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Carbonatites and kamafugites in Italy: mantle-derived rocks that challenge subduction

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The carbonatite and kamafugite (*i.e.* potassic melilitite) rock-types of the Intramontane Ultra-alkaline Province (IUP, Italy) form a geologically rare, albeit not unique, ultramafic association. Their composition is in the range of other kamafugites and carbonatites, especially extrusive carbonatites, in the world (Katwe-Kikorongo and Bunyaruguru in Uganda, Oldoinyo Lengai in Tanzania and Quinling in Gansu, Central China). The kamafugite-carbonatite rock association requires specific tectonic-magmatic prerequirements: 1) metasomatised mantle source (enriched carbonate/phlogopite-bearing peridotite); 2) magma rapid rise to the surface to preserve a near primary state, to carry large mantle nodules and to limit the interaction with the crustal rocks and/or fluids; 3) geometry of the lithosphere suitable to favour the intersection of the local geotherm with the metasomatised peridotite *solidus* and to allow only very small-degrees of partial melting. The Italian kamafugite carbonatite geochemistry encompasses high LILE (Cs, Rb, K, Ba), high Sr-group (Sr plus REE), high LREE/HREE, high incompatible elements (Cr-Ni), but negative Eu anomaly, low light-HFSE^{4+} (Zr-Ti) and intermediate heavy-HFSE (Hf-Ta). This distribution requires a high CO_2 fugacity in the source able to fractionate the HFSE and to produce the Eu anomaly. Based on geochemical criteria used for basaltic rocks, the IUP rocks were attributed by some authors to a subduction geodynamic setting, a fact which produced a catastrophic misunderstanding of these rocks. Worldwide kamafugites and carbonatites occur in intraplate and continental rift settings, the magmatogenetic conditions required for their genesis being unsuitable in a subduction environment, which is instead the dominating model for Italian volcanism. This consideration stimulated this review of the IUP field relationships, mineralogy, petrology and geochemistry. The IUP is sited about 50 km east of the large volcanoes of the Roman Co-magmatic Region (RCR). Plagioleucitites which are typical of the RCR, are also geologically rare and, when regionally associated with carbonatites and kamafugites, form a regional triad very typical of continental rifts. This triad has never been observed in subduction related environments, that are dominanted by large volumes of andesites and dacites. It may be better explained in the frame of a plume model that links the metasomatic process of the IUP mantle source with hydroxyl-CO_2 rich radiogenic fluids and volatiles released within the Mediterranean asthenosphere from a plume head trapped in the transition zone (between the 410 and 670 km discontinuities).

6.1. INTRODUCTION

The geological meaning of the Middle Pleistocene Ca-carbonatite and potassic melilitite rocks (namely kamafugites) of the Intramontane Ultra-alkaline Province (IUP, Lavecchia and Stoppa, 1996; Stoppa and Woolley, 1997) is a crucial point in the discussion of the tecto-magmatic setting of the Tyrrhenian-Apennine system and its geodynamics. But why? Because the carbonatite-kamafugite association is typical of continental rifts and it is the petrological opposite of subduction-related rocks. This is noteworthy and produced rumours among Italian petrologists and geologists.

Carbonatites are magmatic rocks characterised by having more than 50% of carbonate minerals by volume. They represent primitive magmas derived from very low degrees of partial melting of a metasomatised mantle source (Bailey, 1993; Lee *et al.*, 2002). Carbonatites must come from a volatile-rich mantle and the obvious choice of minerals able to release CO_2 are carbonates, which are known to be stable under mantle conditions. It is reasonable to imagine that some CO_2 was trapped during the Earth's accretion and remnants of this are still retained in the lower part of the mantle (Bell and Tilton, 2002).

About 550 carbonatite occurrences are known in the world, almost exclusively located in intracontinental extensional areas (Bailey, 1993; Bell *et al.*, 1999; Woolley, 2003; Yu *et al.*, 2003). Some rare occurrences, namely Fuerteventura in the Canary Islands and Capo Verde Islands, are related to extension of transitional to oceanic lithosphere. Occurrences from converging margin, when investigated, were found to be marbles or late stage calcite veins not genetically linked to primary carbonatite magma. Among carbonatites, extrusive occurrences are comparatively rare (about 10% of total number: Woolley, 2003; Woolley and Church, 2005), due to their faint nature at the Earth's surface conditions. Extrusive carbonatites are particularly important because being prone to eruptions in a near primary state they can give direct information on the composition of the mantle source (Bailey, 1966; Keller, 1989). Often, carbonatites are associated with kamafugites. These are kalsilite-bearing foidites and melilitites, rocks very rich in potassium and calcium, very poor in silica and alumina and with no feldspars.

