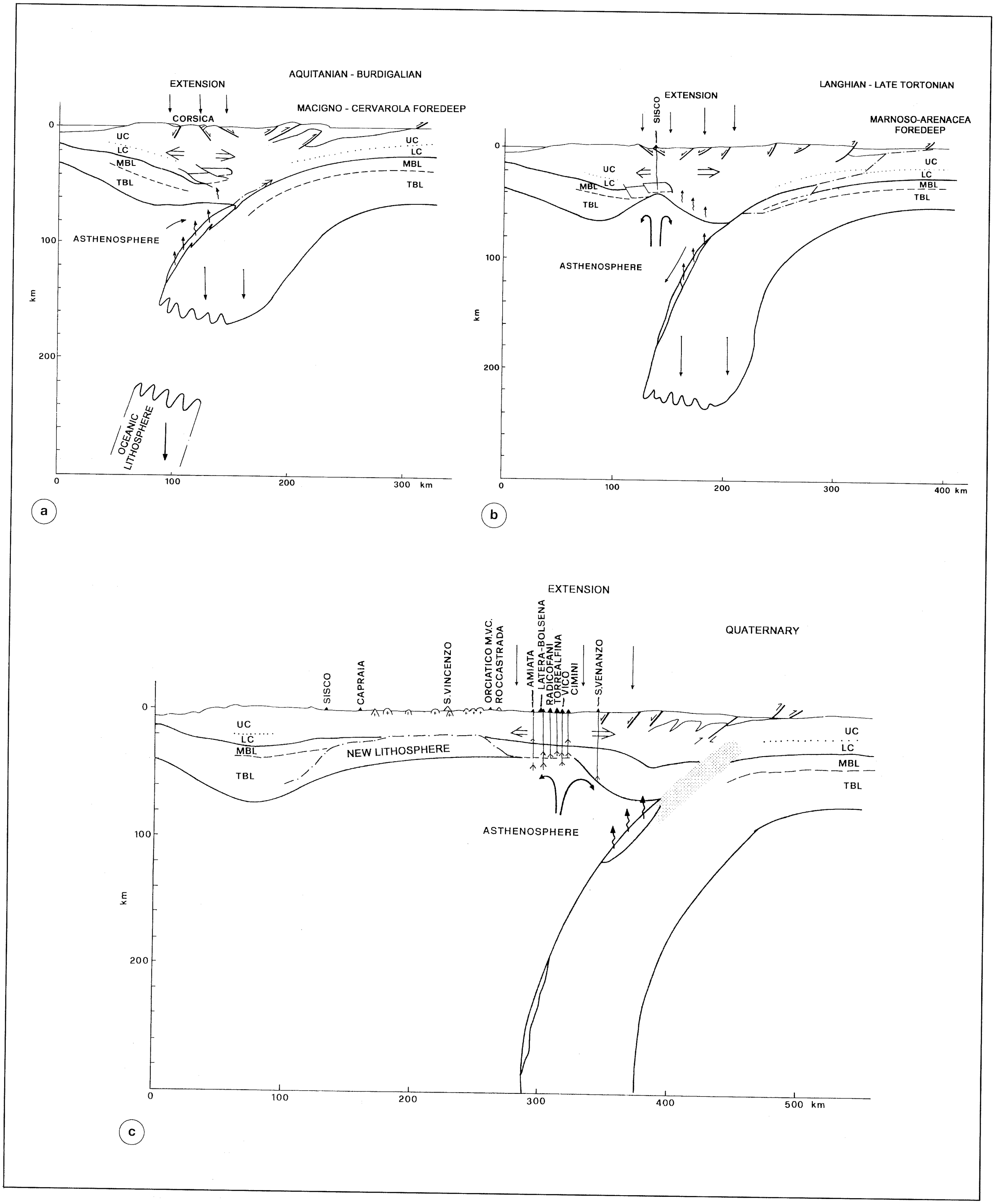
iii) The migration rate toward E-NE of the foredeep and therefore of the velocity of delamination of the Adriatic lithosphere (1.5-2 cm/yr according to Patacca *et al.*, 1992) on the geometry and kinematics of the foreland/foredeep/chain/back-arc system.

iv) The seismological data on the present-day position of the Adriatic slab under the Northern Apennines (Amato *et al.*, 1991; Amato and Selvaggi, 1992).

