Mineralogical and chemical composition and distribution of rare earth elements in clay-rich sediments from central Uganda

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Clay-rich sediments from the Kajjansi, Kitiko, Kitetika, and Ntawo valleys in central Uganda were analyzed for mineralogical and chemical composition, including the rare earth element (REE) contents. The valleys are filled with Quaternary to Recent alluvial and lacustrine sands, silt, and gravels, which formed from the bed rock metasediments of the Buganda-Toro System and from granitoid rocks that include rocks of the basement. The sediments are dominated by kaolinite and quartz, and minor phases include smectite, chlorite, and illite/muscovite. Whole rock chemistry shows that sediment samples rich in SiO_2 have low Al, Fe, Sc and Cr contents. The high chemical index of alteration (CIA) values (87 to 96), chemical index of weathering (CIW) values around 98 and low contents of the alkali and alkali earth elements of the clay-rich sediments suggest a relatively more intense weathering source area. Barium, Rb, Ca, and Mg were probably flushed out by water during sedimentation. The chondrite-normalized REE patterns of the clay-rich sediments show LREE enrichments and a negative Eu anomaly. The high chondrite-normalized La/Yb ratios, and Gd/Yb ratios lower than 2.0, indicate that the sediments are enriched in the LREEs and are similar to typical post-Archean shales, such as Post-Archean Australian Shale (PAAS). The mineralogical composition, REE contents, and elemental ratios in these sediments suggest a provenance from mainly felsic rocks, with only minor contributions from basic sources. The basic sediments were most likely derived from metasedimentary rocks, such as muscovite-biotite schists, which are characteristic of the Buganda-Toro System rocks, whereas the felsic sediments are derivatives of granitoid rocks of the basement. The most significant geochemical finding is that despite intense weathering, which has affected most elements, the REE, Th, and Sc remain immobile.

INTRODUCTION

A suite of sediments from central Uganda was collected to study their mineral and chemical composition, including rare earth element (REE) patterns, and to determine their source rocks. The samples were taken from the quarries at Kajjansi, Kitiko, Kitetika, and Ntawo, which are located in broad valleys with gentle gradients cut in hills capped with laterite. The flat-topped laterite duricrust capped hills form noteworthy topographic features with murram and boulders occurring on hilltops. Murram is essentially a loose gravel made up of fragments of concretionary laterite up to 2.5 cm or 5 cm in diameter, but often contains boulders of laterite, which may be up to 1.5 m in diameter (Tuhumwire *et al.*, 1995). It is variable in distribution and thickness and usually covered by soils. The valleys are filled with papyrus swamps and drain towards Lake Victoria. The sedimentary rocks exposed in these valleys are underlain by granitoids from the basement and metasediments of the Buganda-Toro System (Fig. 1(b)). The basement is composed mostly of igneous and metamorphic rocks of uncertain Precambrian age, with some outcrops of Paleozoic, Mesozoic, or Cenozoic rocks (Holmes, 1951). The Buganda-Toro system extensively overlies the basement. It occupies much of the south, west, and central parts of Uganda and

