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The Kamafugites of Uganda: a mineralogical and geochemical comparison with their Italian and Brazilian analogues

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ABSTRACT. — New mineral chemistry and whole-rock geochemistry of type kamafugites from the East African Toro-Ankole province are compared with Italian and Brazilian kamafugitic rocks showing the diversity of kamafugite compositions. Whereas Brazilian kamafugites are more akin to the Ugandan type rocks in showing a smooth convex-upward trace element abundance curve and similarities in the mineral chemistry, significant chemical differences to the Italian rocks are apparent. The latter are characterized by higher SiO₂, Al₂O₃ and K₂O contents and show negative anomalies for Eu and the high-field strength elements in normalized abundance patterns.

This could be due to slightly distinct source compositions as a result of the different nature of mantle metasomatism preceding kamafugite magmatism. Whereas the Ugandan and Brazilian subcontinental lithosphere was affected by metasomatizing agents derived from the asthenosphere the lithospheric mantle beneath Italy was probably affected by enrichment processes linked with subducted crust.

RIASSUNTO. — Nuovi dati sulla chimica dei minerali e di geochimica di roccia totale delle kamafugiti tipo della Provincia dell'Africa orientale di Toro-Ankole sono stati comparati con le kamafugiti italiane e brasiliane che mostrano una diversità composizionale pur essendo anch'esse kamafugiti. Mentre le kamafugiti brasiliane sono simili alle rocce tipo ugandesi avendo una distribuzione degli elementi in traccia convessa e simile composizione mineralogica, le rocce italiane

sono molto diverse. Quest'ultime sono caratterizzate da più alti contenuti in SiO₂, Al₂O₃ e K₂O, presentano anomalie negative di Eu e di HFSE come visibile nei diagrammi di abbondanza normalizzati. Questo può essere dovuto a piccole differenze nella composizione della sorgente come conseguenza della differente natura del metasomatismo mantellico che ha preceduto il magmatismo kamafugitico. Mentre la litosfera subcontinentale ugandese e brasiliana è stata metasomatizzata da agenti di origine astenosferica, il mantello litosferico sotto l'Italia è stato probabilmente arricchito da processi legati alla subduzione di crosta.

KEY WORDS: *Toro-Ankole, rift magmatism, geochemistry, ultrapotassic rocks, kalsilite, melilite*

INTRODUCTION

Kalsilite-bearing lava and ejecta from the SW Ugandan portion of the African Rift were first described by Holmes and Harwood (1932) and are diagnostic for Sahama's (1974) kamafugite series. Kamafugites represent primitive ultrapotassic rocks which are extremely rare but widespread. They are characterized by SiO₂ undersaturation, low Al, moderately high K but extremely high Ca content and as a consequence of this unusual major element composition modal kalsilite, melilite and perovskite frequently occur.

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Hence, they are akin to ultramafic lamprophyres but differ from lamproites in terms of mineralogy and whole-rock geochemistry.

Kamafugites have been recognized as a potential end-member amongst ultrapotassic magmas (Foley *et al.*, 1987) and hence they are of petrological significance for the genesis of near primary ultrapotassic rocks and its derivatives. However, little is known about the mineral chemistry and trace element geochemistry of the Ugandan type kamafugites. This lack of information hampers comparison with other kamafugite occurrences and other ultrapotassic end-member compositions such as ultramafic lamprophyres and lamproites.

A genetic link between kamafugite and carbonatite has been proposed in Uganda (Holmes, 1950; Bell and Powell, 1969; Lloyd, 1985; Bailey and Collier, 2000; Stoppa *et al.*, 2000) but constraints on this relationship are poor given the insufficient knowledge about these type kamafugites. In contrast, greater effort has been made to reveal this potential relationship from similar occurrences in Italy (Stoppa and Lavecchia, 1992; Stoppa and Cundari, 1995, 1998; Stoppa and Woolley, 1997), where the relation between rock types seems to be clearer.

In this paper we present new mineral chemical and whole-rock geochemical data on southwest Ugandan kamafugite samples of the original Holmes collection. We also compare and contrast the features of Ugandan type kamafugites with their Italian and Brazilian counterparts which have been better studied during the past decade. The major goal of this study is to evaluate the compositional diversity of kamafugite compositions and the role they play in understanding ultrapotassic magmatism.

Toro-Ankole volcanic province

Mid-Miocene to Recent lavas in the Western Branch of the East African Rift are confined to four intrabasinal accommodation zones (Ebinger, 1989; Pasteels *et al.*, 1989; Furman, 1995) and Pouclet *et al.* (1983) noted a trend

towards increasing potassium and CO₂ coupled with increasing silica-undersaturation towards the north, where carbonatites also occur (Barker and Nixon, 1989; Stoppa *et al.*, 2000). Our focus is on the northernmost volcanic province Toro-Ankole (Fig. 1) where ultrapotassic rocks are common. Here, several Quaternary volcanic fields occur to the east and south-east of the Ruwenzori massif along the border between Uganda and Congo (Fig. 2). The volcanic edifices of this area are the type locality of kamafugite: pyroclastics dominate over lavas (Holmes and Harwood, 1932) due to the extremely volatile-rich, explosive nature of the volcanism. Magmatism was active in the Upper Pleistocene and continued intermittently until recent times (Holmes, 1950; Lloyd *et al.*, 1991). According to K-Ar and Ar-Ar age determinations all the volcanics are younger than 50 ka (Boven *et al.*, 1998). Samples investigated in the course of this study come from the SW Ugandan fields Katwe-Kikorongo and Bunyaruguru as well as from Katunga volcano (Fig. 2-3). The Katwe-Kikorongo field lies within the rift valley, whereas Bunyaruguru is situated on the eastern shoulder of the rift depression. The isolated Katunga volcano occurs on the eastern rift flank in the plateau country.

Sample Selection and Analytical Techniques

Samples are from the Holmes Collection of Ugandan volcanic rocks at the University of Durham and Cambridge. Sample locations are listed in Table 1. We selected 20 rocks for geochemical analyses representing the most conspicuous kamafugite members and their allied silicate rocks (Sahama, 1974), originally described by Holmes and Harwood (1932) from these Toro-Ankolean type localities. An investigation of the associated carbonatite lava and ejecta is beyond the scope of this study and the reader is referred to Barker and Nixon (1989) as well as Stoppa *et al.* (2000).

Ejecta and lava material were chosen from Nabugando, Mbuga and Katwe craters of the Katwe-Kikorongo volcanic field. Lava material from the Bunyaruguru field comes from the

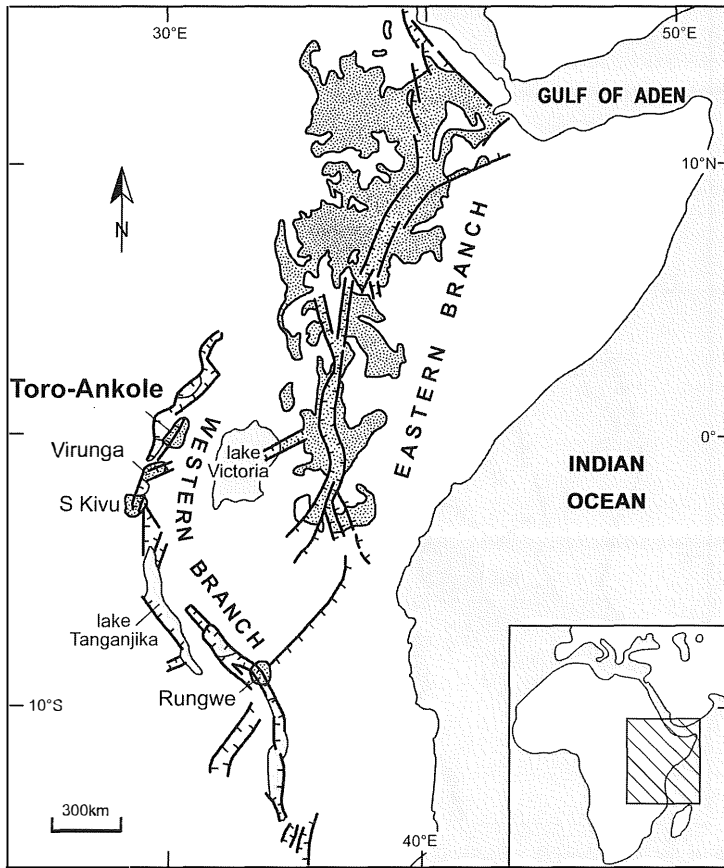


Fig. 1 – Simplified map of the East African Rift showing the distribution of volcanic rocks and volcanic subprovinces (dotted areas). The Toro-Ankole province is situated in the Western Branch rift zone, where magmatism is significantly less voluminous and not as widespread as in the Eastern Branch. Solid tick lines represent major rift-margin faults.

Kabirenge and Lyakauli flows as well as from the Kazimiro crater. Subordinate ejecta are represented by material from Mafuru and Kakunyu crater. Furthermore, we incorporated lava from the eastern slope of the Katunga volcano and an associated lapilli tuff in our investigation.

Mineral compositions were obtained using a JEOL JXA 8900 RL electron microprobe at the Geozentrum Göttingen and analyses are listed in Tables 2-4. Operating voltage was 15 kV for silicates and 20 kV for oxides. Beam current was adjusted to 15 nA with a beam diameter

varying between 2 and 7 μm dependent on both size and content of volatile elements in the crystal of interest.

Major and selected trace elements of the whole-rocks were determined by XRF on fused discs at the University of Greifswald. Additionally, a wide range of trace elements and rare-earth elements (REE) were measured by inductively coupled plasma mass spectrometry (ICP-MS) in Durham. Details of the analytical procedure are given in Turner *et al.* (1999) and selected analyses are listed in Table 5.