Interpretative section in the Aquitanian-Burdigalian – Once the delamination process has started, the introduction of the asthenospheric mantle in the wake left above the foundering lower crustal and lithospheric mantle part of the Adriatic lithosphere (fig. 11a) contributes to increase the density contrast and ultimately results in an acceleration of the delamination within the Adriatic plate. As the petrogenesis of Northern Apennine magmatism requires the incorporation within the upper mantle of large amounts of crustal materials we postulate that the initial decoupling occurred within the lower crust.

The petrogenesis and the age (15-13.5 Ma) of the Sisco lamproite require the presence in the uppermost mantle of a strongly residual harzurgitic source which had recently been enriched in a component derived from «subducted» carbonate-free continental materials, probably during the lower-middle Miocene. The infiltration of melts, probably of intermediate composition, derived from the lower crustal material of the foundering slab into the overlying mantle wedge should produce a significant acceleration of the delamination process. This should be caused, not only by the increase in the density contrast between the delaminated lithosphere, in which garnet and clinopyroxene remain as eclogite residue, and the overlying asthenosphere, but also by the decrease of the viscosity of the latter.

Interpretative section in the Langhian-lower Tortonian – The increase in delamination rate induces a strong convection which causes an acceleration of the diapiric uprising of the already buoyant crustal contaminated part of the asthenosphere. This process, in turn, produces thermal erosion of the Corsica plate TBL and local partial melting of crustal materials imbricated in the thickened crustal wedge formed



AQUITANIAN - BURDIGALIAN
EXTENSION
MACIGNO - CERVAROLA FOREDEEP
CORSICA
UC
LC
MBL
TBL
ASTHENOSPHERE
OCEANIC LITHOSPHERE
km
a
LANGHIAN - LATE TORTONIAN
EXTENSION
SISCO
MARNOSO-ARENACEA FOREDEEP
ASTHENOSPHERE
b
EXTENSION
QUATERNARY
SISCO
CAPRAIA
S.VINCENZO
ORCIATICO M.V.C.
ROCCASTRADA
AMIATA
LATERA-BOLSENA
RADICOFANI
TORREALFINA
VICO
CIMINI
S.VENANZO
NEW LITHOSPHERE
ASTHENOSPHERE
500 km
c

during the initial phases of the continental collision. This first documented post-collisional magmatic event (the Sisco lamproite) indicates that during the Serravallian the lithospheric extension is already so advanced as to cause the partial melting of the recently K-enriched Corsican MBL.

In order to satisfy the constraints imposed by the petrogenesis of the Pliocene and Quaternary magmas of the *saturated trend* it is necessary to postulate the presence under continental Tuscany and Northern Latium of a part of the Adriatic MBL (fig. 11c). We assume that this occurred through the imbrication of at least part of the MBL Adriatic lithosphere in the root of the chain (fig. 11b).

During the upper Miocene-Pliocene – The magmatism, dominated by plutonic and volcanic acid products, of the phases II (7.3-6 Ma)