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Fig. 1. (a) Simplified geological map of Uganda, modified after MacDonald (1966). The inset shows the location of Uganda in Africa. (b) Generalized geological map of study area and the surrounding areas, central Uganda (modified after MacDonald, 1966), showing locations of the analyzed samples reported in Tables 1 and 2. The inset map of Uganda shows the location of the study areas.
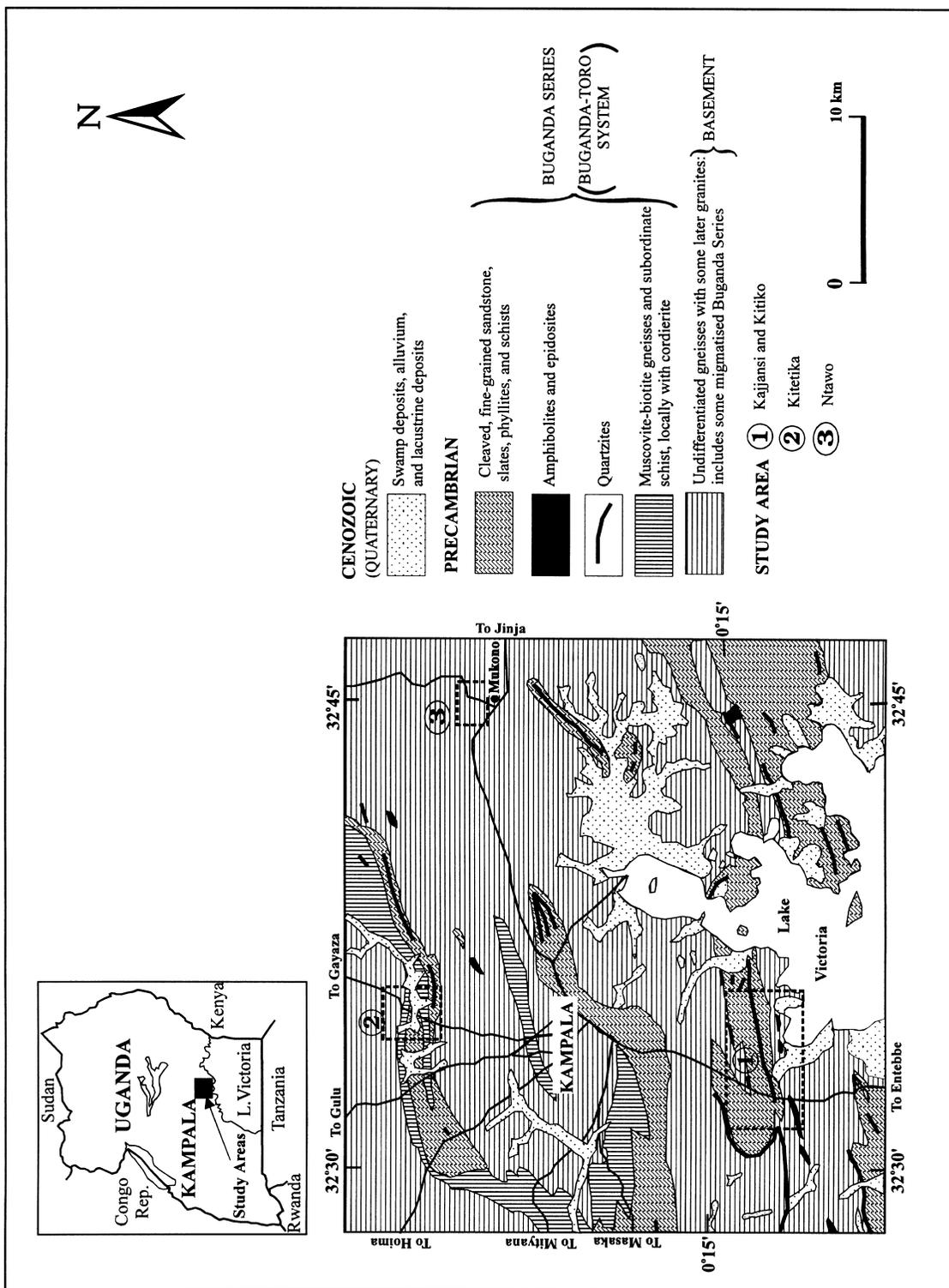
(b)

Fig. 1. (continued).

stretches from Jinja to the Rwenzori mountains in western Uganda (Fig. 1(a)). The Buganda-Toro rocks are of low metamorphic grade and comprise mainly arenites, argillites, phyllites, schists, grits, granites, and meta-volcanics (McConnell, 1959).

