CO_2 as the propellant of carbonatite-kamafugite cognate pairs and the eruption of diatremic tuffisite

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ABSTRACT. — Tuffisite pipes are characteristic of ultramafic rocks among which the rare association of kamafugite and carbonatite is prominent. Four main areas are known at present where this association is found: Katwe-Kikorongo and Bunyaruguru in Uganda, IUP localities in Central Italy, Mata da Corda in Brazil and Qinling in Gansu, China. In all areas dominant volcanic forms are pipes (diatremes) with maar-tuff rings. Tuffisite lapilli-bearing breccia fills the diatremes and tuffisite lapilli tuff surges form pyroclastic aprons around the vents. Tuffisite lapilli are so named to reflect their specific structure, which has probably been generated during a deep magmatic tuffisitisation. Mantle xenoliths are typical of these rocks and the only realistic agent of acceleration to the surface is a deep-seated concentration of volatiles with a high proportion of CO_2. The genesis of the kamafugite-carbonatite association can be assessed both in terms of field occurrence and geochemistry. In three cases out of the four the kamafugite-carbonatite association occurs in intracratonic grabens, only Italy being controversial. Specific magma composition is germane to a specific magma propagation mechanism producing a distinctive style of intrusive and extrusive pyroclastics that argues cogently for a fundamentally similar tectonic environment.

RIASSUNTO. — La formazione di condotti riempiti da tuffisite sono una caratteristica del magmatismo ultrafemico la cui espressione superficiale è rappresentata dalla rara associazione di rocce carbonatitiche e kamafugitiche. Ci sono quattro regioni al mondo conosciute per la presenza di kamafugite: il Katwe-Kikorongo e il Bunyaruguru in Uganda, la Provincia Ultralcalina Intramontana (IUP) in Italia centrale, Mata da Corda in Brasile e Qinling, nella Provincia di Gansu, Repubblica Popolare Cinese. In tutte queste zone la morfologia vulcanica dominante è l'associazione di anelli di tufo, maar e diatremi. Tuffisiti a lapilli riempiono i condotti e formano coltri piroclastiche, messe in posto da ondate piroclastiche, attorno ai crateri. I lapilli nelle tuffisiti hanno una struttura loro specifica che si pensa generata da processi profondi di frammentazione magmatica e, considerata la unicità di tali piroclastiti, suggeriamo di chiamarli *lapilli tuffisitici* per distinguerli geneticamente da tutti gli altri lapilli. La presenza di xenoliti mantellici è anche tipica di queste rocce per le quali il solo mezzo realistico di propulsione verso la superfice è la CO_2. La genesi dell'associazione kamafugitico-carbonatitica può essere definita sia in base alle sue carattersitiche geologiche che geochimiche. In tre casi su quattro questa associazione è indubitabilmente collocata in graben continentali mentre solo per l'Italia la collocazione tettonica è controversa. Tuttavia, una così specifica composizione magmatica deriva da specifiche condizioni genetiche e di messa in posto da cui deriva uno stile eruttivo unico ed inconfondibile, un assieme di evidenze che possono solo convergere verso un'ipotesi di assegnazione tettonica univoca.

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KEY WORDS: *diatreme-maar, tuffisitic lapilli, kamafugite-carbonatite provinces, CO_2, intracratonic setting.*

Introduction

The eruption as tuffisite of Ca-carbonatite cognate with kamafugitic products (most commonly olivine melilitite) appears to be a natural rule, which demands radically different physical and chemical conditions with respect to those of most other rock types. Conditions that result in high velocity propagation of magma rich in juvenile volatiles, which translates to maar-pipe formation (diatreme), base surge deposits and ejection of mantle nodules. Magma ascent needs to be 10-30 m/sec, to prevent mantle xenoliths settling. The only realistic agent of acceleration is deep-seated concentration of volatiles in a fluidised system with a high proportion of carbon dioxide (Lloyd and Stoppa, 2003). Ca-carbonatite and kamafugite tuffisite deposits are a hallmark of intracratonic extensional tectonics that result in graben formation. There is a kindred relationship between these rift associated magmas and «more» cratonic occurrences such as kimberlites and lamproites. The term tuffisite was originally coined to describe a sub-volcanic tuff whose physical components range from large blocks to ash with mantle-crust wall-rock xenoliths and peculiar lapilli of olivine melilitite (Cloos, 1941). Tuffisite lapilli are discrete, very smooth, spherical-elliptical lapilli of primary magmatic material that is often accreted onto high-pressure nuclei in a fluidised gas-liquid-solid stream. Fragmentation is a deep-seated process (Bailey 1990) but accretion can take place at any level en-route to the surface, lapilli as shown by cores of crustal xenoliths and lower-pressure phenocrysts. Tuffisite lapilli can also occur extrusively in maar deposits (Stoppa, 1996; Stoppa and Principe 1998). The level of initiation of magma fragmentation is subcrustal based on high-pressure mineral fragments that core the lapilli (Lloyd and Stoppa, in press). Tuffisitic lapilli are important because they represent the interface between the erupting magma and the volatile component.

The term kamafugite describes a distinctive extrusive rock association of K-rich olivine melilitite with kalsilite+/-leucite+/-K-nephehline in the groundmass (katungite), kalsilite+olivine+clinopyroxene (mafurite) and leucite/kalsilite+olivine+clinopyroxene (ugandite) (Holmes 1950, Tappe *et al.* this volume). Essentially the kamafugite association is ultramafic because rocks are dominated by cafemic minerals melilite and clinopyroxene, while leucite is replaced by kalsilite only in the most silica undersaturated compositions. Mitchell (1977) has observed that tuffisite lapilli occur in specific ultramafic volcanism such as carbonatite, melilitite, lamproite and kimberlite, and kamafugite should be added to this list.

In this paper we focus on the kamafugite-carbonatite-tuffisite association and what it implies for mantle source composition, conditions of partial melting and subsequent evolution. The crystal fractionation-assimilation modelling used in respect to other rocks, such as basaltic types, cannot be used to model this association.

Distribution and lithology of kamafugite-carbonatite association

There are few examples of eruptive carbonatite-kamafugite association; they have been recorded from the Cretaceous (Brazil), Tertiary (China), Pleistocene (Italy) and Recent (Africa). All occurrences are small volume extrusives and form labile volcanic structures in high-rate sedimentation environments such as grabens. It is presumed that older occurrences may exist elsewhere. Tuffisites, mantle-derived debris and maar-diatremes are reported from all the above occurrences. The Brazilian volcanics are quite strongly affected by supergene weathering; the younger occurrences of Italy, Africa and China are better preserved.