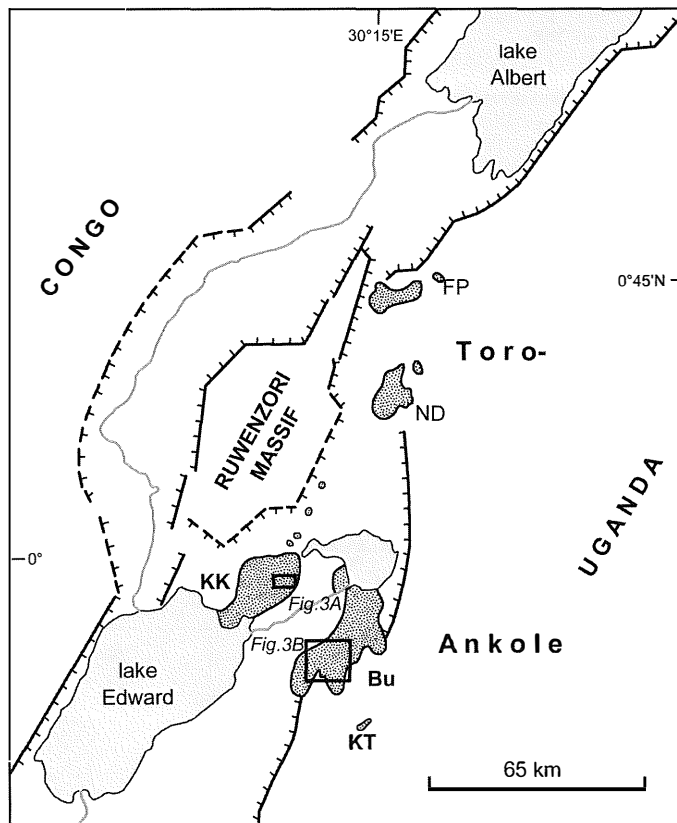


Fig. 2 – Sketch map of the Toro-Ankole volcanic province east and southeast of the Ruwenzori Horst. Studied sample material comes from ring craters in the Katwe-Kikorongo (*KK*) and Bunyaruguru (*Bu*) field as well as from the isolated Katunga volcano (*KT*). Carbonatite lavas occur in the northern fields Fort Portal (*FP*) and Ndale (*ND*). Tick lines are rift boundary faults.

TABLE I
Sample list for Ugandan Kamafugites

Sample #	Volcanic field/Volcano	Locality/Crater	Rock type
C3946	Katunga	E foot of hill	Katungite
C3948	Katunga	1 mile E of summit	Katungite
C4035	Bunyaruguru	Kakunyu	Ugandite
C4788	Bunyaruguru	Kabirenge	K-Ankaratrite
C4793	Bunyaruguru	Lyakauli	Mafurite
C5549	Katwe-Kikorongo	Nyamununka	Lct-Ankaratrite
C5595	Katwe-Kikorongo	Mbuga South	Lct-Ankaratrite
C5619	Katwe-Kikorongo	Mbuga	Lct-Ankaratrite
C5624	Katwe-Kikorongo	Mbuga	K-Ankaratrite
C5775	Katwe-Kikorongo	Katwe	Katungite

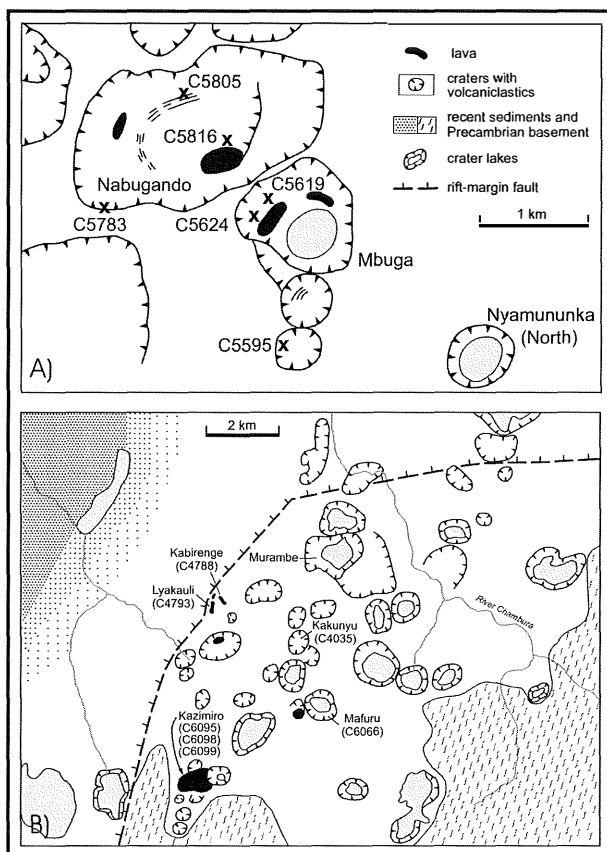


Fig. 3 – Sample sites in parts of the Katwe-Kikorongo (A) and Bunyaruguru fields (B). The sample numbers are maintained from the original Holmes collection and topographical and geological details are from Combe and Holmes (1945) as well as Holmes (1952).

TABLE 1: *Continued*

Sample #	Volcanic field/Volcano	Locality/Crater	Rock type
C5783	Katwe-Kikorongo	Nabugando	Lct-Ankaratrite
C5805	Katwe-Kikorongo	Nabugando	Lct-Ankaratrite
C5816	Katwe-Kikorongo	Nabugando	Lct-Ankaratrite
C6066	Bunyaruguru	Mafuru	Mafurite
C6095	Bunyaruguru	Kazimiro	Ugandite
C6098	Bunyaruguru	Kazimiro	Ugandite
C6099	Bunyaruguru	Kazimiro	Ugandite
C15010b	Katunga	?	Katungite
C15016	Katunga	?	Katungite-Lapilli Tuff
C15017	Katunga	?	K-Ankaratrite

TABLE 2
Selected clinopyroxene and melilite analyses from Ugandan Kamafugites

Mineral	Clinopyroxene							Melilite			
	Mafurite		Ugandite		Ankaratrite			Katungite			
Rock type											
Sample #	C6066	C6066	C4035	C4035	C4788	C5783	C5783	C3946	C3948	15010b	
	mpc- core1 Ti-Di	mpc- core2 green salite	pc- core2 green salite	pc- rim2 Ti-Di	pc- core1 green salite	pc- core1 Ti-Di	pc- rim1 Ti-Di	mpc- core Åk	mpc- core Åk	mpc- core Åk	
SiO ₂	51.62	51.75	51.06	50.49	47.92	50.68	46.71	43.07	42.85	43.81	
TiO ₂	1.06	0.57	0.56	1.09	0.89	1.77	3.42	0.1	0.06	0.03	
Al ₂ O ₃	1.6	1.23	0.87	1.13	4.31	2.49	4.37	2.93	3.59	2.87	
Cr ₂ O ₃	0	0.04	0.01	0.35	0.03	0.06	0.02	0	0.03	0.03	
FeO	6.39	11.26	18.07	8.07	13.41	5.35	7.21	2.85	3.02	2.95	
MnO	0.13	0.22	0.32	0.13	0.25	0.04	0.12	0.03	0.01	0.1	
NiO	0.03	0	0	0	0	0	0	0.02	0	0	
MgO	14.44	11.06	7.73	13.81	8.9	14.87	13.3	10.83	10.27	11.02	
CaO	22.96	20.9	18.37	22.69	21.62	23.38	23.36	36.85	36.2	6.82	
Na ₂ O	0.66	1.83	2.36	0.7	1.3	0.38	0.56	1.78	2.2	1.62	
K ₂ O	0.03	0	0	0	0.01	0.03	0.01	0.27	0.3	0.33	
SrO	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	0.6	
Total	98.92	98.86	99.35	98.46	98.64	99.05	99.08	98.73	98.53	100.18	
Cations on the basis of 6 O							Cations on the basis of 14 O				
Si	1.926	1.959	1.97	1.905	1.841	1.886	1.754	3.971	3.952	3.998	
Ti	0.03	0.016	0.016	0.031	0.026	0.05	0.097	0.007	0.004	0.002	
Al	0.071	0.055	0.039	0.05	0.195	0.109	0.193	0.318	0.39	0.309	
Cr	0	0.001	0	0.01	0.001	0.002	0.001	0	0.002	0.002	
Fe ^{3+(a)}	0.067	0.129	0.165	0.119	0.167	0.047	0.146	0.08	0.127	0.015	
Fe ²⁺	0.133	0.228	0.418	0.136	0.264	0.12	0.081	0.139	0.106	0.21	
Mn	0.004	0.007	0.011	0.004	0.008	0.001	0.004	0.003	0.001	0.008	
Ni	0.001	0	0	0	0	0	0	0.001	0	0	
Mg	0.803	0.624	0.445	0.777	0.51	0.825	0.745	1.488	1.412	1.499	
Ca	0.918	0.848	0.759	0.917	0.89	0.932	0.94	3.64	3.577	3.6	
Na	0.047	0.134	0.177	0.051	0.097	0.028	0.04	0.318	0.393	0.287	
K	0.001	0	0	0	0.001	0.001	0	0.032	0.035	0.039	
Total	4	4	4	4	4	4	4	10	10	10	
Mg# ^(b)	85.8	73.3	51.5	85.1	65.9	87.3	90.2	91.4	93	87.7	
Mg ₂ Si ₂ O ₆	0.394	0.312	0.222	0.364	0.238	0.405	0.337	Ca ₂ Fe ²⁺ Si ₂ O ₇	0.07	0.054	0.101
Fe ₂ Si ₂ O ₆	0.065	0.114	0.209	0.064	0.123	0.059	0.036	Ca ₂ MgSi ₂ O ₇	0.734	0.702	0.719
Ca ₂ Si ₂ O ₆	0.428	0.411	0.372	0.399	0.354	0.426	0.358	CaNaAlSi ₂ O ₇	0.157	0.196	0.138
CaAl ₂ Si ₂ O ₆	0.014	0.008	0	0.021	0.099	0.013	0.047	Ca ₂ A _{1/2} SiO ₇	0	0	0
Mn ₂ Si ₂ O ₆	0.002	0.003	0.005	0.002	0.004	0.001	0.002	Ca ₂ Fe ³⁺ ₂ SiO ₇	0.019	0.031	0.004
Ni ₂ Si ₂ O ₆	0	0	0	0	0	0	0	Total	0.98	0.982	0.961
CaCrAlSiO ₆	0	0.001	0	0.01	0.001	0.002	0.001				
CaTiAl ₂ O ₆	0.029	0.016	0.016	0.029	0.024	0.049	0.087				
NaAlSi ₂ O ₆	0	0.006	0.012	0	0	0	0				
NaFe ³⁺ Si ₂ O ₆	0.066	0.129	0.164	0.111	0.156	0.046	0.132				
Ca _{1/2} Fe ³⁺ Si ₂ O ₆	0	0	0	0	0	0	0				
KAlSi ₂ O ₆	0.001	0	0	0	0.001	0.001	0				
Total	1	1	1	1	1	1	1				