In this study, the sediments sampled were derived from granitoids and other Precambrian rocks of the basement and metamorphosed Buganda-Toro System. These sediments are heavily altered, mostly to clays (McGill, 1965). Locally, these clay-rich sediments have been used to produce bricks and pottery. All previous studies of these sediments have been directed towards these applications (e.g., McGill, 1965; Nyakairu and Kaahwa, 1998; and references therein). Despite these studies, the chemical and mineralogical compositions of these sediments, and their sources, are still poorly understood. The main aim of this study is to determine the mineralogical and geochemical composition of these sediments, with special focus to the behavior of the REEs. The results are discussed in terms of source area weathering and provenance.

DESCRIPTION OF STUDY AREAS

Kajjansi

Kajjansi valley is a north-western extension of the Murchison bay (area 1 in Fig. 1(b)). The valley is filled with Quaternary to Recent alluvial and lacustrine sands, silt, and gravels, which formed from metasediments of the Buganda-Toro System and from basement granitoids (Fig. 1(b)). Sampling was carried out at the main pit of Uganda Clays Limited factory. The pit has a depth of about 3 to 4 m, which, in places, extends to 5 m. The deposit can be divided into three layers: a gray layer overlying a dark gray or near black layer, which, in turn, overlies a light gray layer. The gray layer thickness varies from 60 to 100 cm, a dark gray layer varies from 90 to 160 cm and a light gray layer varies from 60 cm onwards until saprolite of the bedrock is reached. In some places, the dark gray layer exhibits what appears to be bedding surfaces with impressions of plant leaves and stems, as well as thin laminations of silt and some mud balls. Decomposed swamp vegetation is abundant in both the gray and dark gray layers. The overburden encountered was a thin layer of fine white sand or a black clayey soil with an average thickness of 30 cm.

Kitiko

The outcrops are sediments from a former lake, which was part of Lake Victoria during climatic

Fig. 2. Field photograph taken at Kitiko pit showing sampling method used. In the photograph two layers are identified. The uppermost dark gray layer that is rich in organic matter is underlain by the gray to brown layer, which becomes more brown near the top of the water table. In the top left corner is a pile of locally made bricks and onlookers are in the right hand corner. The sample was collected and placed in the sample container at the very location, and a measuring rod was used to determine the pit depth. The sampling method used was similar in all the four sediment outcrops.

changes in the Pleistocene and Holocene (Bishop, 1969). The surface cover comprises cemented sand and gravel, which is up to a meter thick. However, in some parts of the pit, the surface cover is represented by a near black layer rich in organic matter as shown in photograph (Fig. 2). Below this is a 3–5 m thick sediment layer, which is locally used in brick and tile making. No bedding due to specific grain-sizes was observed. The sediment is gray to brownish, becoming more brown near the water table (Fig. 2).

Kitetika

The valley is filled with Quaternary to Recent alluvial and lacustrine sands, silt, and gravels,

which are derived from underlying metasediments of Buganda-Toro system and granitoid rocks of the basement (Fig. 1(b)). The outcrop is 1 to 2 m thick, and is composed of a sandy sediment, with bedding of different colors. In a pit dug in this area, three distinct horizontally bedded layers, whose thicknesses are quite different from each other were observed. The bottom layer was sampled, which comprises a brownish-gray sediment, with small sandstones, a middle, grayish and an uppermost black layer due to organic matter.

Ntawo

The Ntawo area comprises horizontally layered sediments, with a thickness of approximately 2 to

Table 1. Semi-quantitative (wt%) mineralogical composition of Kajjansi, Kitiko, Kitetika, and Ntawo sediments, Central Uganda, analysed by X-ray diffractometry. Calculations performed using a modified method after Schultz (1964).