Italy

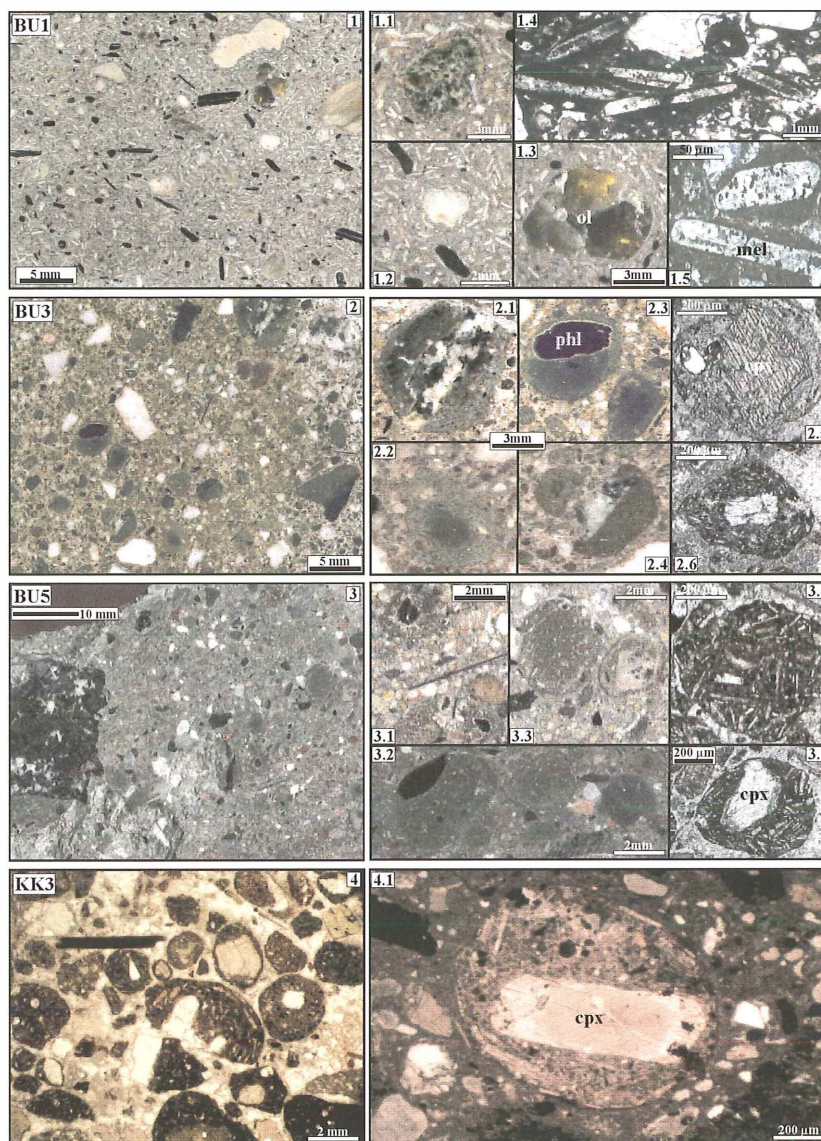The carbonatite-kamafugite association of Italy is found in a widespread maar-diatreme

Fig. 1 – Plate of photographs of tuffisites and tuffisite lapilli from Uganda. 1) BU1 - Melilitite bomb from Bunyampaka (Kasenyi): faintly agglutinated concentric lapilli. 1.1) Granular ultramafic kernel in a lapillus. 1.2) Detail of concentrically arranged melilite around a quartzite kernel. 1.3) Polycrystalline olivine coated with melilitite lava shells. 1.4) Melilite laths surrounded by melilitite glassy matrix. 1.5) Melilite (mel), showing peg structure, mantled by glassy matrix. 2) BU3 - Tuffisite from Kichwamba (Bunyaruguru): general texture. 2.1) ijolitic nodule coring a lapillus. 2.2) Cored concentric lapillus. 2.3) Lapillus with phlogopite crystal cleavage fragment. 2.4) Cored lapilli: upper left with a clinopyroxene core; bottom right broken lapillus with a felsic kernel. 2.5) Microphyric lapillus with clinopyroxene kernel. 2.6) Porphyritic lapillus with clinopyroxene kernel. 3) BU5 –Welded lapilli tuff from Rubirizi (Bunyaruguru): general texture. 3.1) Lapillus containing a core with a reaction corona. 3.2) and 3.3) Various composite lapilli associated with concentric shelled lapilli. 3.4) and 3.5) Porphyritic melilitite lapilli with and without a kernel. 4) KK3 – Carbonatitic tuff from Murumuli (Katwe Kikorongo): general texture. 4.1) cored lapillus with concentric arrangements of melilite laths.
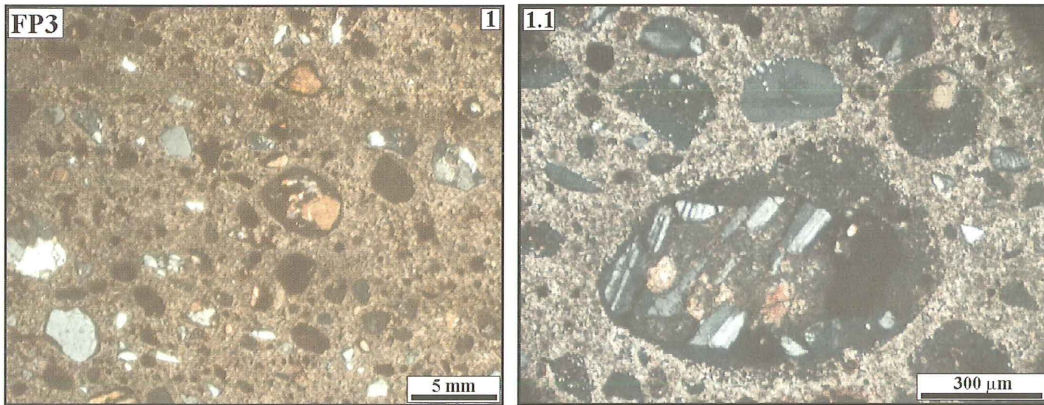
Fig. 2 – Fort Portal (Uganda) carbonatite tuff blanket 1) – General view showing crustal or mafic kernels coated by melilitite glass. 1.1) – Spherical and drop-like melilititic, ash-sized achneliths cored by crustal kernel and mafic fragments.

(12 incidences) province extending for a length of about 350 km along Pleistocene tectonic depressions within the Apennines area (Lavecchia and Stoppa, 1996). Kamafugite, carbonatitic kamafugite and carbonatite associations occur at San Venanzo, Cupaello, Polino, Grotta del Cervo, Oricola (Stoppa and Woolley, 1997; Barbieri *et al.*, 2000; Stoppa *et al.*, 2002). Venanzite and Coppaelite are kamafugite holotypes (see Sahama 1974), katungite and mafurite respectively. Grotta del Cervo rock is a melilite-free kamafugite similar to the «coppaelite». Polino and Oricola are Ca-carbonatite. Melilitolic rocks occur at San Venanzo and Colle Fabbri (see this volume).

Tuffisite with concentric lapilli occurs at S.Venanzo, Polino and Grotta del Cervo. These rocks show an ultramafic assemblage of kalsilite, diopside, phlogopite, ± melilite, ± Ti-garnet and olivine characterised by high Mg, Ni (up to 0.52 wt% NiO) and Cr (up to 0.19 wt% Cr_2O_3) contents. LREE-apatite, perovskite, Zr-garnet and Ti-magnetite are commonly accessory minerals together with leucite and hauyne. The kamafugites have peralkaline character (K+Na/Al up to 1.25) and very high K_2O/Na_2O ratio (c. 20). Carbonatitic kamafugitic tuffs are widespread. Carbonatites *sensu stricto*, but co-eruptive with kamafugites, occur at Cupaello and Oricola. In addition, a Ca-carbonatite occurs in isolation at Polino

having essential calcite and accessory Zr-schorlomite and Th-perovskite plus small mantle xenoliths composed of Cr-phlogopite, forsterite and chromite, which form at least 20% of the rock.