With this paper, we intend to disseminate comprehensive information about the Italian carbonatite-melilitite association. Field relationships, mineralogy, petrology and geochemistry are fully addressed. Particular attention is focused on the cause-effect relationship which determines the distribution of the High Field Strength Elements (HFSE). In the past, the HFSE fractionation in the IUP rocks and also in rocks from other Italian alkaline provinces, has been largely used as a fundamental discriminating factor for the definition of the Italian tectonic setting as subduction-related (Civetta *et al.*, 1989; Conticelli and Peccerillo, 1992; Serri *et al.*, 1993; Wilson and Bianchini; 1999; Tappe *et al.*, 2003, among many others). We criticise the indiscriminate application of geochemical criteria established for plagioclase-bearing rocks (*i.e.* basaltic rocks) to the IUP rocks, which are plagioclase-free rocks. A comparison of the IUP with the leucitites of the Roman Co-magmatic Province (RCP, Washington, 1906) helps to disclose a new interpretative view of the tectonic and magmatogenetic processes in the Italian mantle. These are coherently considered in the frame of a new stimulating hypothesis proposed by Bell *et al.* (2004, 2006) and based on the Italian isotopic mantle taxonomy which relates the IUP and the RCP to a deep mantle plume.

6.2. THE CARBONATITE AND KAMAFUGITE ASSOCIATION IN ITALY

6.2.1. Tectonic setting and vocanological features

Since the beginning of the last century, kamafugites were known from San Venanzo (Umbria) and Cupaello (Latium). Recently, a new kamafugite occurrence was reported from Grotta del Cervo, in Abruzzo, extending the IUP southeastward (Stoppa *et al.*, 2002). During the last 15 years, carbonatites coeval and co-genetic with the above kamafugites, were discovered in Central Italy at Polino (Umbria), Cupaello (Latium) and Oricola (Abruzzo) (fig. 6.1a). Another important area where carbonatites occur in association with melilitites, of lesser potassic character, is Vulture Volcano (Basilicata) in Southern Italy. A considerable amount of work has been devoted to these rocks (Stoppa, 1988, 1996; Lupini *et al.*, 1992; Stoppa and Lavecchia, 1992; Stoppa and Lupini, 1993; Stoppa and Cundari, 1995; Stoppa and Liu, 1995; Sharygin *et al.*, 1996; Stoppa and Woolley, 1997; Stoppa and Cundari 1998; Stoppa and Principe, 1998; Comodi *et al.*, 1999; Jones *et al.*, 2000; Rosatelli *et al.*, 2000; Barbieri *et al.*, 2001; Stoppa *et al.*, 2002, 2003, 2005; Panina *et al.*, 2003; Solovova *et al.*,

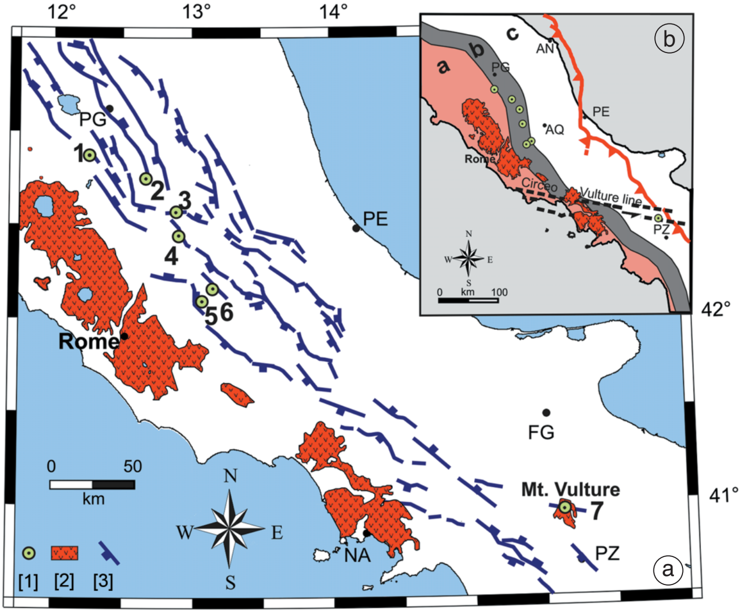

Fig. 6.1a,b. a) Location map of the IUP and RCP. Key: [1] carbonatite-melilitite occurrences of the Intra-montane Ultra-alkaline Province (IUP): **1** – San Venanzo; **2** – Colle Fabbri; **3** – Polino; **4** – Cupaello, **5** – Oricola; **6** – Grotta del Cervo; **7** – Monticchio; [2] volcanic products of the Roman Co-magmatic Province (RCP); [3] Plio-Quaternary normal and normal-oblique faults. b) Schematic tectonic zoning (after Lavecchia *et al.*, 2002): **a** – thinned crust domain (~25 km); **b** – zone of overlapping of the thinned Tuscan crust above the Adriatic crust; **c** – thickened crust domain (35-40 km); red line with triangles = outer front of the Apennine fold-and-thrust belt system.

2005). A detailed 'state of the art' can be found in the EUROCARB special issue edited by Rosatelli and Stoppa (2003) and in the LITHOS special issue edited by Wall *et al.* (2005).