Sample	Depth (cm)	Kaolinite	Chlorite	Smectite	Quartz	Feldspars	Calcite
KAJJANSI DEPOSIT							
KJ-1	390	27	11	3	12	48	
KJ-2	300	45	9	7	38	1	
KJ-3	240	39	19	15	25	3	
KJ-4	120	46	14	19	18		4
KJ-5	60	34			64	1	
KJ-6	30	26	8	19	45	3	
KITIKO DEPOSIT							
KS-1	240	67	15		16	2	
KS-2	210	75			24	1	
KS-3	180	54			32	14	
KS-4	150	34	12	19	31	4	
KS-5	120	62			38		
KS-6	90	55	23		21	1	
KS-7	60	54		28	18		
KS-8	30	44			55	1	
KITETIKA DEPOSIT							
KT-L	120	51	26		23		
KT-M	90	36			62	2	
KT-U	60	30			67	3	
KT-A	30	18		4	78		
NTAWO DEPOSIT							
NT-1	180	32		16	49	3	
NT-2	150	47			46	7	
NT-3	120	19			77	4	
NT-4	90	22	8		64	7	
NT-5	60	30	7	10	50	3	
NT-6	30	24	13	20	39	3	1

3 m, which developed from the granitoid basement rocks. The bottom layer consists of a gray/brown sediment, which is overlain by a gray layer, followed by a gray sandy layer and a brown/dark soil cover with abundant organic matter. A pit dug in the center of the Ntawo valley shows three distinct layers. A gray layer at the bottom is overlain by a black layer together make a sediment that is about 2 m thick. This sediment is overlain by 0.5 to 1 m of soil cover.

MATERIALS AND METHODS

For this study, we analyzed 24 sediment samples from Kajjansi, KJ ($n = 6$); Kitiko, KS ($n = 8$); Kitetika, KT ($n = 4$), and Ntawo, NT ($n = 6$). Representative samples were collected at different depth (Table 1) from the bottom to the top of each of the outcrops, corresponding, to macroscopic features (e.g., color of different layers) (Fig. 2). Sample masses were reduced to 250 g by coning and quartering, followed by drying at 60°C for 12 h. Aliquots of 20–30 g of each dried sample were powdered in an agate mill. Mineralogical analysis was performed using a Philips powder X-ray diffractometer (PW 3710), operated at 45 kV/35 mA using Ni-filtered CuK_α radiation, with automatic slit and on-line computer control. Semi-quantitative analyses were made using a modified method after Schultz (1964). The samples were X-rayed using both random powder and oriented slides for identification of mineral composition, and the diffractograms were processed using Philips PC-APD software, version 3.6.

Major element oxides and some trace elements (Sr, Y, Zr, Nb, Ni, Cu, V, and Ba) concentrations were determined by X-ray fluorescence (XRF) spectrometry at the University of the Witwatersrand, Johannesburg, South Africa. Details of the XRF method are described by Reimold *et al.* (1994). Other trace elements were determined at the Institute of Geochemistry, University of Vienna (Austria), by instrumental neutron activation analysis (INAA). Samples weighing about 150 mg each were sealed in polyethylene capsules and, together with rock standards AC-E

and Allende, G-2 (cf., Govindaraju, 1989; Bowman, 1994), irradiated for 8 hours in the 250 kW Triga reactor of the Atominstitut der Österreichischen Universitäten, Vienna (Austria), at a neutron flux of 2.10^{12} n $cm^{-2}s^{-1}$. For details of the INAA method, including precision and accuracy, see Koeberl (1993).

MINERALOGY

The XRD patterns of all whole-rock samples, which were obtained following the method of Brown and Brindley (1984), indicate the predominating presence of kaolinite and quartz, with minor muscovite or illite. Iron mineral peaks were not observed, indicating that no hematite was incorporated in the clay minerals. Smectite and chlorite are present in trace amounts in some of the samples. Identification of secondary minerals was difficult, because their peaks tended to be obscured by the greater peaks of the major minerals kaolinite and quartz. Semi-quantitative analyses, following a method modified after Schultz (1964), showed differences in bulk mineral compositions between the individual sediments (Table 1). For example, the kaolinite content varies from 18 wt% for KT-4 to 67 wt% for KS-1, with samples much richer in quartz being poorer in kaolinite. The KS samples contain high amounts of kaolinite, with two of the samples consisting of smectite. The NT and KT samples have high quartz contents, with a few of them showing minor amounts of chlorite and smectite. All of the sediment samples contain only small amounts of feldspar and calcite, except for KJ-1, which has 48 wt% feldspar. All sediments are, therefore, rich in kaolinite and quartz, which indicate that they are derived mainly from felsic sources. The minor illite and illite-weathered products, such as smectite and chlorite present in some samples, and the low feldspar abundance, suggest a contribution from basic sources. The felsic sediments are derivatives of granitoid basement rocks, whereas the basic component is derived from the basic schists of either the basement or the Buganda Series (cf., Cullers, 1994a).