At Vulture volcano, about 200 km south of the above outcrops, the Monticchio Lakes Formation (MLF) is a small volume of ol-melilitite and Ca-carbonatite spread over a wide area by violent, maar forming eruptions (Stoppa and Principe, 1998). Vulture tuffisitic lapilli have a carbonatitic melilitite coating, which describes an ellipse and is evidence of rapid rotation in the gas stream. Embayments, which have been preserved by «deposition» of the outer shell of calciocarbonatite (Fig. 3), point to abrasion by a particle-loaded gas stream. In some cases the inner shells are discontinuous and appear to consist of several stages of accretion (Fig. 3) that remain more or less discrete. A supercooled state can explain the ability of the melt to adhere to the kernel. A consistent change in magma composition from inner to outer shells, i.e. calciocarbonatite is always the final coating, implies lapilli development concomitant with separation of silicic and carbonatitic fractions, over vertical distance and time.

There are mantle xenoliths of lherzolite, wehrlite, harzburgite and dunite, up to 11 cm across and 1kg. Geothermobarometric analysis
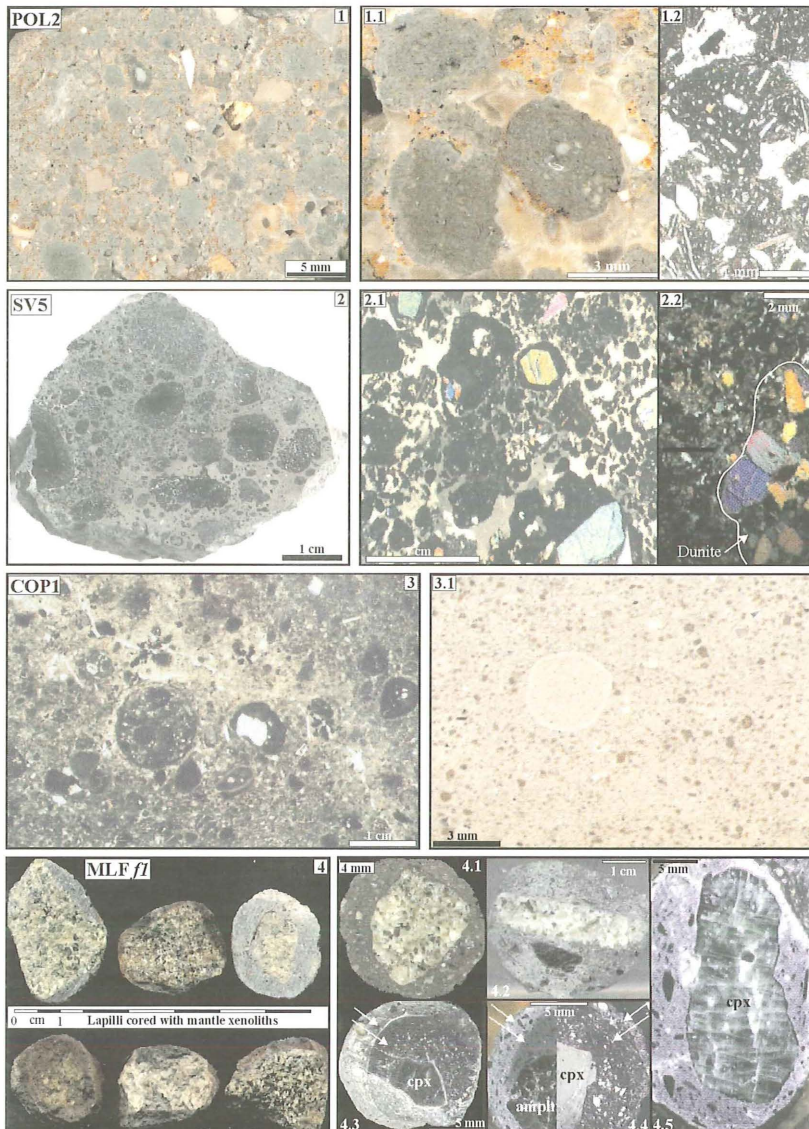
Fig. 3 – Plate of photographs of tuffisites and tuffisite lapilli from Italy. 1) POL1 – Ca-carbonatite tuffisite from Polino (Umbria): tuffisite lapilli and angular fresh lithics from the country limestones. 1.1) lapilli with concentric structures outlined by dark phlogopite laths. 1.2) Agglutinated porphyritic carbonatite lapilli in carbonate matrix. 2) SV5 – Carbonatitic kamafugite tuffisite from San Venanzo (Umbria): kamafugite lapilli in a carbonatite matrix. 2.1) Olivine cored lapilli. 2.2) Dunite nodule in the lapilli tuff. 3) COP1 – Carbonatite tuff from Cupaello (Lazio). 3.1) Carbonatite lapillus cored by cpx with concentric calcite laths set in a carbonatite matrix made of small carbonatite droplets and crystal fragments. 4) MLF f1 – Uncoated, 'polished' ultramafic nodules and nodules coring lapilli from the Monticchio Lakes Formation of Vulture (Basilicata). 4.1 and 4.2) Lherzolite fragments coring melilitite lapilli. Note that a spherical shape of the lapillus is obtained independently from the kernel shape, indicating accretion rather than a simple coating. 4.3 and 4.4) Lapilli cored by high pressure Cr-clinopyroxene or hastingsite-amphibole with double coating layers; internally of melilitite and externally of carbonatite composition (*with arrows*). Note irregular shells and asymmetric kernel indicating further accretion after erosion of inner layers.

of Vulture group 1 xenoliths indicates final equilibration in the lithospheric mantle at about 14-22 kbar and 1050-1150°C (Jones *et al.* 2000). These larger xenoliths are typically without a magma jacket. The lack of magma coating suggests that only the smaller particles (microxenoliths) are coatable. While this may be related to mechanics of fluid transport and magma accretion, the fact that in basanite maars xenoliths are commonly jacketed (e.g., Dreis and Meerfeld in the West Eifel, Germany) implies that there is less melt available in these kamafugite-carbonatite eruptions and that transport is effected by gas.

Uganda

In the west branch of the East African rift the kamafugite fields of Katwe-Kikorongo and Bunyaruguru are dominated by around 230 pyroclastic rings (Tinkler, pers. comm. 1969; Reece 1953) containing small bombs and tuffisite lapilli of K-rich olivine melilitite (katungite). Clinopyroxene-rich mafurite-ugandite types occur either as lithics in tuffs or as small flows (0.07 km³ in total, Combe 1939).

Phlogopite clinopyroxenite microxenoliths or large mica plates that are probably of mantle origin frequently core the olivine melilitite tuffisite lapilli (Lloyd *et al.*, 2002). Crustal debris and phenocrysts of melilite and olivine are also quite common lapilli cores (Lloyd and Stoppa, 2003). Tuffisites contain mantle xenoliths of phlogopite clinopyroxenite, phlogopite wehrlite and phlogopite dunite that typically lack magma coatings (Lloyd *et al.,* 1999 and references therein).