The IUP is located along and within the Apennines Mountain Chain. The volcanic centres are related to the Plio-Quaternary normal and normal-oblique faults that border NNW-SSE striking horst and graben structures. The Vulture volcano, in Southern Italy, lies close to the outer front of the Apennine thrust belt, on a regional E-W transfer fault (Circeo-Vulture line in Lavecchia, 1988) (fig. 6.1b). It shares many geochemical features with the IUP rocks and especially with those from the Abruzzo region (Stoppa *et al.*, 2002), but it is geographically isolated from them by a gap of about 250 km. So far, no igneous occurrence has been reported in between (fig. 6.1a).

The IUP magmatic activity ranges in age from about 490 to 130 kyr with a peak at around 250 kyr. Most of the IUP occurrences are extrusive, monogenetic and of small volume, ranging from 10^6 to 100^6 m^3. Volcanic forms include cylindrical conduits (namely diatremes) similar to those of the kimberlites, filled by peculiar breccias, with concentric shelled lapilli, often nucleated by an ultramafic lithic («spin lapilli»: Junqueira-Brod *et al.*, 1999; Stoppa *et al.*, 2003). Diatremes are coupled with high-energy volcanic forms, such as maars and tuff rings produced by the turbulent expansion of CO_2-rich surges (fig. 6.2a,b). The IUP rocks typically carry mantle debris and even discrete large peridotitic nodules of lherzolite, wehrlite and dunite, up to 11 cm across and weighing up to 1 kg (fig. 6.2c,d). The IUP rocks erupt mainly as a mixture of silicate crystals and glass fragments suspended in a very fine-grained carbonate matrix. CO_2 is the only readable agent of acceleration of kamafugite-carbonatite breccias and xenoliths to the surface (see discussion in Stoppa *et al.*, 2003).

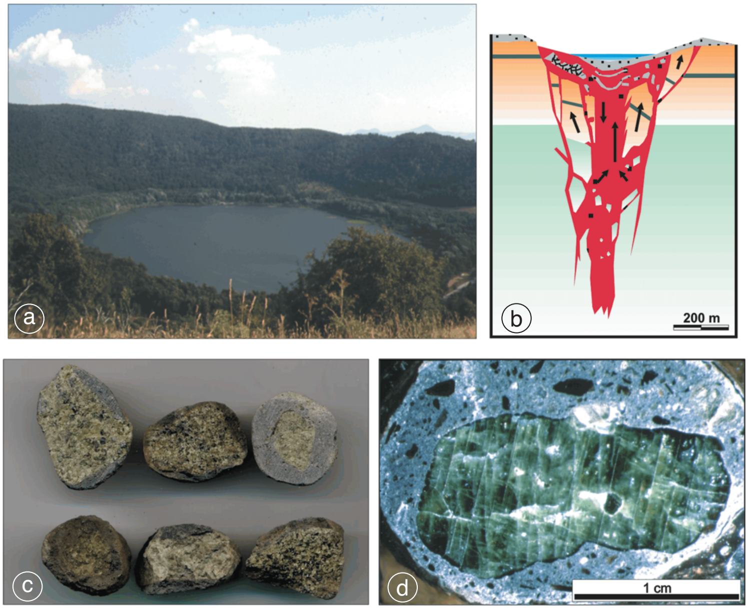

Fig. 6.2a-d. a) Maar at the small Monticchio lake (Mt. Vulture, Lucania); b) sketch of a typical IUP diatreme; c) spinel lherzolite xenoliths from Monticchio; d) tuffisitic lapillus with Cr-diopside at the core and concentric shells of melilitite and carbonatite, from surge deposits at Monticchio.

6.2.2. Geochemistry

The IUP kamafugites are characterised by very strong silica undersaturation (SiO_2wt%<42) and very high calcium (CaOwt%>15), features which, at an extreme, generate Ca-carbonatites (table 6.I). The IUP kamafugites have a strong potassic character with $K_2O/Na_2O>10$ and low Al_2O_3 with Alk/Al≥1 (*i.e.* they are peralkaline rocks). They also have high Mg and Fe content. A modal consequence of the chemistry is the appearance of SiO_2 undersaturated potassic minerals (kalsilite and leucite) plus typical cafemic minerals (melilite, diopside, melanite or schorlomite, wollastonite, monticellite, cuspidine) and peralkaline minerals (götzenite, khibinskite, delhayelite). A mineral association which is unique to these kinds of rocks. Both primitive carbonatites and kamafugites have the high Cr-Ni contents (>1000 ppm) and the high Mg# ($Mg/Mg+Fe^{2+}>70$) required by melts in equilibrium with a mantle source (*i.e.* near primary mantle melt). This feature coupled with the high amounts of incompatible elements, such as LILE (K, Rb, Cs, Sr, Ba) and HFSE (Th, U, Zr, Hf, Ta, Ti, Nb, REE), indicate a very low degree of partial melting of the mantle source. This is due to the high propensity of the above elements to be partitioned in the partial melt liquid. In addition, the mineralogy of the IUP rocks (carbonate, phlogopite, apatite, hauyne) indicates that their parental magma was very rich in volatiles (CO_2, F-OH, SO_2) which are great elemental scavengers influencing compositional variations of the source.