WHOLE-ROCK GEOCHEMISTRY

Table 2 lists the results of the major and trace element analyses for the Ugandan sediments compared to the average compositions of the Singo granite from Nagudi *et al.* (2000); the upper crust (UC) and Post-Archean Australian Shale (PAAS), from Taylor and McLennan (1985), and the North American Shale Composite (NASC), from Gromet *et al.* (1984). The Singo granite occurs in western central Uganda, intrudes into local metasediments, and is one of the few granitoids in Uganda that has been studied for its trace element composition. Thus, it can be used as a proxy for granites in the study area. As expected from weathered rocks, there is a large variation in the major element content for all analyzed samples. For example, the SiO_2 contents range from 51 to 85 wt%, the TiO_2 content from 0.58 to 1.67 wt%, the Al_2O_3 content from 7.61 to 27.08 wt%, and the Fe_2O_3 content ranges from 1.46 to 12.20 wt%. The contents of MgO, CaO, and MnO are all low. The Na_2O and K_2O contents range from 0.04 to 0.17 wt%, and from 0.56 to 1.09 wt% respectively. Nesbitt and Young (1982, 1984, 1989, 1996) and

Nesbitt *et al.* (1996) used the ternary diagrams Al_2O_3-$(CaO + Na_2O)$-K_2O (the A-CN-K), diagram and $Fe_2O_3 + MgO$-$(CaO + Na_2O + K_2O)$-Al_2O_3 (the A-CNK-FM), diagram to deduce weathering trends. On both the A-CN-K diagram (Fig. 3), and the A-CNK-FM diagram (Fig. 4), all the sediments display an intense weathering history. The sediments plot in a region clearly suggesting different relative contents in Al_2O_3, CaO, Na_2O, and K_2O from those of Singo granite, PAAS, NASC, and UC, and plot closer to high Al_2O_3 contents, which is suggestive of a relatively high intensity of weathering. Weathering has proceeded to a stage at which significant amounts of the alkali and alkali earth elements were removed from the sediments. Albite has not been identified in the samples, indicating that the sediments are mature.

Weathering studies show that Ca, Na, and Sr are rapidly lost during chemical weathering and the amount of these elements lost is proportional to the degree of weathering (Wronkiewicz and Condie, 1987, and references therein). Two chemical weathering indices have been proposed: CIA (chemical index of alteration); Nesbitt and Young (1982), and CIW (chemical index of weathering);
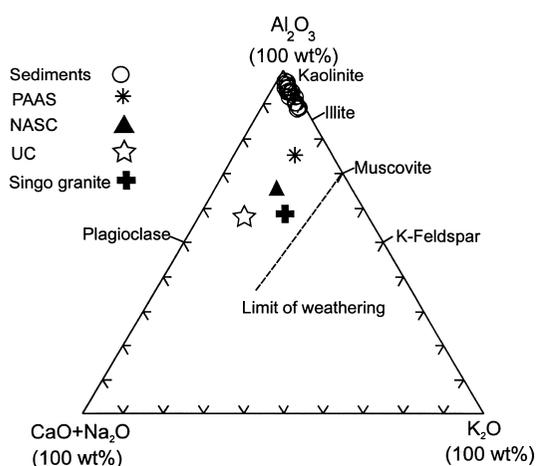