The presence of carbonate liquid is testified by carbonatite bomb and lapilli in surge deposits of Murumuli , Katwe Kikorongo (Stoppa *et al.,* 2000). Tuffisites contain a maximum of ca. 30 wt.% $CaCO_3$ mostly as fine grained matrix (Fig. 4, CaO vs CO_2). Primary carbonate, either as calcite - magnesian calcite or dolomite, contains notable Sr (up to 1.6 wt.% SrO). Within the matrix of tuffisitic lapilli some ameboidal calcite segregations contain up to 1.3 wt.% BaO. Lapilli of Mg-

calcite (max. 5.3 wt.% MgO) and fine-grained clasts of monocrystalline Mg-Sr calcite occur rarely. Occasional microphenocryst tabular plates of Sr-Mg calcite are found inside melilitite lapilli. (microprobe analyses, Lloyd *et al.* unpublished).

The Fort Portal Ca-carbonatite north (75 km) of the kamafugite fields is dominated by carbonatite lapilli-ash cones and blanket surge deposits. Until now silicate magmatism has been considered entirely absent and the link with kamafugite magmatism has been dependent upon the proximity to Katwe-Kikorongo and Bunyaruguru. A new collection of Fort Portal rocks (fieldwork by N. Eby, F.E. Lloyd, F. Stoppa and A.R. Woolley, 1997) has revealed carbonate ash matrix supporting silicate droplets and tuffisite lapilli in the blanket surge. These lapilli show features very similar to the olivine melilitite lapilli found in the kamafugite diatremes (F.E. Lloyd, F. Stoppa, D.K. Bailey and A.R. Woolley in preparation) (Fig. 2).

The Ca-rich nature of Ugandan kamafugites is reflected in high modal proportions of either melilite (~20 modal%, Ak78, Na-melilite 21.5) or diopside (~28-60 modal%; Ca# = 100xCa/Ca+Mg, between 53 and 56) (Lloyd *et al.,* 1991). All rocks contain accessory perovskite and titanomagnetite. Aluminous Ti and Ba-rich phlogopite (7-8 wt.% TiO_2, 5-6 wt.% BaO) is an occasional phenocryst and peralkaline phlogopite a common trace-accessory late groundmass mineral along with trace apatite, calcite and very rarely richterite.

Bulk rock chemical compositions are low in silica (SiO_2 ranging between 35 and 45 wt.%) and alumina (Al_2O_3 6-11 wt.%) and high in Ti, Ca and K and range from slightly peraluminous to peralkaline (Lloyd 1985). They are enriched in LREE and LILE and show elevated Nb/Zr ratios (ca. 0.7 for katungite) together with moderate-high Cr and Ni in olivine-rich rocks.

China

Cenozoic (largely Miocene) kamafugites associated with extrusive carbonatite in West Quinling, Gansu Province, Peoples Republic of
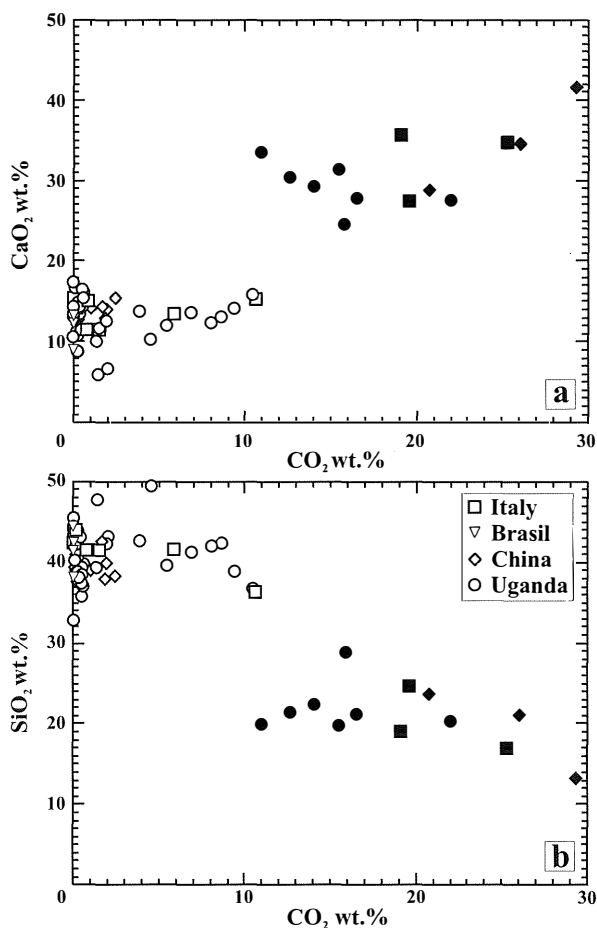
Fig. 4 – Compositional variation diagram for kamafugite (open symbols) and carbonatites (solid symbols): a) CO_2 vs CaO; b) CO_2 vs SiO_2. A broad correlation is apparent. Kamafugites contain typically about 14-15 CaO wt% as silicate. A 'flat' CO_2-SiO_2 distribution in Uganda carbonatite could be explained by a decrease in other non-silicates (Ti-mag, perovskite) as carbonate increases.

China have been described by Yu *et al.* (2001a; 2003). Overlapping initial Sr and Nd isotopic data support a paragenetic relationship between the kamafugite and carbonatite in this continental setting (ibid). Volcanic products include xenoliths of lherzolite and websterite as well as wehrlite and clinopyroxenite. Garnet lherzolite gave the highest P/T condition being equilibrated at T between 1127 and 1266°C and P between 29 and 36 kbar. Tuff rings, lava flows and dykes occur in this area. In addition, pyroclastic kamafugite occuring in 13 volcanic pipes is described as «spherulitic agglomerates with spherulite lapilli» and resembles tuffisites with tuffisite lapilli. These lapilli contain xenocrysts of mantle olivine showing strain lamellae.

Kalsilite, leucite and K-rich nepheline reflect the sodi-potassic character. Melilite is akermanite-Na-melilite typical for rocks of the

kamafugite group. The majority of olivine is forsterite 83-91. Phlogopite is aluminous (10.2-11.4 wt.% Al_2O_3) and Ti-rich (8.5-15.2 wt.% TiO_2). Accessory perovskite, Ti-magnetite, phlogopite and K-richterite are all characteristic of kamafugites. Low magnesium calcite (<1% wt.% MgO, 0.25 wt.% FeO^t) occurs in the ground mass and in general is as low as 1wt.% but some analyses report up to 10 wt.%. There are also carbonate ocelli.

Chemical compositions (Table 1) are typical of kamafugites: silica 38-40 wt.% and Al_2O_3<10 wt.%, with enhanced Ti, Ca and P. Total alkalis (K_2O+Na_2O) reach 6.5 wt.%.

Incompatible elements and especially LILE (K, Rb, Th) are particularly high but some HFSE (Nb, Ta, Hf) are relatively low. Concentrations of Sr, Ba and Zr are high, up to 1491, 1700 and 421 ppm, respectively, in addition to high contents of compatible elements Ni (up to 469 ppm) and Cr (up to 462 ppm). The LREE reach 569 ppm and LREE/HREE ratios are up to 9.4. A Eu negative anomaly is apparent in some samples. Associated carbonatites show similar trace and rare earth element patterns to the kamafugites (Yu *et al.*, 2001b). They are calciocarbonatites relatively rich in SiO_2 ranging from 13.4-23.6 wt.%. Carbonate component ranges from 47.8 to 67.6 wt.%.