TABLE 3
Selected phlogopite and olivine analyses from Ugandan Kamafugites

Mineral Rock type	Phlogopite						Olivine				
	Katungite		Mafurite		Ugandite	Ankaratrite	Katungite	Mafurite	Ugandite	Ankaratrite	
Sample #	C5775 gm1 TFP	C5775 gm2 TFP	C6066 gm2 TFP	C6066 gm4 TFP	C6099 gm2 TFP	C5549 gm2 TFP	C3946 pc	C6066 pc	C6095 pc	C5549 pc	
SiO ₂	39.32	39.91	42.94	42.97	37.96	40.00	SiO ₂	40.29	39.96	40.01	39.05
TiO ₂	2.32	2.34	1.93	1.67	5.51	4.83	TiO ₂	0.03	0.04	0.06	0.04
Al ₂ O ₃	8.94	8.41	5.67	5.02	10.63	10.09	Al ₂ O ₃	0.04	0.08	0.04	0.05
Cr ₂ O ₃	0.00	0.00	0.00	0.02	0.03	0.01	Cr ₂ O ₃	0.10	0.16	0.08	0.02
FeO	8.73	9.04	5.78	6.47	5.57	6.30	FeO	9.32	8.48	9.04	16.20
MnO	0.06	0.08	0.04	0.04	0.07	0.02	MnO	0.10	0.14	0.11	0.29
NiO	0.05	0.00	0.02	0.00	0.04	0.03	NiO	0.37	0.36	0.41	0.08
MgO	23.01	22.69	23.26	23.29	21.62	21.02	MgO	49.30	49.61	49.77	43.59
CaO	0.08	0.08	0.06	0.09	0.03	0.01	CaO	0.14	0.11	0.19	0.52
Na ₂ O	0.23	0.31	1.66	1.60	0.28	0.58	Na ₂ O	0.03	0.02	0.03	0.00
K ₂ O	9.64	9.64	10.21	10.16	9.62	9.63	K ₂ O	0.00	0.01	0.01	0.00
BaO	1.07	1.07	0.77	0.77	2.16	2.11					
F	1.80	1.81	7.19	7.14	4.72	5.80	Total	99.75	98.97	99.76	99.88
Cl	0.00	0.01	0.01	0.09	0.01	0.00					
H ₂ O ^(a)	3.25	3.25	0.67	0.65	1.85	1.36					
Total (less O=F)	97.75	97.87	97.17	96.98	98.11	99.34					
On the basis of 8 tetrahedral cations and 22 oxygen equivalents						Cations on the basis of 4 oxygens					
Si	5.821	5.903	6.334	6.366	5.598	5.837	Si	0.988	0.984	0.979	0.988
Al ^(IV)	1.560	1.466	0.986	0.877	1.848	1.735	Ti	0.001	0.001	0.001	0.001
Fe ^{3+(IV)}	0.619	0.631	0.681	0.758	0.555	0.428	Al	0.001	0.002	0.001	0.002
[T]	8.000	8.000	8.000	8.000	8.000	8.000	Cr	0.002	0.003	0.002	0.000
							Fe ^{3+(a)}	0.021	0.026	0.039	0.020
Al ^(VI)	0.000	0.000	0.000	0.000	0.000	0.000	Fe ²⁺	0.170	0.148	0.146	0.322
Ti	0.258	0.260	0.214	0.186	0.611	0.530	Mn	0.002	0.003	0.002	0.006
Mg	5.079	5.003	5.115	5.144	4.753	4.573	Ni	0.007	0.007	0.008	0.002
Ca	0.012	0.012	0.009	0.014	0.005	0.002	Mg	1.802	1.821	1.815	1.644
Mn	0.008	0.010	0.004	0.005	0.008	0.002	Ca	0.004	0.003	0.005	0.014
Fe ^{2+(VI)}	0.462	0.487	0.032	0.044	0.132	0.341	Na	0.001	0.001	0.001	0.000
[M]	5.819	5.773	5.375	5.392	5.510	5.448	K	0.000	0.000	0.000	0.000
							Total	3.000	3.000	3.000	3.000
Ba	0.062	0.062	0.044	0.045	0.125	0.121					
Na	0.067	0.088	0.475	0.460	0.081	0.163	Mg# ^(b)	90.3	91.1	90.6	82.5
K	1.821	1.819	1.921	1.920	1.810	1.793					
[A]	1.949	1.969	2.440	2.425	2.015	2.076					
Cr	0.000	0.000	0.000	0.003	0.004	0.001					
Ni	0.006	0.000	0.002	0.000	0.005	0.003					
F	0.843	0.847	3.354	3.345	2.201	2.677					
Cl	0.000	0.003	0.003	0.023	0.002	0.000					
OH	3.157	3.151	0.643	0.632	1.796	1.323					
Total	4.000	4.000	4.000	4.000	4.000	4.000					

(a) calculated assuming stoichiometry, (b) Mg# = 100Mg/(Mg+Fe²⁺+Fe³⁺+Mn) in atomic units, pc - phenocryst, gm - groundmass, TFP - tetraferriphlogopite

TABLE 4
Selected nepheline, kalsilite and leucite analyses from Ugandan Kamafugites

Mineral	Nepheline			Kalsilite						Leucite	
	Ankaratrite		Ugandite	Katungite	Mafurite		Ugandite			Ugandite	Ankaratrite
Rock type	C5619	C5805	C6099	C3948	C4793	C4793	C6099	C6066	C6066	C6095	C5783
Sample#	mpc	gm	gm	gm	incl	gm	gm	gm	oc	gm	mpc
SiO ₂	42.31	40.89	41.04	38.92	38.10	37.85	38.46	37.92	37.74	53.82	54.01
TiO ₂	0.05	0.06	0.06	0.13	0.10	0.09	0.09	0.10	0.06	0.29	0.20
Al ₂ O ₃	32.42	32.28	31.43	30.48	23.70	23.57	29.35	25.56	28.87	22.18	22.49
Cr ₂ O ₃	0.00	0.01	0.00	0.03	0.02	0.01	0.04	0.01	0.00	0.00	0.00
FeO	0.84	1.10	2.32	2.06	5.82	7.24	2.23	5.17	2.20	0.95	0.67
MnO	0.03	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
NiO	0.01	0.00	0.05	0.02	0.01	0.01	0.02	0.01	0.02	0.00	0.02
MgO	0.12	0.13	0.30	0.18	1.41	0.99	0.30	0.68	0.25	0.04	0.02
CaO	0.06	0.03	0.06	0.23	0.00	0.02	0.00	0.00	0.03	0.00	0.00
Na ₂ O	16.42	15.21	15.40	6.96	0.94	0.77	2.08	1.42	1.40	0.09	0.02
K ₂ O	6.81	8.90	8.18	19.38	27.84	27.64	26.35	27.03	27.44	21.37	21.24
BaO	0.05	0.06	0.00	0.03	0.20	0.26	0.05	0.18	0.04	0.04	0.01
Total	99.13	98.72	98.86	98.44	98.14	98.45	99.00	98.08	98.05	98.78	98.72
Cations on the basis of 4 O						on the basis of 6 O					
Si	1.037	1.013	1.018	1.011	1.034	1.031	1.020	1.027	1.013	1.985	1.992
Ti	0.001	0.001	0.001	0.003	0.002	0.002	0.002	0.002	0.001	0.008	0.006
IV Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.008
VI Al	0.936	0.943	0.919	0.934	0.758	0.757	0.917	0.816	0.913	0.949	0.970
Cr	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Fe ^{3+(a)}	0.017	0.023	0.042	0.031	0.132	0.165	0.037	0.117	0.049	0.029	0.021
Fe ²⁺	0.000	0.000	0.006	0.014	0.000	0.000	0.012	0.000	0.000	0.000	0.000
Mn	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Ni	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Mg	0.004	0.005	0.011	0.007	0.057	0.040	0.012	0.027	0.010	0.002	0.001
Ca	0.002	0.001	0.002	0.006	0.000	0.001	0.000	0.000	0.001	0.000	0.000
Na	0.780	0.731	0.741	0.351	0.050	0.041	0.107	0.075	0.073	0.006	0.001
K	0.213	0.281	0.259	0.643	0.964	0.961	0.891	0.934	0.939	1.005	0.999
Ba	0.000	0.001	0.000	0.000	0.002	0.003	0.000	0.002	0.000	0.001	0.000
Total	2.991	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	4.000	4.000
KAlSiO ₄	21.1	27.9	25.8	65.1	94.8	95.2	88.9	92.4	93.1	67.6	67.0
NaAlSiO ₄	77.0	72.1	73.5	34.8	4.3	3.4	10.1	6.8	6.9	0.0	0.0
SiO ₂	2.0	0.0	0.7	0.2	0.9	1.3	1.0	0.8	0.0	32.4	33.0

(a)calculated assuming stoichiometry, mpc - microphenocryst, gm - groundmass, oc - ocelli

TABLE 5
Major (wt %) and trace (ppm) element analyses of selected rocks from Toro-Ankole