Fig. 3. Al_2O_3-$(CaO + Na_2O)$-K_2O plot of sediment samples (after Nesbitt and Young, 1982, 1984, 1989, 1996; Nesbitt et al., 1996), compared to data for Post-Archean Average Shale (PAAS) and Upper Crust (UC) given by Taylor and McLennan (1985); and North American Shale Composite (NASC) given by Gromet et al. (1984).
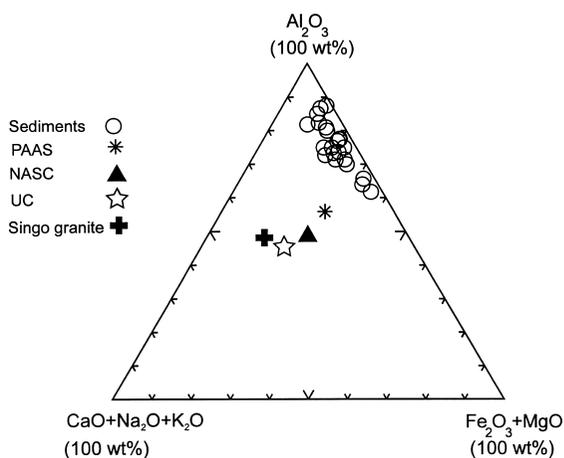
Fig. 4. Triangular Al_2O_3-$(CaO + Na_2O + K_2O)$-$Fe_2O_3 + MgO$ plot of sediment samples (after Nesbitt and Young, 1982, 1984, 1989, 1996; Nesbitt et al., 1996) in comparison with Post-Archean Average Shale and Upper Crust (data from Taylor and McLennan, 1985) and North American Shale Composite (data from Gromet et al., 1984).

Table 2. Major and trace element composition of Kajjansi, Kitiko, Kitetika, and Ntawo sediments, Central Uganda