Brazil

Kamafugites of Cretaceous age occur in Mata da Corda and Santo Antonio da Barra areas, Minas Goias and form interbedded lavas, tuffs, and epiclastic deposits (Brod *et al.*, 2000). In most cases pyroclastics have been intensely altered making it difficult to identify its exact nature (Sgarbi *et al.*, 2001). Some pipe sections contain tuffisite lapilli, e.g. Serra do Bueno, but the original mineralogy is largely unidentifiable. The mineralogy has been reported from the lavas, which are better preserved (Sgarbi *et al.*, 2000). Olivines have Mg# (=Mg/Mg+Fe^{2+}) from 0.83 to 0.91, clinopyroxene is mainly diopside, phlogopite is aluminous (9-13 wt.% Al_2O_3) and Ti-rich (3-8 wt.% TiO_2) similar to typical phlogopite phenocrysts from Ugandan kamafugites (Lloyd

et al., 2002) but richer in BaO (average 2.5 wt.% from Mata da Corda and 7 wt.% from San Antonio da Barra). The main feldspathoids are kalsilite and leucite. Perovskite and Ti-magnetite are ubiquitous. The fresher lavas have the composition of typical kamafugites except that they are low in alkalis, which is probably a consequence of deuteric alteration. No extrusive carbonatite has been reported from this region. It may be that carbonatite is absent here, or yet to be discovered, or it might be present but highly altered.

DISCUSSION

In the best-known kamafugite-carbonatite localities, those of Italy and Uganda, the close association of kamafugite and carbonatite is inescapable. The new discoveries of kamafugite-carbonatite in China lend weight to the significance of this association. Physically the silicate and carbonate fractions are intimately mixed in tuffisite in addition to occurring discretely (Tables 1 and 2), which translates to a range of values in the CO_2 versus SiO_2 plot (Fig. 4b). Similar suites of mantle xenoliths, another distinctive feature, are found in both fractions pointing to derivation from a single mantle source. Chemically the silicate and carbonate fractions share and exhibit the major and trace element signature peculiar to each locality (Fig. 5a and b, Fig. 6a-c). Some features are common and concern Zr, Nb, (Ta, Hf), and Yb negative anomalies, which are typical of extrusive carbonatites in general. A spectacular example of isochemical relationship exists in Italy among kamafugites and carbonatites (Fig. 6d). In most cases carbonatites and associated kamafugites show parallel patterns. Uganda has higher REE in carbonatites, China in Kamafugites (Fig. 6a-d). Italy displays a cross over relationship with LREE/HREE higher in carbonatites, which is the expected cross over produced by higher Kd for LREE in carbonatite with respect to the comagmatic conjugate kamafugite (Fig. 7c). The Uganda kamafugites

TABLE 1

Comparative features of kamafugite localities.

Locality	Tectonic setting	Rock type	Lapilli cores	Agpaitic index	Mg #	Nb/Zr	La/Yb	Sr^{87}/Sr^{86}; ^{143}Nd/^{144}Nd
Umbria	Pliocene continental graben	Olivine leucite melilitite, Kalsilite melilitite	Phlogopite peridotite and clinopyroxenite	1.25	87-92	0.041	34	0.7105, 0.5120 0.7111, 0.5120
Abruzzo	Pleistocene continental graben	Kalsilite melafoidite	Phlogopite clinopyroxenite	0.77	88	0.06	39.2	0.7108, 0.5120
Vulture	Strike-slip regional fault	Olivine melilitite	Lherzolite, wehrlite, spinel lherzolite, spinel wehrlite	0.39	85	0.30	69	0.7056, 0.5126
Katwe-Kikorongo	Cenozoic continental rift	Olivine melilitite' Kalsilite Melafoidite, Nepheline leucitite	Phlogopite dunite, Phlogopite clinopyroxenite, Melilite Crustal debris	1.03	75	0.52	104.8	0.7047, 0.5126
Bunyaruguru	Cenozoic continental rift	Olivine melilitite, kalsilite+olivine+ clinopyroxene, leucite+olivine+ clinopyroxene	Phlogopite dunite, Phlogopite clinopyroxenite, Melilite Crustal debris	1.25	82	0.71	155.8	NA
Qinling	Cenozoic continental rift	Olivine melilitite, kalsilite+olivine+ clinopyroxene, leucite+olivine+ clinopyroxene	Peridotite debris	0.67	81	0.29	42	0.7044, 0.5128
Mata da Corda	Mesozoic intraplate incipient aulacogen	kalsilite+olivine+ clinopyroxene, olivine+leucite+ clinopyroxene	Not documented	0.47, 1.00	73, 62	0.53, 0.35	125.3	
San Antonio da Barra	Mesozoic intraplate incipient aulacogen	kalsilite+olivine+ clinopyroxene, olivine+leucite+ clinopyroxene	Not documented	0.78, 0.77	83, 72	0.53, 0.31	158,	208

TABLE 2

Comparative features of the Ca-carbonatites associated with kamafugites

Locality	Occurrence	Xenoliths Xenocrysts	Mg no.	Nb/Zr	La/Yb	Sr^{87}/Sr^{86}; $^{143}Nd/^{144}Nd$
Umbria	Tuffisitie lapilli and matrix, tuffs, and tuff matrix	Phlogopite peridotite	92	0.044	65	0.7104, 0.5121
Abruzzo	Ash tuff, lapilli, tuff matrix.	Cr-phlogopite, Cr-diospide, olivine	61-84	0.16	105	0.7108, 0.5121
Vulture	Ash tuff, tuff matrix, soevite ejecta.	Spinel lherzolite, Spinel wehrlite		0.22*	269*	0.7060*, 0.5126*
Katwe-Kikorongo	Ash matrix in tuffisite, Rare bomb, lapilli	Phlogopite dunite-wehrlite, Phlogopite clinopyroxenite, Alkaline syenite	86**	0.53**		
Bunyaruguru	Ash matrix in tuffisite	Phlogopite dunite-wehrlite, Phlogopite clinopyroxenite,	86**	0.60**		
Fort Portal	Droplet and tuffisite lapilli,blanket surge deposit	Microxenoliths of phlogopite dunite-wehrlite, phlogopite clinopyroxenite, garnet granulite	85	0.85		0.7042, 0.5126
Qinling		Garnet lherzolite, Garnet websterite	95	0.31	55	
Mata da Corda	?Ash matrix in tuffisite and/surge deposits	Pyrope, Olivine, Phlogopite, Alkaline lithics				
Santo Antonio da Barra	?Ash matrix in tuffisite and/surge deposits	Pyrope, Olivine, Phlogopite, Alkaline lithics				