The incompatible trace elements content of the IUP kamafugites and carbonatite is depicted in fig. 6.3a-c and normalised at chondritic abundance. It is generally 3 orders higher than the primordial mantle or chondrite content, 2 orders higher than the sedimentary carbonate content (fig. 6.3a), 1 order higher than the upper crust content (fig. 6.3b) and similar to the average Ca-carbonatite content (fig. 6.3c). The Italian kamafugite carbonatite geochemistry encompasses high LILE (Cs, Rb, K, Ba),

Table 6.I. IUP bulk rock compositions. Data from Stoppa *et al.* (2002); Stoppa and Woolley, (1997); Stoppa and Cundari (1998).

Locality	Polino	Cupaello	Oricola	San Venanzo	Grotta del Cervo	Cupaello
Sample	Carbonatite	Carbonatite	Carbonatite	Kamafugite	Kamafugite	Kamafugite
SiO_2	16.00	18.1	24.70	41.20	42.50	44.12
TiO_2	0.51	0.37	0.38	0.76	0.89	1.17
Al_2O_3	3.90	2.51	10.45	11.90	12.60	8.01
Fe_2O_3	3.65	2.25	4.91	3.08	6.24	5.62
FeO	1.31	0.12	1.30	3.74	1.74	2.07
MnO	0.07	0.04	1.19	0.09	0.13	0.11
MgO	7.31	7.83	1.12	11.90	7.28	11.66
CaO	38.30	34.32	27.50	15.20	15.40	14.23
Na_2O	0.05	0.03	1.47	0.98	2.49	0.29
K_2O	0.49	1.01	4.18	7.58	5.11	6.5
P_2O_5	0.59	0.82	0.28	0.47	0.46	1.23
CO_2	24.00	25.58	19.65	1.03	0.00	0.15
LOI	2.93	7.59	nd	1.43	1.29	4.84
Total	99.1	100	97.1	99.4	96.1	100
Mg#	0.91	0.99	0.61	0.85	0.88	0.90
Rb	26.0	81.5	186.0	452.0	453.0	506.9
Pb	31.0	50	129.0	28.0	43.0	144
U	9.0	5.3	76.5	8.0	7.0	31
Th	59.0	41	72.8	37.0	25.0	129
Ba	3181.0	789.5	2945.0	725.0	648.0	4358
Nb	20.0	17	25.0	14.0	16.0	45.8
Ta	0.9	0.9	<1	0.8	1.0	3.3
La	111.0	88.9	170.0	74.8	74.5	249.5
Ce	232.0	166	316.0	160.0	160.0	516
Sr	1824.0	1295	2395.0	1720.0	1040.0	3776
Pr	28.2	21.15	30.7	20.3	20.2	Nd
Nd	113.0	71.5	88.4	84.7	78.0	227
Sm	22.2	12.3	10.4	17.1	14.7	39
Zr	345.0	201	104.0	345.0	294.0	855
Hf	8.0	7.95	6.0	8.3	14.0	23
Eu	4.7	2.305	2.7	3.3	2.4	6.4
Gd	15.8	12.2	9.5	12.2	9.9	25.9
Tb	1.7	0.9	1.1	1.5	1.1	Nd
Dy	7.5	5.6	5.0	7.6	5.1	12.4
Y	38.0	14	20.0	29.0	25.0	48
Ho	1.0	0.7	0.7	1.2	0.9	Nd
Er	2.6	1.7	1.9	3.1	2.1	4.4
Tm	0.3	0.2	<0.5	0.4	0.3	Nd
Yb	1.5	0.79	1.9	2.2	1.9	2.6
Lu	0.2	0.095	0.3	0.3	0.3	0.45
Ni	308.0	29	27.0	143.0	52.0	74
Cr	501.0	33.5	16.0	757.0	60.0	48

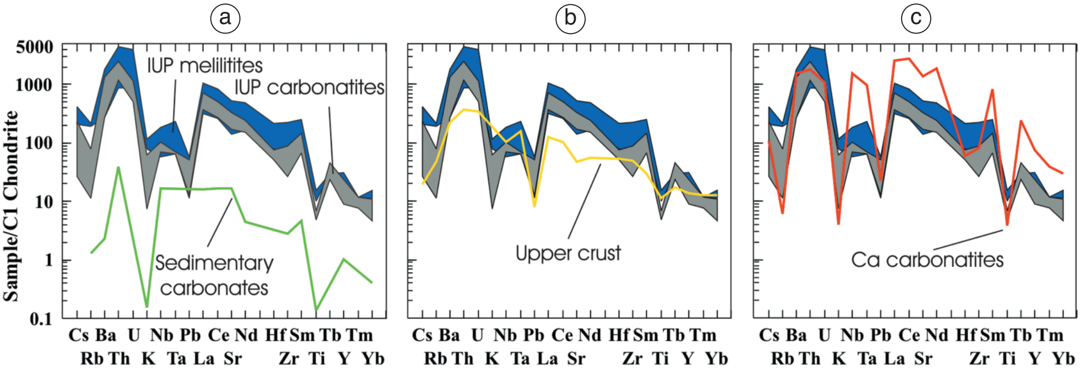

Fig. 6.3a-c. Chondrite normalised (C = 1) multi-element diagrams showing IUP carbonatite and kamafugite ranges compared with a) sedimentary carbonates (Stoppa and Woolley, 1997), b) upper crust (Taylor and McLennan, 1985) and c) average Ca-carbonatite (Wolley and Kempe, 1989).