Fig. 11a-c. Neogene-Quaternary geodynamic model of the Corsica-Northern Apennine orogenic system in the sector comprised between Capo Corso-Livorno-Cesenatico and Bonifacio-Civitavecchia-San Benedetto del Tronto (after Serri *et al.*, 1991, 1993). The magmatic centres are located in the diagram (c) with the same procedure as in fig. 10. The rheology of the continental lithosphere is simplified into a four layer model: UC = Upper Crust, fragile; LC = Lower Crust, ductile; MBL = Mechanical Boundary Layer, fragile; TBL = Thermal Boundary Layer, ductile (Molnar, 1988; Menzies, 1990). The thickness of the crust and of the lithosphere are constrained by the data of Panza *et al.* (1980), Boccaletti *et al.* (1990), Della Vedova *et al.* (1991); the thickness of each of the four layers is arbitrary. The horizontal open arrows indicate the lower crustal zones of the chain where ductile extensional flow is thought to be more intense. The driving mechanism of the delamination/subduction process of the Adriatic lithosphere is the gravitational sinking of the lithospheric roots of the chain (essentially TBL) thickened during the initial stages of the continental collision. a) Interpretative section at the lower Miocene after the beginning of the continental collision between the Adriatic and Corsica plates. It is implicit from the back-thrusted Corsican MBL that the continental collision produced a double-vergent chain (Keller and Pialli, 1990). The beginning of the marine sedimentation in the Aleria and St. Florent basins in the Burdigalian (Orszag-Sperber, 1978) indicates that in the Corsican sector of the chain the extension was already well advanced about 17 Ma ago. The dash-point line with a double arrow marks a hypothetical trajectory of propagation of the decoupling surface within the Adriatic lithosphere. To allow the incorporation of large amounts of crustal materials within the upper mantle, as required by the petrogenesis of the Northern Apenninic magmatism we envisage that the initial level of decoupling is located within the lower crust. b) Interpretative section at the Langhian-lower Tortonian during the first magmatic phase (Sisco). The Sisco source is located in the MBL of the Corsica lithosphere (depth less than 50 km). The harzburgite protolith was metasomatized by a K-rich component derived from the Adriatic continental crust subducted and/or imbricated below Corsica MBL during the lower/middle Miocene continental collision. To satisfy the constraints imposed by the petrogenesis of the Tuscan lamproites, the propagation of the decoupling surface toward upper crustal level should allow at least part of the Adriatic lithosphere MBL to be imbricated in the Northern Apennine chain. This process occurred during the lower/middle Miocene continental collision or, perhaps as shown in fig. 11b, during the continental lithosphere delamination. The rapid, buoyant uprising of the crustally-contaminated part of the asthenosphere causes a small-scale, large magnitude convection, which in turn induces rifting/magmatism in a limited sector of the chain in each of the four defined phases. c) Interpretative section at the Quaternary during the fourth magmatic phase. Crosses: acid plutons dominantly produced by crustal anatexis during the phases II and III. Open triangles: acid volcanic centres dominantly produced by crustal anatexis during the phase III. Full triangles: volcanic centres with mantle-derived magmas. The preferred locations of the sources of the phase IV magmas are marked with root-type arrows. *New lithosphere* indicates the continental lithosphere formed in the time span between the upper Miocene to the present-day through solidification of underplated magmas and cooling of the asthenosphere that came into direct contact with the MBL/TBL of the Corsica plate and with the crustal and MBL units of the Adriatic lithosphere imbricated in the roots of the Apennine chain. The advection of heat which caused widespread anatexis of the crustal roots of the chain under the Tuscany took place through the diapiric uprising of the crustally-contaminated asthenosphere and via underplating of potassic magmas derived from it.

and III (5-2.2) took place. This acid magmatism requires wholesale partial melting of the continental crust as well as ubiquitous mixing with mantle-derived magmas generated from a crustal contaminated asthenosphere. This acid Tuscan magmatism is found inside an ellipsoidal area (about 150×300 km) centred at Giglio Island, defined as the Tuscan Crustal Dome (fig. 5), where mantle-derived magmas unaffected by important crustal contamination processes have not yet been found. In fact, the primitive mantle-derived magmas (Zenobito centre-Capraia, Orciatico and Montecatini Val di Cecina) are found just outside the Tuscan Crustal Dome. However the systematic presence of hybrid magmatic inclusions in the acid products testifies the ubiquitous involvement of mantle-derived magmas in their genesis. In conclusion there is a strict cause/effect relation between the buoyant rising of the crustally-contaminated asthenosphere above the Adriatic delaminated/foundering lithosphere and the wholesale partial melting of the continental crust imbricated during Langhian-Tortonian times in the roots of the chain (fig. 11b). The formation of widespread anatectic melts of the Tuscan Crustal Dome is explained by the underplating of potassic magmas derived from the ephemerally K-enriched asthenosphere which intrudes in the wake left above the delaminated/foundering Adriatic lithosphere.