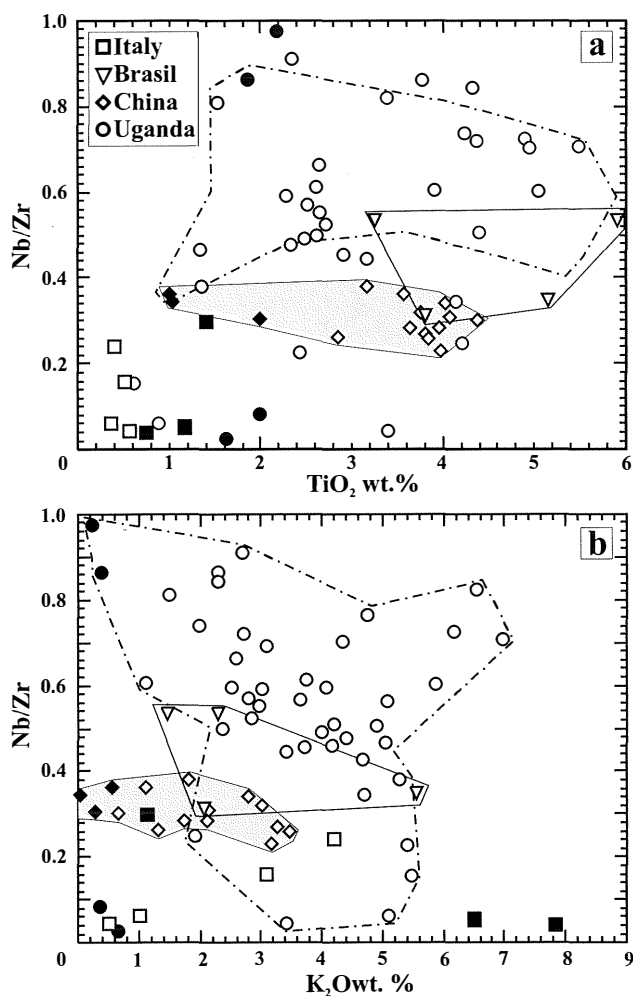*in sövite ejecta, ** in carbonatitic tuffs

Fig. 5 – Compositional variation diagram for kamafugite and carbonatites: a) TiO$_2$ vs Nb/Zr; b) K$_2$O vs Nb/Zr.

are richer in TiO$_2$ and have high Nb/Zr ratio. Associated carbonatites maintain high Nb/Zr but Nb and Zr extend to markedly lower levels (strong negative anomalies) compared with Italy where both kamafugites and carbonatites are richer in Zr and LILE. (Figs. 5, 6). At Qinling, kamafugites and carbonatites are also closely similar, each showing the same contrasts and similarities in comparison to Italy and Uganda, with TiO$_2$ and Nb/Zr,

intermediate to Italy and Uganda (Fig. 5a), and the same lower, Ugandan, levels of Zr and with Th levels the lowest of all the localities (Tables 1 and 2 and Fig. 6a-c). Qinling carbonatites have the lowest K$_2$O contents and the associated kamafugites are generally lower in K$_2$O also. In Italy and Uganda the Sr-Nd isotope systematics for the silicate rocks show near-identical signatures to their coexisting carbonatites (Tables 1 and 2 and Fig. 6a-c). At
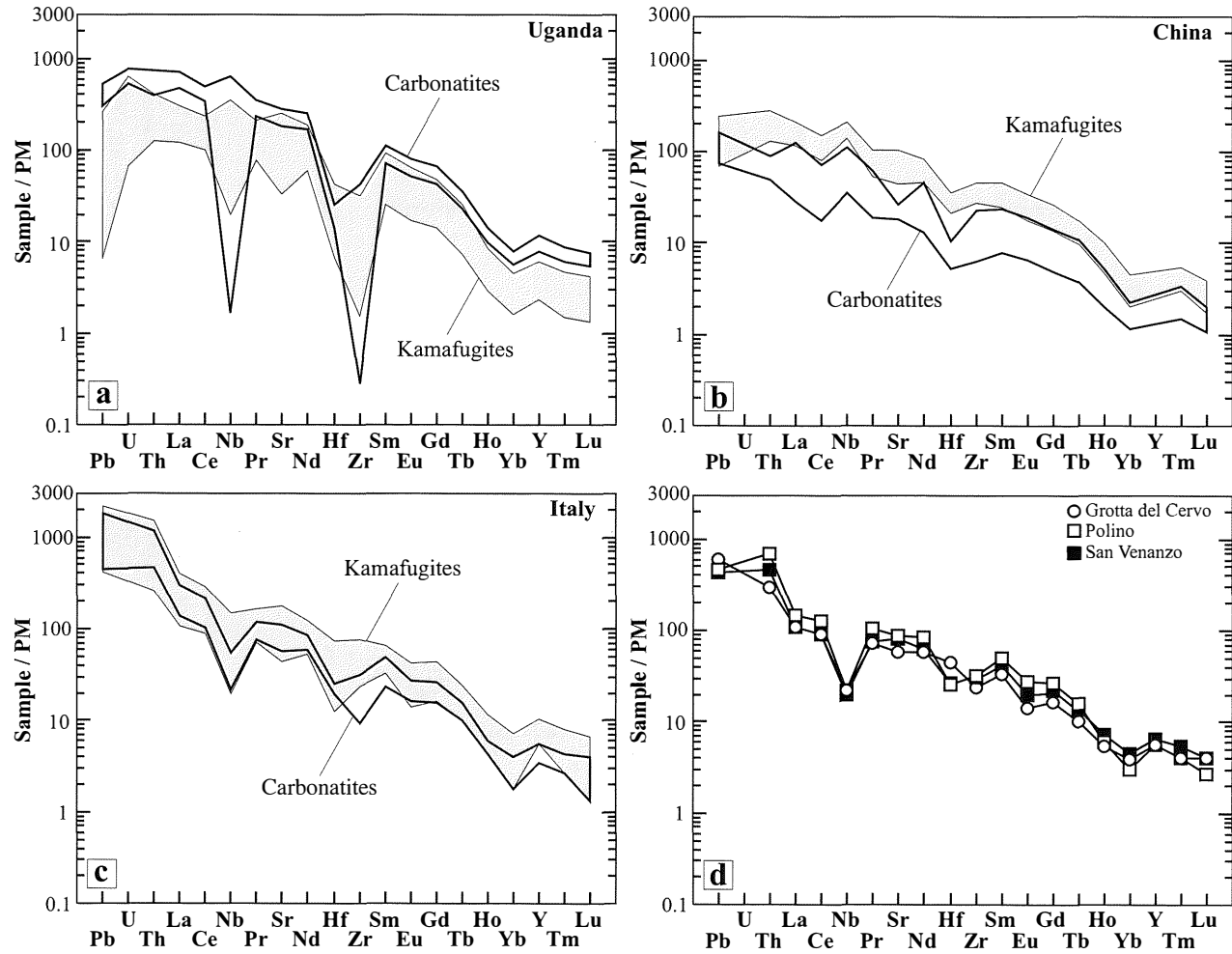
Fig. 6 – Trace element spider diagrams of kamafugites and carbonatites: a) Uganda, b) China; c) Italy. d) Comparison between italian kamafugites. Trace elements normalised for the Primitive Mantle values of Sun and McDonough, 1989.
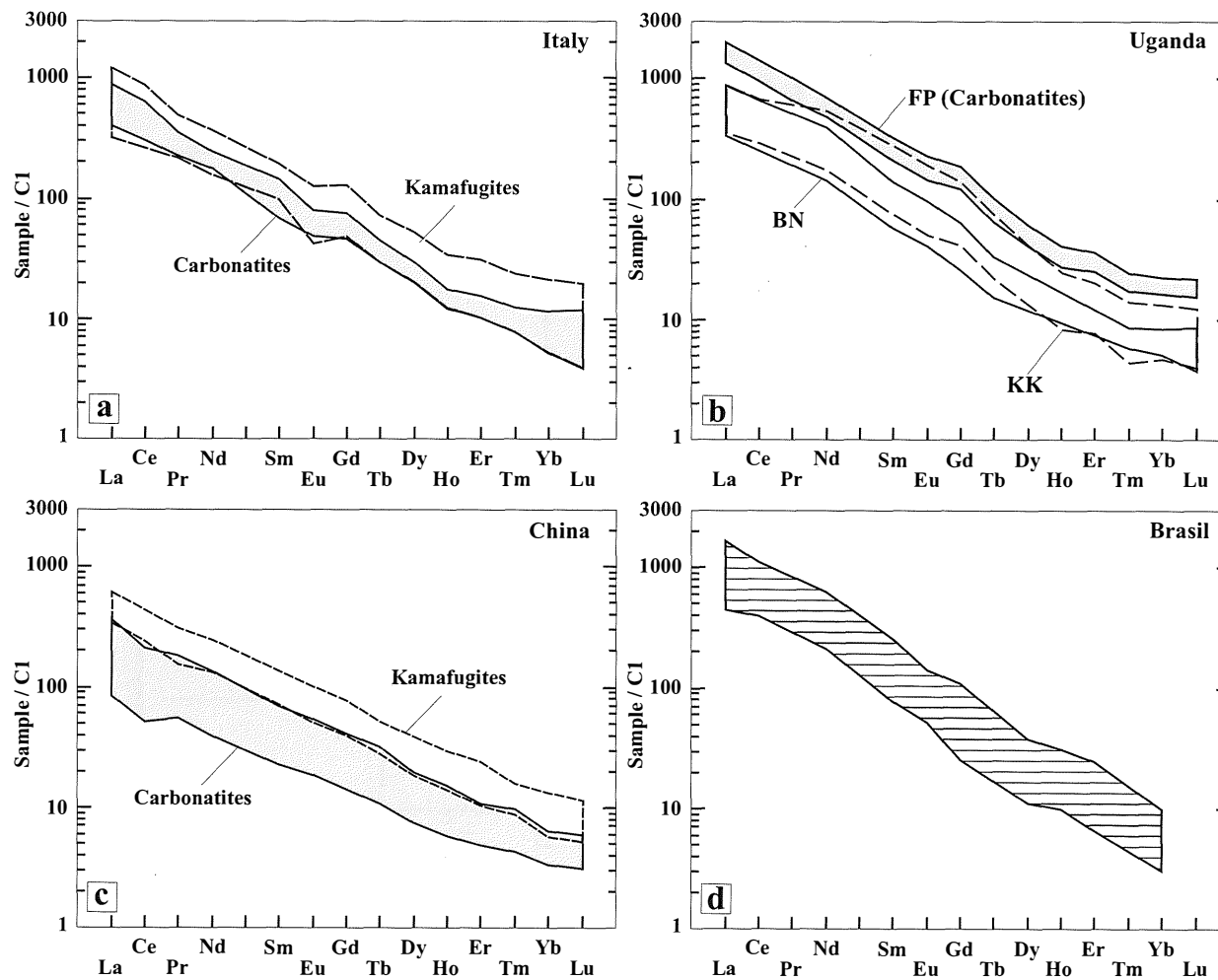
Fig. 7 – REE diagrams of kamafugites and carbonatites from: a) Uganda; b) Brasil; c) China; d) Italy. RE elements normalised for C1 Chondrite values of Sun and McDonough, 1989.