high Sr-group (Sr plus REE), high LREE/HREE, high compatible elements (Cr-Ni), but negative Eu anomaly, low light-HFSE^{4+} (Zr-Ti) and intermediate heavy-HFSE (Hf-Ta). This distribution requires a high CO_2 fugacity in the source able to fractionate the HFSE and to produce the Eu anomaly.

The IUP rock content of Hf, Zr,Ti, Nb and Ta is similar to the upper crust content and appears as negative spikes in the spider diagrams of fig. 6.3a-c. In turn, the content in the Sr-group (Sr plus REE), U and Th is much higher than that in the upper crust.

Rb, K, Pb are lesser abundant in the IUP carbonatites than in the IUP kamafugites, as the calcite cannot easily accommodate these LILE. In general, the IUP carbonatites show slightly lower content of Sr plus REE, but this is likely due to the high propension of the igneous calcite to lose its trace elements when recrystallising to secondary calcite. However, when analysed by Electro Micro Probe or Laser-ICP-Mass Spectrometer, the primary calcite always contains much higher Sr-Ba plus REE elements compared to the silicate component (Stoppa *et al.*, 2004). Sedimentary limestones have been claimed to be incorporated in the subduction process to explain the Italian carbonatites (*e.g.* Peccerillo, 1998). However, the limestones cannot be involved, as they have still lower LILE-HFSE (fig. 6.3a) than average upper crust, and thus, they are not able to change the LILE-HFSE mantle content or ratio.

A feature peculiar to the IUP rocks is the very high Sr and very low Nd isotopic ratios. $^{87}Sr/^{86}Sr$ ranges between 0.7112 and 0.7055 (decreasing N-S), $^{143}Nd/^{144}Nd$ ranges between 0.5119 and 0.5127 (increasing N-S) and the computed Nd model age ranges from 1.5 to 1.9 Gyr (Castorina *et al.*, 2000). $^{206}Pb/^{204}Pb$ is between 19.37 and 18.74, $^{208}Pb/^{204}Pb$ between 38.96 and 39.33, $^{3}He/^{4}He$ (R/Ra) between 0.26 and 5.66, $^{21}Ne/^{22}Ne$ between 0.03 and 0.07, $\delta^{13}C$pdb (in carbonatites) between -4.6 and -4.7. The $\delta^{13}C$ and $^{21}Ne/^{22}Ne$ ratios are well within the mantle range and testify to a deep genesis in a mantle source with no crustal contamination (Bell *et al.*, 2006). Oxygen ranges from near mantle values to high values, a trend which is typical of most intrusive and extrusive carbonatites (Deines, 1989; Rosatelli *et al.*, 2000).

6.2.3. Comparison with the HK-series

The IUP occurrences are sited 50-70 km east of the large caldera volcanoes of the Roman Comagmatic Province (RCP). The two provinces are almost coeval, since they span from ~0.6 Myr to the present, and both are located at the outer border of the Tuscan-Tyrrhenian extensional system. The RCP domain has been reached by stretching and thinning at all structural levels (upper crust, lower crust, lid) and it is characterised by high heat-flow values (>100 mW/m^2) and positive Bouguer anomalies (0 to +50 mGals). The IUP domain has been reached by the extensional strain field only at the upper crust level and it is characterised by thick crust (35-40 km), unthinned lithosphere (90-100 km thick), negative Bouguer anomaly (0 to –50 mGals) and normal to low regional heat flow values (60 to 40 mW/m^2) (Lavecchia *et al.*, 2002 and references therein).

Whereas the IUP is characterised by monogenic occurrences, the RCP is characterised by large lava plateaux, gigantic calderas related to ignimbritic eruptions and strato-volcanoes. In the RCP there is a considerable amount of different alkaline rocks, but most representative are those of the High Potassium Series (HKS) which consist of plagio-leucitites and leucite phonolites. These rocks are modally and chemically distinguished by the IUP rocks: they have higher SiO_2wt%, lower CaOwt% and are metaluminous (Alk/AL<1). K_2O/Na_2O in general is lower than 10. Carbonatites are unknown in the RCP and melilitic foidites rarely occur. The latter are easily distinguished from the kamafugites as they do not contain normative larnite.

The trace element HKS geochemistry is qualitatively similar to that of IUP rocks having a similar pattern of incompatible elements, the Eu negative anomaly in the REE chondrite normalised pattern and the high Sr and low Nd isotopic ratios. However, HFSE abundances, LREE/HREE and $^{87}Sr/^{86}Sr$ are generally significantly lower (Lavecchia and Stoppa, 1996). This broadly relates the HKS to a relatively higher degree of partial melting of a metasomatised mantle source (enriched carbonate/phlogopite-bearing peridotite), that neatly fits with the absence in the RCP of carbonatites and with the much larger magma volumes.