Rock type	Katungite (K-Ol Melilitite)		Mafurite (Ol-Cpx Kalsilitite)		Ugandite (Ol-Kfs Leucitite)		Ankaratrite (K-Nephelinite)	
Sample #	C3948	C5775	C4793	C6066	C4035	C6099	C5595	C5783
SiO ₂	36.64	32.29	37.1	40.15	41.06	41.84	39.84	40.75
TiO ₂	3.96	4.94	5.62	3.32	3.94	4.1	5.1	5.31
Al ₂ O ₃	6.89	5.69	6.65	7.49	5.75	6.26	6.71	11.03
Fe ₂ O ₃ *	11.56	12.62	12.19	10.62	11.04	11.93	14.56	13.71
MnO	0.2	0.21	0.2	0.17	0.14	0.14	0.18	0.25
MgO	13.82	14.78	12.54	16.67	22.55	20.89	10.97	5
CaO	15.76	15.02	13.06	10.34	8.29	7.36	15.64	12.43
Na ₂ O	1.83	1.43	0.79	0.96	0.9	0.77	1.34	3.12
K ₂ O	3.23	2.51	5.81	7.03	2.91	5.01	2.13	4.88
P ₂ O ₅	0.95	1.08	1.34	0.46	0.29	0.31	0.52	1.16
LOI	3.99	7.4	3.26	1.28	2.55	0.13	1.99	1.22
Total	98.83	97.97	98.57	98.49	99.42	98.74	98.99	98.86
Mg# ^(a)	70.3	69.9	67.1	75.7	80.2	77.6	59.9	41.9
La	219.44	185.29	221.95	150.84	84.88	80.73	88.27	201.06
Ce	420.71	356.27	421.07	284.61	160.71	152.35	172.21	379.74
Pr	48.54	42.06	49.13	32.63	18.93	17.89	21.16	44.34
Nd	169.82	151.36	173.99	113.86	67.15	63.87	77.69	156.51
Sm	19.97	19.87	21.43	14.01	8.3	8.21	10.46	20.3
Eu	5	5.26	5.71	4.12	2.29	2.24	2.93	5.22
Gd	12.09	13.01	13.27	8.87	5.24	5.32	6.86	13.71
Tb	1.08	1.31	1.24	0.84	0.5	0.53	0.69	1.42
Dy	4.06	5.18	4.59	3.37	1.94	2.2	2.84	5.99
Ho	0.61	0.78	0.66	0.54	0.3	0.35	0.44	0.96
Er	1.29	1.64	1.34	1.23	0.66	0.76	0.94	2.18
Tm	0.17	0.22	0.18	0.18	0.1	0.11	0.13	0.32
Yb	1.03	1.2	1.04	1.07	0.55	0.62	0.74	1.81
Lu	0.15	0.17	0.14	0.16	0.08	0.09	0.11	0.27
Cs	0.45	0.75	1.09	0.61	0.9	0.6	0.76	1.38
Rb	108.49	80.41	162.97	189.24	162.9	192.27	75.56	117.21
Ba	1897.58	2196.55	2860.61	3501.27	1369.98	1138.4	1770.45	1675.22
Th	28.34	22.46	26.46	21.24	10.6	10.79	10.54	27.72
U	6.27	5.19	6	4.8	2.37	2.35	2.12	4.63
Nb	238.7	232.74	285.39	173.19	117.87	126.29	124.56	280.6
Ta	12	11.84	16.14	8.59	7.11	8.5	7.64	15.5
Pb	7.46	8.58	8.95	6.43	3.32	3.89	4.05	13.13
Sr	2499.42	2109.95	3033.89	1570.61	2023.65	803.02	1809.77	2622.33
Zr	272.28	393.54	441.85	250.98	159.8	163.01	232.64	515.13
Hf	6.23	8.92	9.72	5.67	4.12	4.4	5.82	11.13
Y	16.96	21.77	18.38	15.64	8.47	9.38	12.15	27.21
Sc	23.84	30.95	25.01	24.05	18.49	21.94	39.15	15.25
V	183.92	339.12	160.25	181.4	137.02	187.73	331.23	442.46
Cr	668.04	542.54	579.54	833.89	861.24	1559.71	488.65	51.9
Ni	283.44	173.26	176.75	563.26	969.33	1065.97	135.86	32.04
Co	53.99	53.24	54.3	60.82	79.01	103.56	60.69	45.14
Cu	116.96	132.42	151.74	93.34	84.36	107.02	98.11	98.66
Zn	125.62	117.1	147.36	94.97	115.59	127.3	128.51	152.2
Ga	13.36	12.69	15.31	12.25	9.84	12.6	15.2	23.73

^(a) Mg# = 100 Mg/(Mg+Fe²⁺) in atomic units, K - potassic, LOI - loss on ignition

Classification of the kamafugitic rocks

The name kamafugite (Sahama, 1974) is an acronym made up of its most conspicuous rock types katungite, mafulite and ugandite, after alkaline mafic volcanics occurring in the Toro-Ankole volcanic province.

Kamafugitic rocks are characterized by the presence of modal kalsilite as a consequence of their extreme silica undersaturation and K-enrichment. This fact is considered as petrogenetically so distinctive and important that Woolley *et al.* (1996) retained the term kamafugite instead of applying the classification of either melilitic or leucitic rocks. Recent IUGS recommendations (Le Maitre, 2002) for the kalsilite-bearing rocks are inconsistent in eliminating local names but retaining the term kamafugite as a series name. Classifying the rocks according to their critical mineral assemblage, katungite is equivalent to potassic olivine melilitite and mafurite to olivine-pyroxene kalsilitite. Woolley *et al.* (1996) and Le Maitre (2002) excluded ugandite from the kamafugitic rocks because it was assumed to lack kalsilite. However, we show that kalsilite does occur and ugandite is a kamafugite equivalent to olivine-kalsilite leucitite.

The kamafugitic rocks from Toro-Ankole are accompanied by ankaratrites (potassic nephelinites, Holmes and Harwood, 1932; Holmes, 1952; Sahama, 1974) which, although not defined as kamafugites, are related to them by fractional crystallization.

PETROGRAPHY AND MINERAL CHEMISTRY OF UGANDAN KAMAFUGITES

Petrography of the Toro-Ankole kamafugites and ankaratrites

Katungite (Potassic Olivine Melilitite)

The porphyritic katungites bear abundant phenocrysts of olivine. Melilitite occurs exclusively as euhedral lath-shaped microphenocrysts in the groundmass. Their

subparallel orientation causes a flow-aligned texture (Fig. 4).

Irregular chromite and euhedral late-stage perovskite occur in great abundance as microphenocrysts in the glassy to microcrystalline groundmass. This rock type is conspicuously lacking in clinopyroxene, the apparent incompatibility of melilitite and clinopyroxene suggests a reaction relation. The fine grained groundmass mainly consists of kalsilite, titanomagnetite and phlogopite flakes.

Mafurite (Olivine-Pyroxene Kalsilitite)

Olivine is the dominant phenocryst phase of mafurite (8-11 vol%) followed by clinopyroxene (3-4 vol%), which is complexly zoned with the cores mostly of green-coloured salite (Fig. 4B). Microphenocrysts of titanian diopside are often sieved. The groundmass consists of needle-like clinopyroxene, tiny flakes of fresh phlogopite, small zoned spinel and perovskite grains as well as interstitial kalsilite (grain size ranging between 5-40 μm). Kalsilite partly forms small euhedral cubes and hexagons sometimes enclosing oxide minerals (Fig. 4B). Mafurites may carry xenoliths of dunite and clinopyroxenite.

Ugandite (Olivine-Kalsilite Leucitite)

Large euhedral olivine phenocrysts (up to 40 vol %) dominate ugandite. The subordinate clinopyroxene of the ugandites (< 2 vol %) often consists of slightly greenish salitic cores and a colourless mantle zone rimmed by purple brownish titanian diopside. Leucite occurs as euhedral to subhedral microphenocrysts, sometimes with oriented inclusions of glass and/or apatite. The groundmass mainly consists of acicular clinopyroxene, interstitial leucite and minor oxides. Among the oxides titanomagnetite is quite common and often overgrows early-stage Cr-spinel. Phlogopite and small amounts of nepheline/kalsilite as well as perovskite additionally occur. Interstitial phlogopite appears in patches and seems to be concentrated in distinct zones.

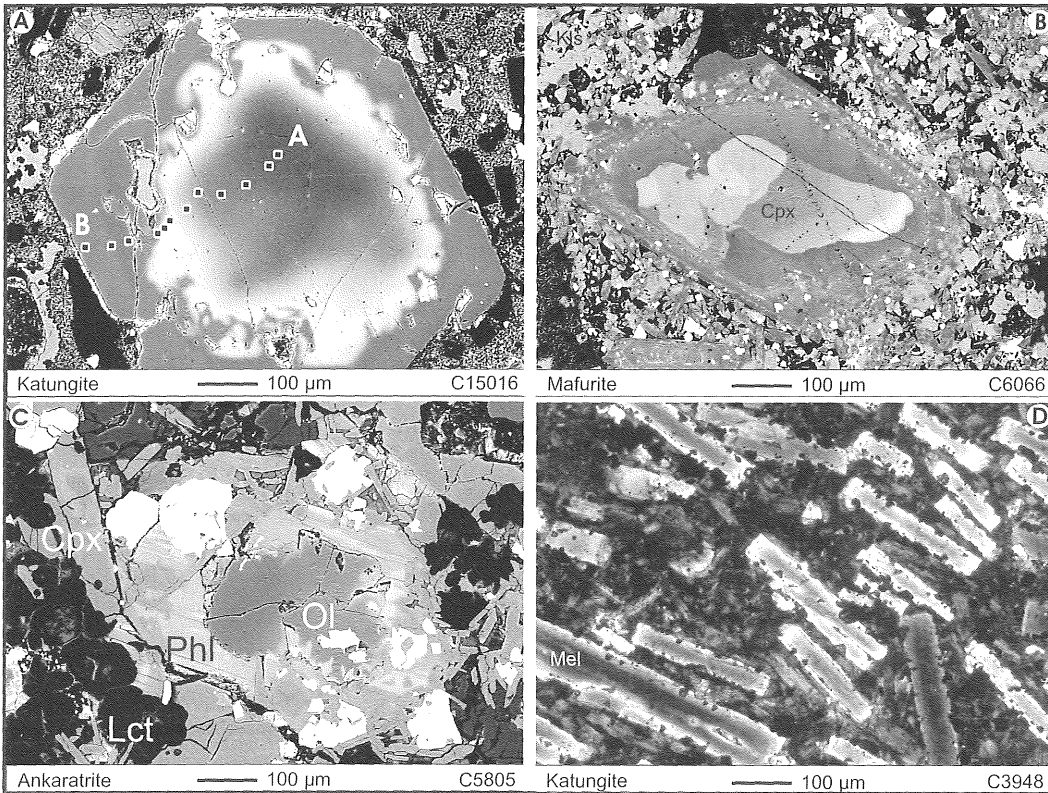


Fig. 4 – Backscattered electron images (A-C) and microphotograph (D) of Ugandan kamafugites: (A) shows a complexly zoned olivine phenocryst with indications of resorption and overgrowth. Line A-B indicates the microprobe traverse from Figure 5. (B) Composite green-core clinopyroxene with a Fe-rich inner (bright area) and less Fe-rich outer core. Mantling material shows an internal zoning which becomes increasingly Fe-rich towards the outside. Bright-grey kalsilite is the main constituent of the matrix. (C) Phlogopite replacing olivine in ankaratrite. (D) Flow-oriented melilite-laths in katungite lava from the Katunga volcano.

Ankaratrite (Potassic Nephelinite)

Ankaratrites are characterized by the predominance of clinopyroxene over olivine. They are coarse grained with holocrystalline texture and do not contain kalsilite. Holmes (1952) distinguished two types: K-ankaratrite and leucite ankaratrite. The former has nepheline as the only feldspathoid phase in the groundmass, in contrast to the more common leucite ankaratrite, in which both nepheline and leucite occur.

Clinopyroxene phenocrysts are abundant and complexly zoned. Of special interest are greenish cores with salitic composition. Olivine

is less common but also appears as large euhedral crystals, in some instances overgrown by reaction rims of phlogopite (Fig. 4C), probably indicating crystallization of phlogopite by incongruent reaction between melt and olivine. Only in rare cases is olivine absent. Oxide phenocrysts are exclusively titanomagnetite and show skeletal forms. Inclusions of olivine may be observed in these opaque grains. Leucite and/or nepheline occur in most cases as fresh euhedral to subhedral crystals in the groundmass as well as interstitial phases. Small flakes of fresh phlogopite are abundant in the matrix while late-stage

perovskite crystals are rare. Further groundmass phases are titanomagnetite and needle-like clinopyroxene.