Qinling Sr-Nd isotope information is not available for carbonatites but the kamafugites plot intermediate to Italy and Uganda (Fig. 8) consistent with their general position in trace element diagrams.

The evidence is very clear that at each of the three localities kamafugites and carbonatites share the same genetic material peculiar to the mantle source for that locality. Moreover the same volcanic style, manifested as mantle xenolith-bearing tuffisite in all four localities (that is Brazil included), indicates a high-velocity explosive eruption mechanism resulting in magma fragmentation.

This consistency of geochemical patterns and volcanic style has to rule out the proposal, suggested by some authors in this volume, that the Italian ULUD, uniquely, is a consequence of subduction.

Such a conclusion has important implications for the mantle melts giving rise to kamafugite-carbonatite cognate pairs. It appears that the kamafugite and carbonatite components had to originate as a unified carbonate-rich ultramafic silicate magma. Bailey (1980) demonstrated

that kimberlite is a near-solidus liquid that erupts by accelerating crack propagation. With geothermal gradients progressively steeper than cratonic, a spectrum of super-solidus carbonatite – alkaline (including kamafugite) melts would be produced (ibid). This provides the possibility for partial melting to give rise to a range of silicate melts with varying proportions of carbonate according to the local geotherm. These melts can rise by exsolution stoping until they reach a critical condition that triggers high-velocity eruption (Bailey 1980).

In all cases, mantle carbonate of metasomatic origin (Lloyd and Bailey, 1975) will be consumed (Bailey 1985). Initial percolating melts will be CO_2 rich and those that follow an adiabat will exsolve gas and pass through Olafsson and Eggler's (1983) carbonate-out boundary, leading to massive CO_2 exsolution (Bailey, 1985). Loss of CO_2 from the melt will lead to a more CaO rich silicate fraction in keeping with observed Ca-enrichment of kamafugite compositions and crystallisation of melilite. The proportion of dissolved carbonatite will be correspondingly reduced,
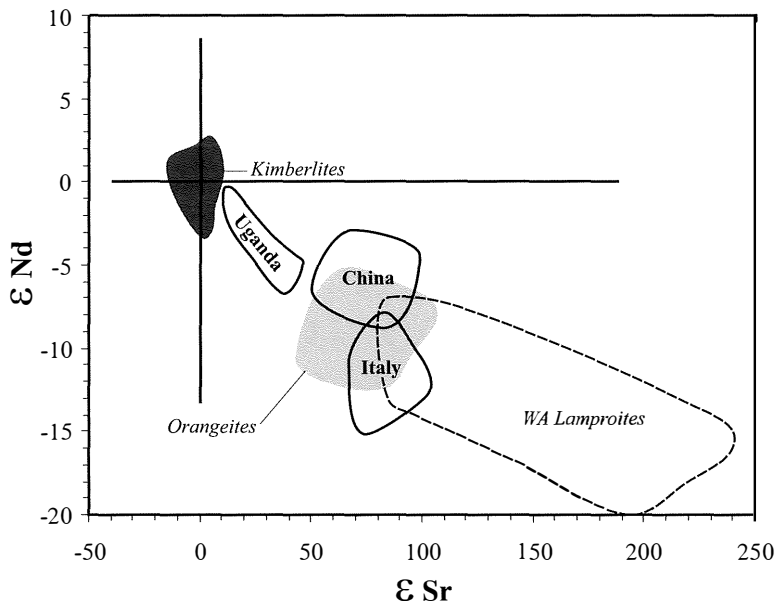

Fig. 8 – εSr vs εNd of the kamafugite and carbonatite association of China, Uganda, Italy.