Interpretative section in the Quaternary – In the Quaternary the locus of the rifting/magmatism is displaced 50-100 km toward NE (phase IV, figs. 5 and 10); the magmatism begins about 1 Ma later than the most important surface uplift event of the Southern Tuscany-Northern Latium region. We interpret this uplift as due to the intrusion of the asthenosphere in the wake left above the delaminated/foundering Adriatic slab; this process is accompanied by the thermal erosion of the Adriatic MBL imbricated in the Apennine chain (fig. 11b,c).

Also the petrogenesis of the Quaternary mantle-derived magmas indicates that the mantle wedge (asthenosphere and Adriatic MBL) had been metasomatized by components derived by «subducted» crustal materials. The proposed geodynamic model in this time span (fig. 11c) is based on the preferred solution of table II, which implies that the mantle sources of the *undersaturated trend* magmas is produced by the combination of three components. This solution requires that the delamination process carried within the upper mantle in addition to the low-Sr crustal materials (*e.g.*, non-restitic acid granulites) also carbonate metasediments. The time/space distribution of the magmatism indicates that the activity of phase IV (1.3-0.8 Ma) begins with the emplacement of products derived from partial melting of the MBL (*saturated trend* magmas: Monti Cimini, Radicofani, Torre Alfina) and, locally, of the continental crust (Monti Cimini); successively (0.6-0.1 Ma) also the crustal contaminated asthenosphere, interpreted to represent the source of the *undersaturated trend* volcanism is activated, as well as the MBL (Latera shoshonites and Vico olivin-latites) and the continental crust (Amiata). In conclusion, in the time span comprised between 0.6 and 0.1 Ma all the layers of the asthenosphere/lithosphere system underwent partial melting.

The geological and geophysical data previously discussed show that the North Apennine orogenesis is still active.

4. Conclusive remarks

The petrogenesis and time/space distribution of the magmatism associated with the formation of the Northern and Southern Tyrrhenian basins, together with the directions and ages of lithospheric extension and/or spreading north and south of the 41°N discontinuity, show that the two arc/back-arc systems have undergone a different structural evolution at least since the middle Miocene (Langhian).

The geochemical components involved in the genesis of the heterogeneities of the mantle sources of this magmatism require two separate, compositionally different slabs: 1) an old oceanic (Ionian) lithosphere still seismically active below the Calabrian arc and the Southern Tyrrhenian region; 2) an almost seismically inactive continental (Adriatic) lithosphere which carried large amounts of upper crustal materials within the upper mantle under the NW Roman Province/Tuscan/Northern Tyrrhenian region. The proposed geodynamic models require:

1) For the Northern Tyrrhenian/Northern Apenninic arc/back-arc system, the delamination and foundering of the Adriatic continental lithosphere as a consequence of the continental collision between the Corsica block and the Adriatic continental margin. This delamination process, which is still ongoing, probably started in the early-middle Miocene, but earlier than 15-14 Ma, as indicated by the age and petrogenesis of the first documented magmatic episode (the Sisco lamproite) of the Northern Apennine orogenesis.

2) For the Southern Tyrrhenian/Southern Apenninic-Calabrian arc/back-arc system, the roll-back subduction and back-arc extension driven by gravitational sinking of the Ionian oceanic subducted lithosphere. This process started after the end of the arc volcanism of Sardinia (about 13 Ma) but earlier than the first recorded episode of major rifting (about 9 Ma) in the Southern Tyrrhenian back-arc basin.

Acknowledgements

This review is based on decades of work on Italian magmatism by numerous authors, who cannot be adequately acknowledged owing to the reduced space for references. This work would not have been possible without the cooperation with F. Innocenti and P. Manetti and extensive, stimulating discussions with many colleagues over the last few years, in particular with G. Pialli and P. Scandone, who are gratefully thanked. Figures 5, 6a,b, 7a,b, 8, 9, 10 and 11a-c, tables I and II are reprinted from, SERRI G., INNOCENTI F. and MANETTI P. (1993): Geochemical and petrological evidence of subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of Central Italy, *Tectonophysics*, **223**, 117-147, with kind permission of Elsevier Science – NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

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