6.3. PROBLEMS WITH HFSE-BASED TECTONIC ASSEGNATIONS

Carbonatites, kamafugites and leucitites are typically intraplate rocks, however the IUP and HKS rocks were claimed by many authors to be associated with subduction because of having a geochemical «orogenic» signature (Civetta *et al.*, 1989; Conticelli and Peccerillo, 1992; Serri *et al.*, 1993; Peccerillo, 2003; Tappe *et al.*, 2003; Becccaluva *et al.*, 2004; Conticelli *et al.*, 2004). This hypothesis was strongly based on the high HFSE fractionation, the Eu negative anomaly, plus the high strontium and low neodimium isotopic ratios observed in the HKS and IUP rocks. Evidently, this information, if taken in isolation, can lead to a misleading interpretation. In fact, the observed content in HFSE, REE and radiogenic isotopes are not exclusive to orogenic contexts, but they may also be found in rocks typically independent from subduction such as carbonatites, lamproites and kimberlites. For example, negative HFSE anomalies of Ta (Hf)-Nb and Zr-Ti characterise the Oldoinyo Lengai, an extrusive carbonatitic volcano of the eastern branch of the East African Rift System (Simonetti *et al.*, 1997).

During the Eighties, rock classifications based on Zr/Ti *versus* Nb/Y (Winchester and Floyd,1977) and on Ti/Zr/Y, Ti/Zr/Sr and Th/Hf/Nb ratios were extensively used to associate basaltic rocks to a specific tectonic setting (Pearce and Cann, 1973; Wood, 1980). This method was strongly criticised by Arculus (1987) and by Muller *et al.* (1992) that emphasised the unsuitability of these parameters for non-basaltic rocks (*e.g.*, plagioclase-free rocks). In these diagrams, the IUP carbonatites and melilitites plot in the andesitic or trachy-andesitic fields generating an evident paradox. In fact, the IUP rocks are not basaltic and are clearly petrologically and mineralogically opposed to andesitic rocks. In the Zr-Nb-Y and Hf-Ta-Yb and Ti-Zr-Y triangular diagrams, the Italian carbonatites coherently plot in the low Nb-Zr, high Hf and high Ti field that is typical of carbonatites associated with potassic mafic rocks and melilitites (field VI and V of Rass, 1998).

If we try to analyse the cause-effect relationship of the HFSE distribution in a subduction environment, we must assume a contamination of the mantle by subducted upper crust (Serri *et al.*, 1993;

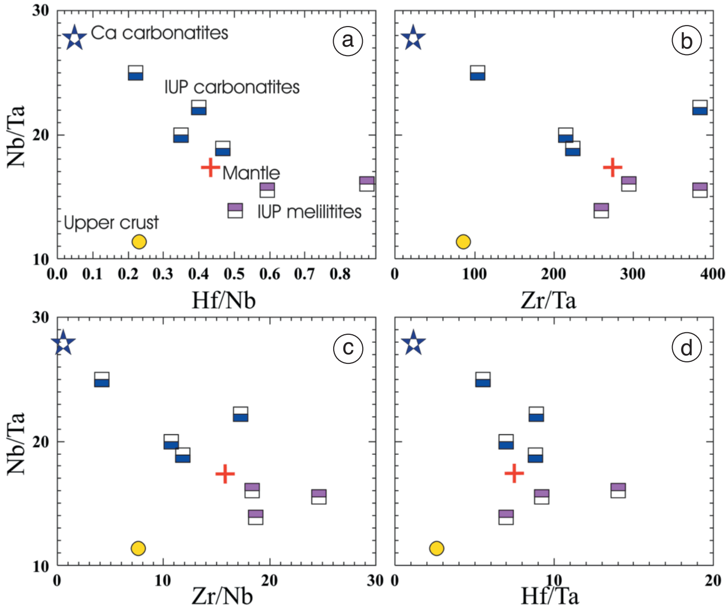

Fig. 6.4a-d. High Field Strength Element (HFSE) ratios for the IUP carbonatites and kamafugites compared with relevant composition (source of data as in fig. 6.3a-c). Note that the IUP carbonatites and melilitites are perfectly in trend along with primitive mantle and average Ca-carbonatite.

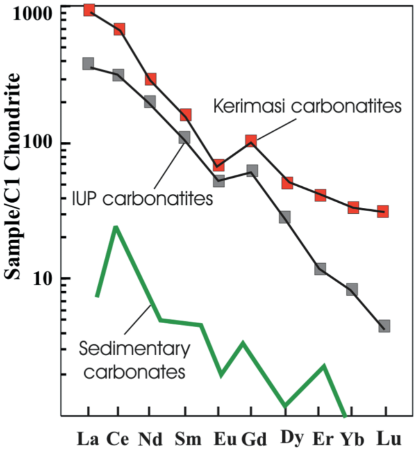

Fig. 6.5. Multi-elemental diagram showing Rare Earth Elements (REE) in the IUP and Kerimasi carbonatites (Tanzania, East African Rift System).