Mineral Chemistry

Olivine

Phenocrystal olivines of the three kamafugite types exhibit a relatively narrow range in their Mg/Fe ratios (91.5-85 Fo), whereas olivines of the ankaratrites (86-82 Fo; NiO < 0.2 wt %) are more evolved. Whereas Fo and NiO decrease from core to rim, Fe, Ca and Mn contents increase. Zoning trends towards Ca-enrichment (0.23-1.59 wt % CaO) may be in response to pressure release during crystallization (Stormer, 1973). More complex reversely zoned olivine phenocrysts were observed in katungite pyroclasts of the lapilli tuff C15016 from Katunga volcano (Fig. 4A). Here, a primitive core zone (Fo 90.3) with an Fe-rich rim (Fo 79.3) is separated by a continuous interface rather than a discrete overgrowth (Fig. 5). Toward the outside, an abrupt change to more Mg-rich composition occurs (Fo 88.4). The contact between the inner, zoned crystal and the outer mantle is well defined but irregularly embayed, suggestive of resorption. Ca content approaches its maximum in this rather primitive rim zone (up to 1.0 wt % CaO), possibly promoted by depressed silica activity of the host magma.

Anhedral, kink-banded olivine crystals may represent mantle xenocrysts, although their composition hardly differs from phenocrystal olivines in the host. Hence, an origin of those crystals as flow deformed phenocrysts cannot be ruled out.

Clinopyroxene

Three generations of clinopyroxene are found in the volcanic rocks of the Toro-Ankole province: (1) pale green-coloured salitic cores, (2) zoned colourless phenocrysts, and (3) purple to colourless groundmass crystals as well as rims of same composition mantling the phenocrysts.

The green-core clinopyroxenes are

compositionally unlike any of the phenocrystal pyroxenes. In addition to being Fe-rich they contain significantly higher levels of Na₂O (up to 2.36 wt %) corresponding to up to 17 mol % acmitic component. The Al₂O₃ content is comparably low (av. 1.5 wt %) with a significant portion of Al occupying the octahedrally coordinated site, which indicates an origin at higher pressures than the diopside phenocrysts (Aoki and Shiba, 1973). Further characteristics are low mg-numbers (100Mg/[Mg+Fe²⁺]), Cr₂O₃ and TiO₂ contents. They resemble more Fe-rich diopsides which display trends from diopside and salite towards augite and ferroaugite. There is a sharp chemical discontinuity between the green salitic pyroxene and the diopside rim or mantle. In contrast to the green cores (Mg# 50-86), colourless mantle zones have extremely high Mg/Fe ratios (Mg# 84-97). In general, the boundary between core and mantle is sharp but irregularly embayed suggesting a period of resorption.

The cores of the complexly zoned phenocrysts consist of Ti-diopside and are characterized by high mg-numbers (71-95) and relatively low SiO₂ content (46.8-52.5 wt %). The Al₂O₃ and TiO₂ contents (both > 1.0 wt %) are generally lower than those of shoshonitic clinopyroxenes, but not as low as lamproitic pyroxenes (Al₂O₃ < 0.5 %; Mitchell and Bergman, 1991). Clinopyroxenes in mafurites and ugandites show the lowest Al₂O₃ content (0.92-2.68 wt %), whereas these in ankaratrites (1.17-4.31 wt %) are the highest (Fig. 6). All the aluminium occupies the tetrahedrally coordinated site in all kamafugites and ankaratrites. These clinopyroxene compositions reflect extreme silica undersaturation and Al deficiency of the host alkaline melt. The clinopyroxenes of mafurites, ugandites and ankaratrites are rich in Ca (Wo₄₇-Wo₅₀) compared to clinopyroxenes from shoshonitic rocks (Wo₄₂-Wo₄₇) from the neighbouring Virunga province (Tappe *et al.*, in prep.). The Cr₂O₃ content is low and amounts to significantly less than 1 wt %.

The latest generation of clinopyroxene that

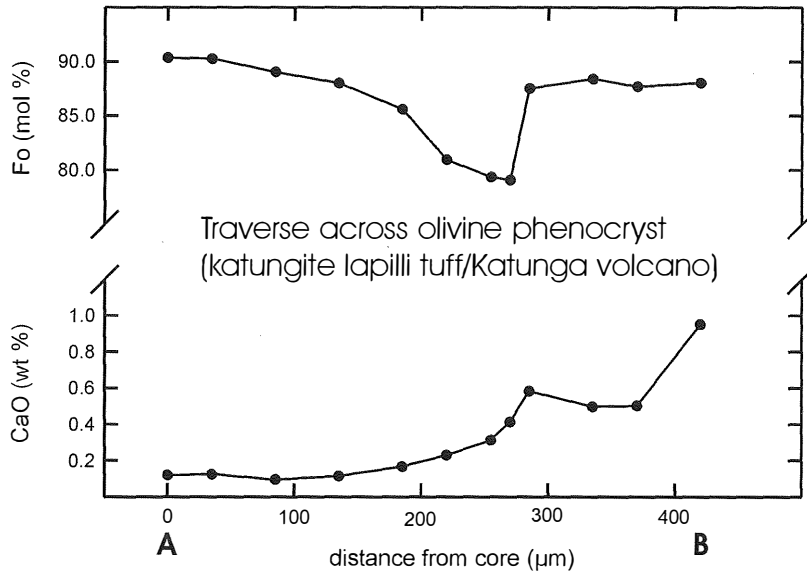


Fig. 5 – Quantitative point analyses across an olivine crystal from the katungite lapilli tuff C15016. BSE image of the crystal with location of the profile A-B is shown in Fig.4. Normal zoning, resorption and overgrowth are apparent from the profile (see text for details).

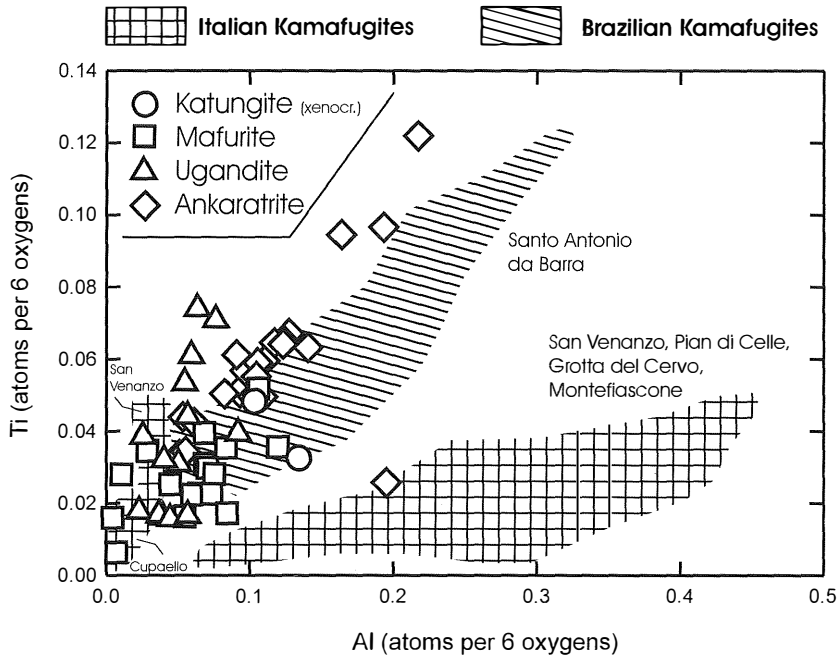


Fig. 6 – Ti versus Al in clinopyroxenes from Ugandan, diverse Italian and Brazilian kamafugites. Data for Italian rocks from Gallo et al. (1984), Cundari and Ferguson (1991), Stoppa and Cundari (1998), Di Battistini et al. (2001), Stoppa et al. (2002). Data for Brazilian pyroxenes from Sgarbi et al. (2000).

forms the outer zones of phenocrysts and xenocrysts resembles the groundmass phases. Core to rim compositional variation occurs in individual phenocrysts and comprises an increase in total Tschermakitic component, as well as decreasing MgO content. Rim- and groundmass clinopyroxene accommodate exclusively tetrahedrally coordinated Al. This is due to their low-pressure, late-stage crystallization from a progressively more silica undersaturated melt. In general, groundmass and rim diopsides are richer in TiO₂ (av. 2.5 wt %) than phenocrysts (av. 1.8 wt %) and contain less SiO₂ as well as Al₂O₃. They contain up to 14 % of Ca-Ti-Tschermak molecule (Tab. 2) as clinopyroxene evolves under decreasing pressure.

Melilite

Melilites from lava material of the eastern slope of the Katunga volcano are relatively åkermanite rich and consist on average of 80.1 % åkermanite (75.5-83.3 mol %) and 15.7 % sodium melilite (13.1-19.6 mol %) component. In comparison with melilite compositions from more common sodic melilitites (Dunworth and Wilson, 1998), Na₂O contents of the African melilitites are lower and K₂O is slightly higher (Fig. 7). Fe-gehlenite proportions are rather low but homogeneous (0.0-3.3 mol %). The gehlenite component is absent because of very low Al₂O₃ contents.

Except for a yellowish hydrous alteration rim with increased Al and Na content, the tabular melilite laths appear to be unzoned in the katungite lava. The pyroclasts of the lapilli tuff C15016 from Katunga volcano consist exclusively of katungite and bear larger melilite crystals than the common lava (up to 0.5 mm). Here, the tabular crystals show oscillatory zoning which is pronounced by carbonate replacement.

Phlogopite

Phlogopite occurs as an interstitial phase in the groundmass of kamafugites but never as phenocrysts. Nearly all of the bright orange pleochroic mica is low Al tetraferriphlogopite,

with Si and Al insufficient to fill the tetrahedral site. A crystal chemical assumption according to which Fe³⁺ occupies the free position was made, followed by an iterative recalculation of the analyses. Rancourt *et al.* (1992) showed that Mössbauer spectroscopy on ferriphlogopites yield the same amount of ferric iron as the difference of [8-(Si+Al)].

A dominant substitution mechanism operating in the tetraferriphlogopites is: ${}^{\text{VI}}[\text{Mg}_2\text{Ti}_{-1}\square_{-1}]$ which creates octahedral site vacancies (Forbes and Flower, 1974). This substitution is negligible in primitive mafurites as well as in katungites but is more important in ugandites and ankaratrites. Additionally, there is a Ba substitution on the interlayer site: ${}^{\text{A}}\text{K}^{\text{IV}}\text{Si}^{\text{A}}\text{Ba}_{-1}{}^{\text{IV}}\text{Al}_{-1}$ probably coupled with the Mg-Ti substitution. This is also indicated by a strong positive correlation between TiO₂ and BaO in phlogopites from katungites, mafurites, ugandites and ankaratrites (Fig. 8).