but the eruption of carbonatite at the surface testifies to incomplete dissolution of carbonate when passing through the carbonate-out boundary. This is a natural result of the propulsion produced by CO_2 exsolution, which does not allow time for complete consumption of the carbonate. In conjunction with passage through the carbonate-out boundary the melt temperature approaches the liquidus where

major gas foaming (CO_2 and H_2O) occurs (Hampton and Bailey, 1984) leading to extensive fragmentation of melt in a gas-fluidised system. The CO_2 diatresis model of Bailey (1985) combines foaming at mantle depth in near conjunction with the carbonate-out boundary. If we assume that tuffitisation and diatresis are related then diatresis should occur in the stability field of the mantle
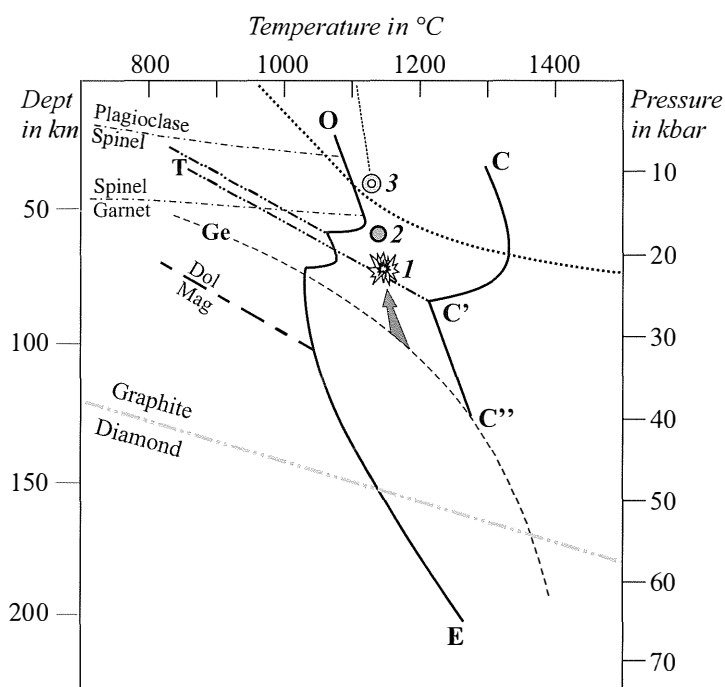

Fig. 9 – Phase stability and diatresis model based on Bailey (1985, Fig. 4). Pressure-temperature diagram to show the ascent of carbonate-rich ultramafic silicate melt, CO_2 diatresis and hypothetical formation of Italian concentric lapilli (based on Vulture and San Venanzo occurrences). **0-E** is the peridotite solidus in the presence of H_2O and CO_2 (Olafsson and Eggler 1983); **C-C'-C''** is the carbonate peridotite solidus and the line **C'-T,** the decarbonation boundary of Wyllie (1979), the *dot-dash line* parallel to this is the equivalent boundary of Olafsson and Eggler (1983). The *thick grey arrow* marks accumulation and ascent of liquid on geotherm **Ge** along an adiabatic path with origin at 1150°C appropriate for Vulture spinel-lherzolite stability field (Jones *et al.*, 2000). *(1)* As the liquid passes through the melt structure transition where CO_3^{2-} becomes unstable, massive gas exsolution induces high velocity eruption (melt diatresis), marked by *starburst*. *(2)* The liquid fragments into droplets that accrete on mantle debris to form lapilli of carbonated melilitite composition *(grey-filled circle)*. *(3)* Lapilli, fragmented liquid and mantle debris ascend in a CO_2 fluidised stream and pass through the silicate-carbonate immiscibility boundary (*heavy dotted line*; Kjarsgaard and Hamilton 1989) and unmixing leads to deposition of outer carbonate coating on lapilli (*double circle with unfilled centre and grey outer shell*). Note that 100% decarbonation of the rising liquid does not occur because carbonate clearly remains in the melt to erupt as carbonatite. The CaO released during decarbonation should encourage precipitation of melilite and clinopyroxene in the silicate melt..

assemblage it carries (Fig. 9). For the Italian carbonatite-kamafugite association of Vulture and San Venanzo this is in the spinel lherzolite stability field (Jones *et al.,* 2000). In the Chinese carbonatite-kamafugite association of Quinling this is in the higher-pressure field of garnet lherzolite (Yu *et al.,* 2001). Different source depth should be one factor contributing to geochemical variation among kamafugite-carbonatite provinces. The xenoliths carried are consistent with the diatresis path proposed by Bailey (1985), which fits very well with mantle evidence in kamafugite-carbonatite. Bailey (1985) suggested that the breakdown of magnesite, where free Ca in the melt has been diminished by diopside crystallisation and is insufficient to absorb all CO_2 as dolomite, might evolve CO_2 and contribute to the acceleration of melts rising from greater depths (kimberlitic source depths ~60 km).

Fragmentation of the carbonate-rich kamafugite magma is a mantle process. Minute droplets are produced when melt is fragmented and concomitant expansion encourages rapid quenching of these droplets, which seals in some volatile and discourages further vesiculation. Some volatile may diffuse out of the smallest particles. The juvenile gases will be concentrated largely as the fluidising medium. The droplets can accrete on appropriate nuclei at any level during passage to the surface. The different assemblages forming nuclei to the tuffisite lapilli in Italy, Uganda and China, listed in Table 1 and pictured in Plates 1 and 2, illustrate the variety of accretion levels, from mantle to crustal, in these localities.

Potential melts can evolve their Ca-, LREE-and LILE-rich peralkaline character over the percolation path from inception on a geotherm to the point of diatresis, and the differences in geochemical signature for the localities discussed are, in part at least, related to this. Further modification by processes such as fractional crystallisation is impossible from the point of rapid eruption that does not allow for settling of mantle xenoliths. The melt evolution documented by tuffisite is that of

silicate and carbonate segregation. In Italy the petrographic evidence is for segregation at mantle depths, as tuffisite lapilli show outer rims of carbonate that include mantle microfragments but no crustal material. In Uganda carbonate is found exclusively as matrix ash, which might suggest a much higher level of segregation, but this may not be the complete picture. The Italian tuffisite lapilli with more than one composition shell are typically much larger than those with a silicate shell only (compare Plates 1 and 2) and this could indicate physico-chemical factors in the fluidised gas-liquid-solid stream that affect the manner of lapilli accretion in ways as yet unrecognised.

Summary

1. The kamafugite-Ca-carbonatite-tuffisite association is pertinent to ultramafic CO_2 rich magmatism;

2. It is manifested in tuffisite-lapilli bearing breccia diatreme fill and tuffisite lapilli tuff surges;

3. Tuffisite lapilli show concentric accretion of melt fragments onto high-pressure to low-pressure xenoliths, xenocrysts and phenocrysts. They provide evidence of rapid rotation in a gas-liquid-solid stream from the point of diatresis in the mantle to subcrustal levels;

4. Tuffisite deposits, mantle xenoliths and geochemical plus isotopic signatures for kamafugite-carbonatite localities in Italy, SW Uganda and China confirm the cognate relationship of these two rock types and their origin as a unified carbonate-rich ultramafic silicate magma;

5. Diatresis and magma fragmentation is a mantle process; segregation of carbonate and silicate fractions can occur at mantle or higher levels;

6. This specific magma type, ultramafic and carbonate-rich, erupting in a unique style of intrusive and extrusive pyroclasts argues for similar geothermal gradient and tectonic environment in all cases.

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