Peccerillo, 1999). Then, the crustal HFSE ratios would be transferred to the mantle and would explain the low Zr-group element content in the derivative magmas, irrespective of the elemental absolute abundance. The latter would be only a function of the degree of partial melting and of the further magma evolution. Also agreeing to use the 'immobile' twin couples Nb/Ta and Zr/Hf ratios, it is evident that the upper crust cannot be a suitable end-member in any process that involves the mantle, the IUP carbonatites and kamafugites (fig. 6.4a-d). As a whole, the addition of upper crust rocks to the IUP source is not only insufficient to explain the HFSE distribution in the IUP rocks (figs. 6.3a-c and 6.4a-d), it is also unnecessary. In fact, most of the IUP HFSE distribution can be coherently explained simply by adding a Ca-carbonatite melt to the mantle. The IUP carbonatites and melilitites are perfectly in trend along with primitive mantle and average worldwide Ca-carbonatite (fig. 6.3c and fig. 6.4a-d). These have the LILE-HFSE distribution very similar to the IUP one, but with higher absolute elemental amounts, larger elemental fractionation and more evident Ti, Zr, Ta, Hf negative anomalies. So, a relatively small addition of carbonatite to the mantle could modify it in a way suitable to produce the IUP rocks.

Especially extrusive carbonatites frequently show a negative Eu anomaly in the chondrite-normalised REE spectra (Stoppa, 2003 and references therein). This is observed both in the Oldoinyo Lengai extrusive active carbonatitic volcano (eastern branch of the East African Rift) and in the Kerimasi extrusive carbonatitic volcano (Tanzania, western branch of the East African Rift) (fig. 6.5). The Eu anomaly is certainly also observed in subduction-related rocks, but in such a case it is associated with plagioclase crystal settling. It must be emphasized that in the IUP rocks, and in the carbonatites in general, there is no ground to involve plagioclase in the removal of Eu^{2+}. The depletion of Eu could result from preferential removal of Eu^{2+} by alkaline CO_2-rich fluids high in trace elements which escaped from the carbonatite added to the mantle source (Solovova *et al.*, 2005).

Extreme isotopic signatures ($^{87}Sr/^{86}Sr$ up to 0.7112) such as those observed in IUP rocks are typical of within-plate potassic rocks such as South Africa micaceous kimberlites and Western Australia lamproites (Stoppa *et al.*, 2003) and are an example of a radiogenic imprinting that reflects an enriched mantle source rather than a crustal contamination (Mitchell and Bergman, 1991; Rock, 1991). In fact, the kimberlites carry diamonds, demonstrating that their radiogenic signature has a deep mantle origin. Radiogenic fluids, rich in volatiles and LILE, may evolve in isolation at the asthenosphere-mesosphere or at the mantle-core boundary layers. Under adequate tectonic conditions, they may arise from the deep mantle reservoir and metasomatise the asthenosphere (O'Nions, 1987).

6.4. THE PLUME HYPOTHESIS

The IUP magmatism and volcanic style is very similar to that of the carbonatitic province of SW Uganda in the western branch of the East African Rift System (EARS) (Bailey and Collier, 2000). Notably, the EARS is an intra-continental rift-system possibly associated with a mantle plume (Simiyu and Keller, 1997; Nyblade *et al.*, 2000; Bell and Tilton, 2001). The IUP rocks are also very similar to the Cenozoic kamafugites and carbonatites from Western Qinling, Gansu province (China) (Yu *et al.,* 2003). The Chinese ultra-alkaline association is located in the NE boundary of the Tibetan Plateau and occurs within Cenozoic grabens bordered by lithospheric faults; it is possibly related to a mantle plume (Yu *et al.*, 2003).

Based on regional Pb, Sr and Nd isotopic data, Bell *et al.* (2004, 2006) associate the IUP and, more in general Italian magmatism and recent tectonics, with a mantle plume, as well. The plume would underlie the Tyrrhenian Sea and extend westward under Sardinia and Corsica, northward towards the Western Alps and eastward under the Italian mainland. The plume is isotopically defined in terms of three end-members: two of them are similar to FOZO (FOcus ZOne) and EM1 (Enriched Mantle 1) defined on the basis of data from OIBs (for review of these components see Hart *et al.*,1992; Hauri *et al.*,1994; Hofmann, 1997), while a third, ITEM (ITalian Enriched Mantle), is much more radiogenic with moderately high U/Pb and Th/Pb, very high Rb/Sr, and low Sm/Nd time-integrated ratios. The EM1- and FOZO-like signatures are usually associated with plume-related magmatism, ITEM has never been found in lavas from present-day subduction zones and the contribution from DMM (Depleted MORB Mantle) and HIMU (High time integrated U/Pb mantle) is minimal in most of the Italian lavas. Then, it is evident that the isotopic signature of the Italian rocks cannot be attributed to involvement of recycled and aged limestone and other upper crust carbonate-rich material. This means that it is not a crustal component, but a deep mantle, possibly plume-related, component. The CO_2-rich fluids or melts produced by a plume head are extremely mobile (*e.g.* Green and Wallace, 1988; Yaxley *et al.*, 1991), thus able to modify the overlying mantle. In particular, CO_2-rich fluids are considered to be capable of producing peculiar mantle cryptic metasomatism dominated by enrichment in LILE and Sr-LREE, not coupled with HFSE (Ti, Zr, Hf, Ta), the latter being elements depleted in the carbonatite melt (*e.g.*, Wendlandt and Harrison, 1979). This is exactly what we observe in the Italian HK and ultra-alkaline rocks.