Phlogopite crystals of all the individual members of the kamafugite series show a distinct chemical composition with significant differences in Al, Fe, Ti, Ba and F content. Micas in mafurites and katungites follow a trend of strong Fe enrichment and Al depletion leading to a composition rich in tetraferriphlogopite component. Mafurite exhibits the lowest Al (down to 5 wt % Al₂O₃), Ba and Ti, but the highest F content (up to 7.6 wt %) of all the analysed micas. Phlogopite of katungite shows the lowest F content (down to 1.5 wt %) and is intermediate between mafurite and ankaratrite/ugandite with respect to Al, Ba and Ti. The most evolved phlogopite occurs in ankaratrites and ugandites, reaching values of 11.7 wt % Al₂O₃, 8 wt % TiO₂ and 5 wt % BaO indicative of a common high T but low P crystallization (Righter and Carmichael, 1996). Fluorine is also high in phlogopites from these volcanics (up to 5.8 wt %).

Nepheline/Kalsilite and Leucite

All analysed nephelines and kalsilites contain more silicon and less aluminium than is represented by the formula (Na,K)AlSiO₄, a common feature of natural members of the

nepheline group. In both ankaratrites and ugandites the kalsilite component shows only insignificant variation (21.1-29.7 mol %) but is not as high as those from nephelines of Mt. Nyiragongo (up to 42.4 mol %; Sahama and Wiik, 1952). The FeO* content (0.84-2.4 wt %) of the investigated nephelines is high and it seems that Fe³⁺ partially substitutes for Al, with the highest observed ferric iron content occurring in nepheline from ugandite (approximately 2.5 wt % Fe₂O₃).

Kalsilite occurs in the groundmass of mafurite and katungite and was detected for the first time in ugandite during the course of this study. The amount of kalsilite end-member component in individual crystals correlates with the whole-rock K-content. It has its maximum at 95.2 mol % in kalsilites from mafurite (up to 7 wt % K₂O) and decreases through 86.5-88.9 mol % in uganditic to 65.1 mol % in katungitic kalsilite (up to 3.2 wt % whole-rock K₂O). Edgar and Arima (1981) reported extremely K-rich nepheline from katungites, which could not be detected in the course of this study.

Kalsilite crystals in the matrix of melilite-bearing ultramafic lamprophyres from the Beaver Lake area in East Antarctica (Foley *et al.*, 2002) show partly a comparably high Na content. Those kalsilite crystals occur in phlogopite-poor parts and are assumed to have become gradually Na-rich by reaction with phlogopite, the latter taking up the K₂O. In contrast, the Ugandan kalsilites show higher Fe₂O₃ content, reaching values up to 2.6 wt %. The Fe content of mafuritic kalsilite is extremely high (on average 6.4 wt % Fe₂O₃).

All analysed kamafugitic leucites are in rather good accordance with the ideal formula KAlSi₂O₆ exhibiting no excess silica as is typical of lamproitic leucites (Foley, 1985). The content of ferric iron varies in a narrow range from 0.7 to 1.5 wt % Fe₂O₃*.

Spinel and perovskite

Most of the oxide minerals in the investigated African kamafugites belong to the spinel group and represent either the chromite or the magnetite series. Weakly zoned Mg-Al-

chromite occurs as microphenocrysts and as inclusions in other phenocryst phases, whereas small titanomagnetite crystals occur in the groundmass and sometimes discontinuously overgrow chromites. The zonation trend shows an increase both in ferrous and ferric Fe, Ti as well as in Zn from core to rim, whereas the Mg and Cr contents decrease. The chromites seem to be in equilibrium with olivine as indicated by petrography (inclusions) and a linear relationship between Mn and mg-number controlled by exchange between these both phases.

In ankaratrites, abundant microphenocrystal and groundmass oxides (up to 6 vol %) are exclusively titanomagnetite.

Small euhedral perovskite crystals occur in the groundmass of all kamafugites reflecting their low silica and high Ca content. They exhibit a rather uniform chemical composition approaching the ideal formula CaTiO₃ and contain less than 10 mol % of minor components, particularly Nb, Ce and Fe.

Oscillatory zonation occurs in perovskite from katungites and involves only subtle variations in LREE, alkalis, Nb and Fe on a very fine scale. Sometimes these crystals are arranged around olivine phenocrysts and form a «necklace texture» which is also widespread in kimberlites (Chakhmouradian and Mitchell, 2000) and type aillikites.

Among the investigated kamafugites katungite, mafurite and ankaratrite are the members with the highest Fe content in perovskite (up to 1.72 wt % Fe₂O₃*), whereas in ugandite Fe₂O₃* amounts to less than 1 wt %.

WHOLE-ROCK CHEMISTRY

Major elements

Katungites, mafurites, ugandites and ankaratrites are characterized by silica undersaturation (32.3-42.8 wt % SiO₂) and moderate to high K₂O content (2.1-7.0 wt %). Furthermore, low Al₂O₃ content and high CaO (up to 16.6 wt %) as well as high MgO (up to 22.5 wt %) content are marked features of the

kamafugites (Fig. 9). Kamafugites from Toro-Ankole show a range in their mg-numbers between 67 and 80, whereas the ankaratrites have much lower Mg/Fe ratios ranging between 42 and 61 (Tab. 5).

In the kamafugite rock group K_2O exceeds Na_2O , with K_2O/Na_2O ratios varying between 1 and 10. Foley *et al.* (1987) recognized them as representing one end-member amongst ultrapotassic magma compositions and distinguished them as standard members of Group II from lamproites (Group I) and Roman Province type rocks (Group III).

Trace elements

Kamafugitic lava from the Toro-Ankole province is strongly enriched in LREE and other incompatible trace elements. The kamafugites have the highest incompatible element concentrations of all volcanic rocks from the Western Branch of the African rift (compare Furman, 1995; Rogers *et al.*, 1998; Furman and Graham, 1999). They display negative anomalies for K, Pb and P in the mantle-normalized abundance pattern (Fig. 10). The relative K-depletion is strongest in katungites and leucite ankaratrites. The Pb depletion and HFSE enrichment in Ugandan kamafugites is reflected in high Ce/Pb (29-57) and low Th/Ta (1.3-1.9) ratios approaching values typical of ocean island basalts (Chauvel *et al.*, 1992). Furthermore, a marked plateau occurs at Nb-Ta, whereas a trough is formed at Zr-Hf. Titanium is slightly higher than neighbouring elements in ugandites and ankaratrites (not shown).

A smooth convex-upward primitive mantle-normalized abundance curve is characteristic for members of the Ugandan kamafugite series (Fig. 10), although occasional spikes do occur for individual rocks.

COMPARISON WITH ITALIAN AND BRAZILIAN KAMAFUGITES

In the central Italian Umbria-Latium ultra-alkaline district (ULUD) and Roman Province,

kamafugitic magmatism took place during the Late Pleistocene. Here, the San Venanzo and Cupello volcanoes are the best investigated localities (Gallo *et al.*, 1984; Cundari and Ferguson, 1991; Stoppa and Cundari, 1995, 1998; Peccerillo, 1999). Newly discovered kamafugite exposures at Grotta del Cervo further south in the district were reported by Stoppa *et al.* (2002). In the Roman Province kamafugitic rocks occur only as ejecta in the Montefiascone volcanic complex (Di Battistini *et al.*, 2001) and the Alban Hills volcano (Aurischio and Federico, 1985; Federico *et al.*, 1994; Federico and Peccerillo, 2002).

In Brazil, kamafugites occur along the northern margin of the Parana basin in the Upper Cretaceous Minas-Goiás Alkaline Province (Sgarbi and Gaspar, 2002). Rocks of kamafugitic affinity occur in all the subprovinces, but the best investigated examples are from the Alto do Paranaíba (Gibson *et al.*, 1995; Carlson *et al.*, 1996; Araujo *et al.*, 2001) and Santo Antonio da Barra region (Sgarbi *et al.*, 2000; Sgarbi and Gaspar, 2002).

Petrography and Mineral Chemistry

The ULUD kamafugites of central Italy have been described as olivine melilitites (venanzite) and kalsilitites (coppaelite) and broadly resemble African katungite and mafurite, respectively (Gallo *et al.*, 1984; Cundari and Ferguson, 1991). Ejected material from the Roman Province was classified as pyroxene-kalsilite melilitolite and kalsilite melilitolite; these are regarded as intrusive counterparts of kamafugitic lava (Di Battistini *et al.*, 2001) and probably represent olivine-free cumulates.

Kalsilite-bearing mafurites and leucite ugandites from Brazil are often intensively altered, particularly analcimitized. The only melilite-bearing kamafugite, initially reported as katungite (Danni and Gaspar, 1994), contains clinopyroxene and leucite and was renamed by Sgarbi and Gaspar (2002) as melilite ugandite. In general, the Brazilian kamafugites are less olivine-phyric than the