The major trace and isotopic composition of the IUP and HKS products, coupled with the abundance of mantle-derived CO_2 in Tuscany (Chiodini *et al.*, 1999) and at Etna (about 10% of the global CO_2 discharged from worldwide volcanoes) and with the intense thinning of the Tyrrhenian lithosphere are considered by Bell *et al.* (2006) features consistent with plume activity. Given the absence in Italy of extensive volumes of flood basalts, the lack of evident domal uplifts and of deep thermal anomalies, Lavecchia and Creati (2006) suggest that the head of such a plume would not have reached a sufficiently high level to produce basaltic liquids. In their opinion, most of the Italian tectonic features (extensive stretching of the lithosphere, eastward tectonic and magmatic polarity, metasomatism of the magmatic mantle source) are consistent with an easterly growing plume head trapped within the transition zone (between the 670 km and 410 km discontinuities) and fed by a deep plume from the core-mantle boundary. The growth of the plume head within the transition zone creates a volume excess within the asthenosphere which leads to consequent stretching and thinning of the overlying lithosphere. Low viscosity CO_2- and H_2O-rich fluid would escape from the plume head upward and metasomatise the overlying asthenosphere. The escaping fluids would retain the geochemical and isotopic Sr-Nd-Pb signatures of *D″* core-mantle boundary layer, that is convectively isolated from the middle and the upper mantle (Bell and Tilton, 2002).

The plume model may help to explain the IUP occurrences, but a major problem that it encounters is the tomographic velocity patterns detected in the Mediterranean region. This shows a large-scale high-velocity anomaly placed in the transition zone at the bottom of the upper mantle, coupled with a large-scale low velocity anomaly in the overlying asthenosphere (Piromallo and Morelli, 2003). In order to reconcile the tomographic anomalies with the trapped plume model proposed by Lavecchia and Creati (2006), it is necessary to hypothesise that the velocity pattern may reflect chemical rather than thermal variations (Choi, 2005). Faster zones within the transition zone would represent a highly depleted and dehydrated plume head which has lost volatiles and fluids during upward migration. In turn, the overlying low-velocity zone might represent a plume-modified asthenosphere region metasomatised and enriched by low viscosity fluids and volatiles released by the plume head.

6.5. FINAL COMMENTS

Subduction-related rocks are different from the IUP carbonatites and kamafugites in terms of tectonic context, lithology and HFSE geochemistry. Even though most authors follow the cow path of a subduction tectonic assignation by HFSE fractionation, in this paper we have proven that in the case of carbonatites and associated alkaline rocks, including the IUP rocks, the HFSE distribution must have a different petrological significance. From a geochemical point of view, the subduction hypothesis is unnecessary and it is insufficient to explain the HFSE observed in the IUP rocks and in carbonatites elsewhere. Mantle metasomatism operated by carbonatitic fluid/melt is the only readable process able to explain the compositional characteristic of the IUP magma source. The carbonatite fluid cannot have been released by a subducted lithospheric slab, as the carbonate sedimentary cover and the upper crust do not match the requested composition to change the mantle composition towards the IUP isotopic and chemical signature. Extreme isotopic signatures such as those observed in the IUP ($^{87}Sr/^{86}Sr$ up to 0.7112) were never recognised in subduction related rocks, but only in within-plate potassic rocks and associated carbonatites. In Italy, Uganda and Central China, carbonatites and kamafugites form a very homogeneous, specific and peculiar rock association (Stoppa *et al.*, 2003), whose common geodynamic setting is extensional, intra-continental, independent from subduction and possibly plume-related.

The Italian carbonatite findings met widespread acceptance from the international carbonatitological community, but in Italy they are still resisted. This is because ideas on carbonatites genesis conflict with the dogma of subduction. Of course in other ultra-alkaline localities, like Uganda and China, subduction is impossible, so other hypotheses are essential. The carbonatitic-melilititic rock-types in Italy do indeed present a challenge to understanding the geodynamic context of the Tyrrhenian-Apennine system of Italy. Is this context plume related, as suggested by Bell *et al.* (2004, 2006)? This is certainly a question that is worth exploring, but above all it is fundamental to open a debate and to explore alternative solutions to the subduction model. In fact, after more than 30 years since its first application to Italy and in spite of hundreds of papers, the subduction model, with all its incredible variants, is evidently inadequate to explain the complexity of the Italian geology.

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