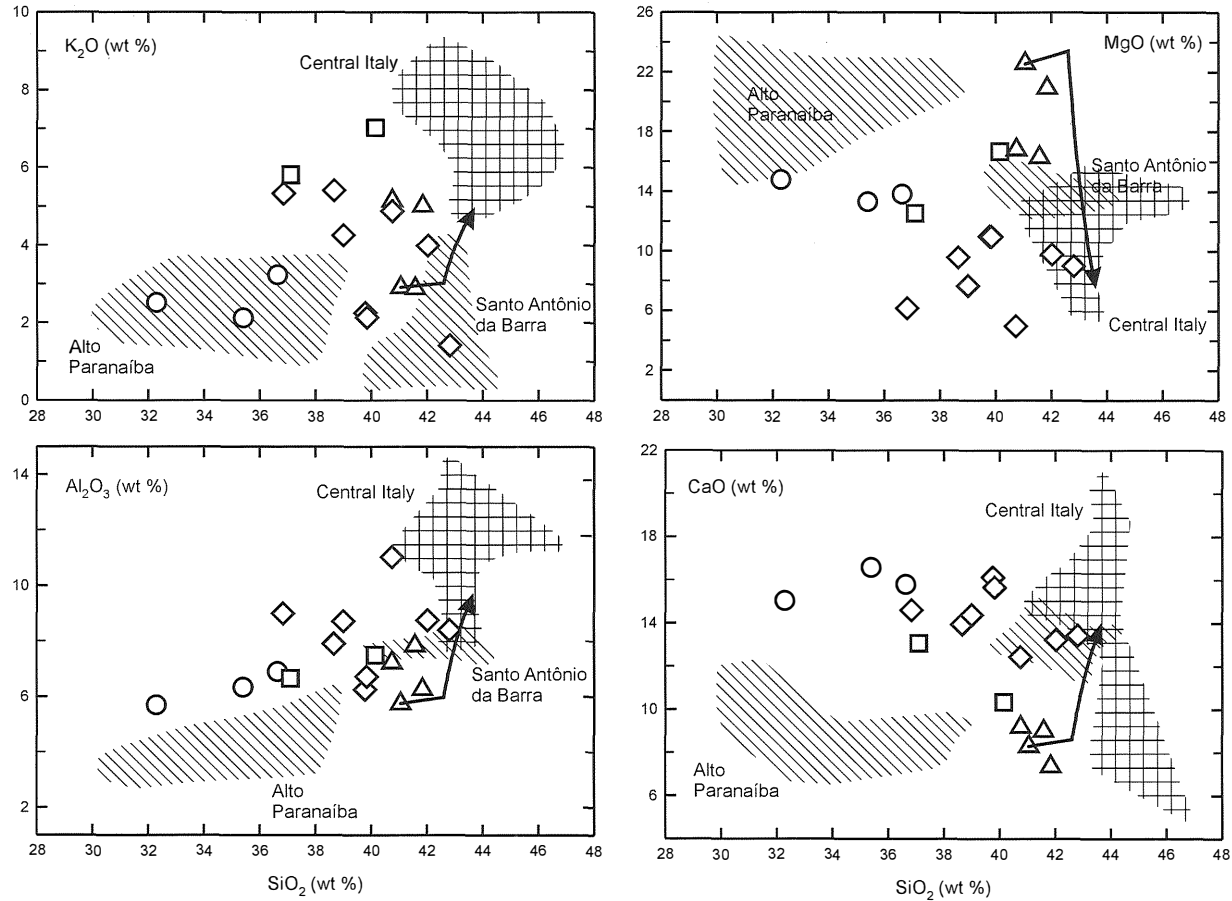


Fig. 9 – K_2O , MgO , Al_2O_3 and CaO versus SiO_2 for kamafugites from Uganda, Italy and Brazil. Arrows represent a fractionation path simulated by the software MELTS (Ghiorso and Sack, 1995). Starting composition was the ugandite C4035 and olivine is the only liquidus phase between 1531 and 1200°C (1 kbar, fO_2 at NNO). A stepwise removal of approximately 35% olivine shifts the initial ugandite composition towards ankaratritic composition. Data for Italian kamafugites are from Gallo *et al.* (1984), Stoppa *et al.* (1995), Stoppa and Cundari (1998), Peccerillo (1998), Di Battistini *et al.* (2001), Stoppa *et al.* (2002). Data for Brazilian rocks are from Carlson *et al.* (1996), Araujo *et al.* (2001), Sgarbi and Gaspar (2002). Symbols as in Figure 6.

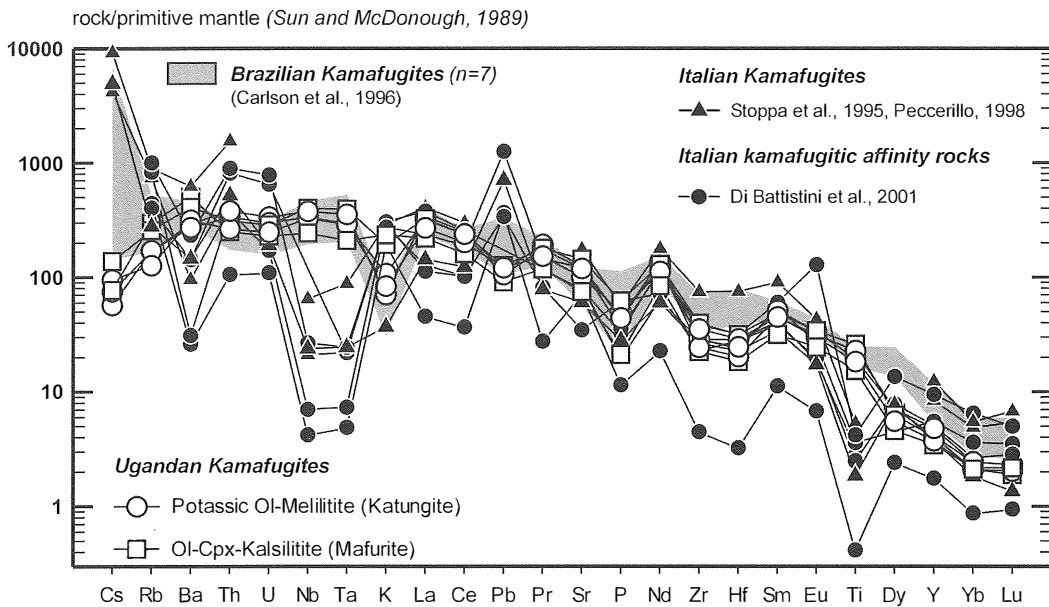


Fig. 10 – Primitive mantle-normalized incompatible element distribution pattern of representative Ugandan, Italian and Brazilian kamafugites and kamafugite affinity rocks. The Ugandan katungites and mafurites are displayed as open circles and open squares, respectively.

African type rocks (Gibson *et al.*, 1995) but also contain appreciable amounts of kalsilite.

Kamafugitic clinopyroxenes reach comparably high Al and Ti values, what distinguishes them from nearly pure diopside typical of lamproites and orangeites. Different kamafugite occurrences exhibit minor differences in Al und Ti content (Fig.6). Clinopyroxenes from the Ugandan type rocks seem to follow an evolutionary trend with increasing Al and Ti content from mafurite and ugandite towards ankaratrite.

The Italian kamafugitic rocks exhibit two different trends with respect to Al and Ti. Firstly, the kalsilite-bearing rocks of Cupaello are, like their Ugandan counterparts, extremely Al and Ti poor, whereas a slight increase in Ti and Al occurs towards the San Venanzo melilitic rocks. Secondly, some kamafugite clinopyroxenes from San Venanzo, Pian di Celle and Grotta del Cervo as well as pyroxenes from the kamafugite affinity rocks of Montefiascone and Colle Fabbri show

extremely high Al contents and lie off the general kamafugitic trend.

These high Al but low Ti contents in clinopyroxenes from ULUD kamafugites and Roman Province kamafugitic ejecta seem to be a response to a more aluminous but HFSE depleted host magma composition. A pressure effect on the clinopyroxene chemistry is negligible in highly potassic systems as was shown by the experiments of Edgar *et al.* (1976).

The trend of increasing Al and Ti content is also characteristic for the mafuritic to uganditic clinopyroxenes from the Brazilian Santo Antonio da Barra subprovince but no differences are exhibited between rock types.

Melilite from the ULUD kamafugites and from Montefiascone kamafugitic ejecta are distinct from the microphenocrysts of Ugandan katungites in bearing more Fe²⁺ and Al and exhibiting a trend towards decreasing Mg (Fig. 7). A gehlenite end-member component is absent in melilites from Ugandan katungites

and Italian kalsilitites (Cupaello) reflecting the characteristic Al depletion of the system. Melilite crystals from San Venanzo have slightly higher Al contents (up to 7 mol % gehlenite) but the melilitites from the related Colle Fabbri melilitolite are, like the clinopyroxenes, highly aluminous (up to 47 mol % gehlenite). In contrast to more common sodic melilitite the soda-melilitite component is comparably low (6.4-25 mol %) in both Italian and Ugandan melilitites (Fig. 7).

Phlogopites from the kamafugites of San Venanzo and Grotta del Cervo as well as from mafurites of the Alto Paranaiba province show similar low Ba and Ti contents to the Ugandan mafurites and katungites (Fig. 8). An increase in Ba and Ti occurs towards the ugandites from Toro Ankole as well as from the Alto Paranaiba province. This trend proceeds towards the ankaratrites. Mafurites and ugandites from Santo Antonio da Barra are extremely Ba- and Ti-rich and resemble kimberlitic mica compositions. The F content of phlogopites from San Venanzo (up to 6.3 wt %) is as high as in phlogopites from African mafurites and ugandites. Fewer F data are available from Brazilian kamafugites, but these show lower F contents (up to 2.6 wt %) similar to Ugandan katungites.

Kalsilite of the Brazilian and Italian kamafugitic rocks approaches the end-member composition and a sodium-rich kalsilite as observed in Ugandan katungites with $K_{85}Ne_{15}$ solid solution has only been reported from Nyiragongo volcano (T. Platz, pers. comm.) and from alnöitic ultramafic lamprophyres (Foley *et al.*, 2002). All the kamafugitic kalsilites have a comparable Fe content ranging between 0.8-3.6 wt % Fe_2O_3 . Exceptionally high Fe contents up to 8 wt % occur in kalsilite from Ugandan mafurites.

Early-stage Cr-spinels from melilitic rocks of San Venanzo are Al richest (up to 19 wt % Al_2O_3) amongst the kamafugites. This is in good agreement with the comparably high Al content of the bulk rock, indicating higher Al content of the primitive magma. The Cr content is high (46-52 wt % Cr_2O_3) and compares well

with the spinels from Ugandan mafurites. Values for Mg and Fe^{2+} show a narrow range for all the kamafugites. The ferric iron content in spinels of kamafugitic rocks from San Venanzo is the lowest observed and might indicate a low oxygen fugacity in the magma. Ugandan mafurites approach similarly low Fe^{3+} values. The Cr-spinels of mafurites and ugandites from the Alto Paranaiba province have a comparably low Cr_2O_3 content (37-45 wt %) to spinels from the African katungites and ugandites. The values for Mg, ferrous and ferric iron are also similar to the type ugandites.

Perovskites from kamafugites approach the $CaTiO_3$ end-member composition with characteristically low alkalis and REE contents. The sparse data show that the Brazilian and Italian perovskites are slightly richer in Na (up to 2 wt % Na_2O) than their Ugandan counterparts ($Na_2O < 0.5$ wt %; see also Lloyd *et al.*, 1996).

Whole-rock chemistry

The new whole-rock trace element data show that the Ugandan kamafugites are similar to their Brazilian counterparts, but are significantly different to the Italian kamafugites (Fig. 10). The Ugandan kamafugites are similar to the Brazilian rocks in showing smooth slightly convex-upward incompatible element patterns (Fig. 10), and both have a narrow abundance range for moderately incompatible elements, suggesting a limited amount of crystal fractionation in their evolution. Ugandan mafurites show no trough in the pattern at K, in contrast to katungites from Uganda as well as mafurites and ugandites from Brazil. The Ugandan rocks exhibit the lowest Cs and Rb but highest Ba abundances. Italian kamafugites contrast strongly with both Ugandan and Brazilian rocks in showing an «arc signature» with negative spikes for Ba, Nb, Ta, P, Zr, Hf and Ti and a marked peak at Pb.

The Italian kamafugitic rocks are characterized by higher SiO_2 , Al_2O_3 and K_2O content than their Brazilian and Ugandan analogues (Fig. 9). The ejecta of kamafugitic

affinity from Montefiascone and the Alban Hills show the highest Al contents (up to 15 wt % Al_2O_3) closely followed by the Grotta del Cervo kamafugites (12.6 wt %) and the classic San Venanzo melilitites (10-12 wt %). The latter have up to 9 wt % K_2O .

Brazilian kamafugites resemble the range of Ugandan kamafugitic rock types, but show distinct chemistry between the Alto Paranaíba and Santo Antonio da Barra subprovinces. Sgarbi and Gaspar (2002) proposed a fractional crystallization relationship for Santo Antonio da Barra mafurites (12-15 wt % MgO) and ugandites (5-8 wt % MgO).

Kamafugites from all three regions have strong LREE/HREE fractionation (Fig. 11) with low HREE concentrations suggestive of residual garnet or clinopyroxene during melt generation. Distinct MREE-HREE patterns may indicate distinct roles for clinopyroxene between kamafugite provinces.

Negative Eu-anomalies are restricted to the Italian rocks and point to an upper crustal end-member in their magma genesis (Peccerillo, 1998). Ultrapotassic rocks from Serbia (Prelevic *et al.*, 2001) show a similar Eu-anomaly. Here, fractionation of Eu seems to be controlled by the presence of residual apatite during melt generation, requiring no low-pressure fractionation in these primitive rocks with a mg-number of 80 (D. Prelevic, pers. comm.). This is in agreement with the experimentally determined apatite/liquid partition coefficients which show convex-upward REE patterns (Watson and Green, 1981). If apatite is controlling the REE distribution, the absence of negative Eu-anomalies in Ugandan kamafugites might be in response to the comparably high melting rate of the widespread metasomatized, apatite-bearing upper mantle beneath the western branch of the African Rift (see Lloyd *et al.*, 1985). This Ugandan source apatite is assumed to have no Eu-anomaly, as is the case for metasomatic apatites from rift settings such as the Eifel, Massif Central, New South Wales and south Yemen (Chazot *et al.*, 1996; O'Reilly and Griffin, 2000).

PETROGENETIC IMPLICATIONS FOR KAMAFUGITES

Source characteristics and fractional crystallization of African kamafugites

The kamafugite group of Toro Ankole can be regarded as a continuum; various petrographic gradations between rock types have been described by Holmes and Harwood (1932) and Holmes (1950). Some of those mineralogical variations have been attributed to heteromorphic reactions (Yoder, 1986) implying distinct physicochemical conditions during emplacement.

However, end-member katungite, mafurite and ugandite are chemically distinct in terms of major elements. They cannot be related through fractional crystallization. The only fractionation relationship seems to exist between olivine-rich ugandite and potassic nephelinite (ankaratrite). Geochemical modelling of this relationship and simulation with the program MELTS (Ghiorso and Sack, 1995) show that the stepwise removal of approximately 35 % olivine from ugandite results in residual melt compositions close to ankaratrite (Fig.9). As the silicate liquid approaches ankaratritic composition, the calculated olivines (Fo 84) closely resemble the remnant olivines (Fo 82.5-86) found in ankaratrite (Fig.4C). Phlogopite reaction rims indicate incomplete removal and later reaction of the fractionated olivines now in disequilibrium with the host magma composition (Luth, 1967) but might also be a consequence of falling temperature. Conditions for the calculation were 1 kbar and $f\text{O}_2 = \text{NNO}$ buffer, as guided by the low ferric value of spinels, by low Fe_2O_3 content of leucite, and by Ca-rich olivines (Fig. 5).

The compositional differences between kamafugitic rock types point to differences in depth or degree of melting. Major differences in source composition can be excluded because of the similar REE distribution pattern and nearly constant incompatible trace element ratios (e.g. $\text{Zr/Nb} = 1.3-1.9$).

Numerous experiments have been performed to evaluate the source mineralogy of

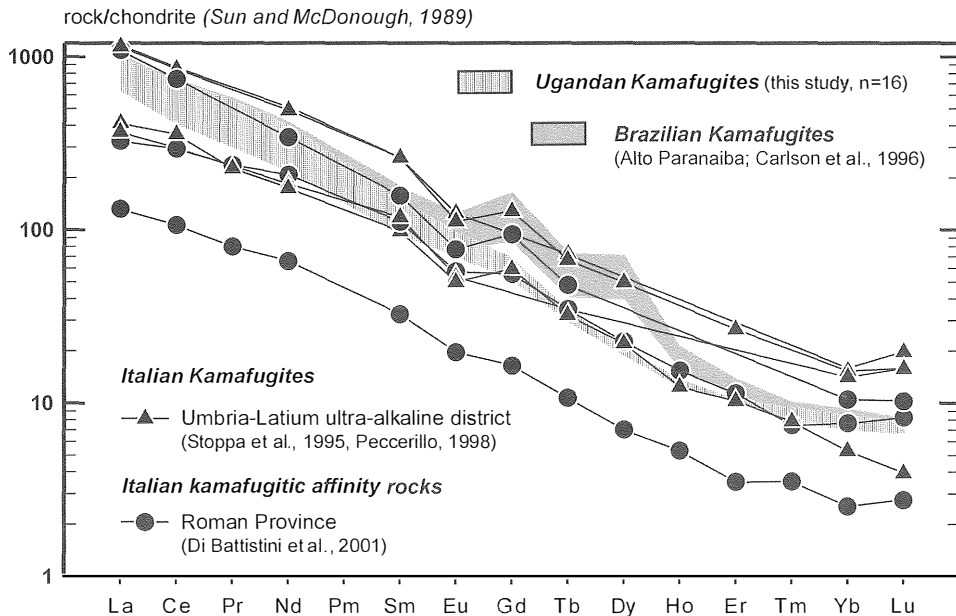


Fig. 11 – Chondrite-normalized REE distribution pattern of Ugandan kamafugites from Toro-Ankole in comparison with Italian and Brazilian occurrences.

kamafugitic magma (Edgar *et al.*, 1976; Ryabchikov and Green, 1978; Edgar *et al.*, 1980; Lloyd *et al.*, 1985; Edgar, 1991). These show that clinopyroxene, phlogopite, CO_2 and H_2O play an important role in the genesis of kamafugites, possibly as widespread mica clinopyroxenite (Lloyd and Bailey, 1975; Arima and Edgar, 1983) or wehrlitic veins in mantle peridotite at the base of the lithosphere (Foley, 1992; Gibson *et al.*, 1995). The ratio of $\text{CO}_2/\text{H}_2\text{O}$ in the source must have been high as indicated by the presence of primary groundmass carbonate in some kamafugites and their association with carbonatites (von Knorring and Du Bois, 1961; Barker and Nixon, 1989; Stoppa *et al.*, 2000).

Petrogenetic difference between provinces

Sahama's (1974) kamafugite series, whose definition was based on Ugandan kalsilitite-bearing volcanics, has more recently been extended by newly discovered Italian and Brazilian kalsilitic-melilitic rocks. It is

important to note that these are not the only kamafugites but the best studied.

The Italian kamafugites show the greatest deviation from the Ugandan type rocks and hence differences in petrogenesis between both provinces must be strongest. As an example, the olivine melilitite from San Venanzo represents a much Al-richer melt composition than any known from the Ugandan type area. This is manifested in the chemistry of Cr-spinel, melilite and phlogopite. Higher Si, Al and K content as well as comparably low Ce/Pb, high Th/Ta ratios and negative Eu-anomalies point to an upper crustal end-member in the petrogenesis of Italian kamafugites. This end-member might be of sedimentary derivation brought to mantle depths via subduction (Conticelli and Peccerillo, 1992).

However, there is considerable debate between researchers who consider the central Italian magmatism to be a consequence of petrogenetic processes typical of continental

rift settings (Cundari, 1980; Vollmer *et al.*, 1981; Cundari and Ferguson, 1991; Stoppa and Lavecchia, 1992; Lavecchia and Stoppa, 1996; Stoppa and Woolley, 1997; Castorina *et al.*, 2000; Lavecchia and Boncio, 2000) and those who argue for a fundamental link between subduction and enrichment of the mantle sources beneath central Italy (Edgar, 1980; Holm and Munksgaard, 1982; Peccerillo, 1985; Rogers *et al.*, 1985; Beccaluva *et al.*, 1991; Conticelli and Peccerillo, 1992; Serri *et al.*, 1993; Peccerillo, 1998).

A subduction-related metasomatism of the Italian lithospheric mantle was demonstrated for the Finero phlogopite-peridotite (Zanetti *et al.*, 1999), which was tectonically emplaced as a thrust slice in the Italian Alps. Furthermore, all the Italian kamafugites, including the most primitive, show negative anomalies for Ta, Nb and Ti indicative of ancient subduction processes. Cessation of subduction in this part of the Mediterranean occurred in the Lower Tertiary (Venturelli *et al.*, 1984) and Late Pleistocene kamafugite magmatism occurred in an extensional rift setting (Lavecchia and Boncio, 2000), reactivating the stored subduction signature.

The differences between Brazilian and Ugandan kamafugites in mineral and whole-rock major element chemistry are only minor and the trace elements are similar, as are their tectonic settings. Kamafugites from both Toro-Ankole and Minas-Goiás Alkaline Provinces penetrated Proterozoic mobile belts in the vicinity of Archean cratons. Here, magmatism was triggered by plume activity in an extensional tectonic regime (Gibson *et al.*, 1995; 1997; Simiyu and Keller, 1997).

We agree with Bailey and Collier (2000) that a thick lithosphere, low geothermal gradient, extensional tectonics and an important role for volatiles are essential for kamafugite magmatism, but there are indications that the nature of mantle metasomatism preceding kamafugite magmatism can differ. Whereas the Ugandan and Brazilian subcontinental lithosphere was affected by metasomatizing agents derived from the asthenosphere (Davies

and Lloyd, 1989; Gibson *et al.*, 1995; Carlson *et al.*, 1996), the lithospheric mantle beneath central Italy was probably affected by enrichment processes linked with subduction-related crust (Peccerillo, 1999).

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