Sample	KAJJANSI						KITIKO							
	KJ-1	KJ-2	KJ-3	KJ-4	KJ-5	KJ-6	KS-1	KS-2	KS-3	KS-4	KS-5	KS-6	KS-7	KS-8
SiO_2	51.59	54.33	70.39	55.26	76.08	69.07	53.43	58.08	70.89	70.88	71.50	55.25	74.98	64.11
TiO_2	1.29	1.17	1.67	1.38	1.02	1.32	1.39	1.20	1.25	0.72	1.07	1.06	0.58	1.11
Al_2O_3	22.91	20.62	16.41	23.96	12.29	14.88	23.88	25.78	16.78	14.41	14.42	27.08	11.92	20.00
Fe_2O_3	9.68	12.20	3.11	6.09	3.27	5.19	6.84	3.35	2.25	3.62	4.90	3.38	2.70	4.61
MnO	0.04	0.05	0.04	0.03	0.03	0.05	0.04	0.04	0.05	0.04	0.03	0.03	0.03	0.03
MgO	0.57	0.13	0.05	0.24	—	0.06	0.14	—	—	0.05	—	0.04	—	—
CaO	0.38	0.17	0.15	0.25	0.11	0.17	0.16	0.09	0.09	0.20	0.07	0.16	0.18	0.13
Na_2O	0.10	0.06	0.08	0.10	0.07	0.10	0.12	0.05	0.05	0.08	0.07	0.14	0.08	0.07
K_2O	0.83	0.74	0.97	0.66	0.62	0.71	1.01	0.80	1.00	0.70	0.81	0.63	0.56	0.72
P_2O_5	0.08	0.09	0.05	0.06	0.04	0.09	0.25	0.10	0.03	0.04	0.14	0.04	0.03	0.13
LOI	12.39	10.58	7.51	12.44	6.88	8.66	11.88	10.97	7.38	8.98	7.38	12.78	9.26	9.42
Total	99.86	100.14	100.43	100.47	100.41	100.30	99.14	100.46	99.77	99.72	100.39	100.59	100.32	100.33
Sc	26.8	17.8	13.8	22.8	10.1	14.6	22.7	17.4	12.8	12.1	14.7	24.9	11.8	14.9
V	178	193	124	180	97	124	160	149	122	84	113	248	78	164
Cr	128	110	102	153	72.6	101	151	146	129	132	96.3	304	112	134
Co	11.4	7.96	6.16	9.01	5.29	8.39	6.41	4.21	3.71	5.99	6.05	6.05	4.46	5.54
Ni	36	27	22	36	15	23	31	24	18	21	23	44	16	22
Cu	13	20	<2	17	<2	5	17	<2	<2	<2	9	20	2	<2
Zn	81.9	49.9	60.3	85.5	46.0	55.2	80.9	47.2	49.5	59.8	63.8	75.0	59.2	50.6
As	3.21	3.83	1.72	2.55	1.35	1.62	2.68	0.72	0.84	1.27	1.31	3.08	0.83	2.12
Rb	74.6	57.9	61.6	53.2	37.9	48.8	88.6	50.2	52.5	58.8	62.3	59.5	40.9	55.7
Sr	51	40	55	59	38	48	53	32	32	37	41	38	35	36
Y	25	24	32	48	22	35	64	33	27	43	30	41	53	33
Zr	372	385	587	496	361	504	538	712	869	372	380	493	231	584
Nb	68	50	61	73	44	54	74	64	54	45	47	85	39	55
Sb	0.59	0.37	0.29	0.39	0.30	0.37	0.60	0.38	0.36	0.24	0.25	0.65	0.15	0.46
Cs	3.59	2.16	2.26	3.52	1.69	2.19	3.62	2.43	2.02	2.99	2.59	3.63	2.42	2.46
Ba	205	187	272	631	210	290	299	153	194	184	292	243	208	189
La	62.8	46.9	83.4	94.4	46.0	72.9	144	78.1	54.3	71	68.5	90.2	76.0	74.6
Ce	76.6	54.9	117	154	63.0	117	306	157	77.9	116	120	135	152	139
Nd	30.0	21.6	51.9	78.6	30.7	42.9	125	51.9	37.2	56.4	52.6	63.6	73.4	59.5
Sm	6.23	4.30	7.97	11.2	4.30	8.45	19.0	7.98	5.06	8.56	7.51	9.38	10.5	8.09
Eu	1.20	0.90	1.46	2.20	0.86	1.61	3.17	1.38	1.41	1.58	1.34	1.61	2.03	1.46
Gd	4.49	2.73	4.63	7.19	2.67	5.04	9.70	5.13	5.31	4.17	4.29	5.75	4.49	5.44
Tb	1.04	0.62	1.00	1.25	0.58	1.00	1.65	0.92	0.96	0.81	0.79	0.99	0.73	0.89
Tm	0.64	0.42	0.64	0.75	0.35	0.64	0.89	0.60	0.61	0.45	0.48	0.61	0.53	0.58
Yb	4.48	2.73	4.21	5.47	2.40	4.35	6.57	4.16	3.99	3.38	3.50	4.21	3.78	3.60
Lu	0.68	0.44	0.65	0.83	0.39	0.66	1.03	0.63	0.61	0.54	0.55	0.65	0.56	0.57
Hf	10.1	10.7	17.0	12.2	8.60	12.7	13.8	18.2	23.5	10.1	10.7	12.8	5.40	17.3
Ta	4.93	3.09	4.27	4.58	2.32	3.60	5.03	4.03	3.35	3.08	3.15	5.90	2.17	3.77
Th	29.6	24.2	24.9	28.7	15.1	22.7	38.2	28.4	29.0	23.0	22.4	43.5	22.3	28.6
U	6.23	4.50	5.00	5.15	2.72	4.50	6.71	4.76	4.53	3.41	4.18	5.61	2.95	5.19
CIA	92.9	94.5	91.8	94.7	92.6	92.3	93.8	95.9	92.7	92.0	92.8	95.7	91.8	94.6
CIW	96.4	98.1	97.6	97.5	97.5	96.9	98.0	99.1	98.6	96.7	98.4	98.1	96.3	98.3
La/Sc	2.34	2.63	6.04	4.14	4.55	4.99	6.34	4.49	4.24	5.87	4.66	3.62	6.44	5.01
Th/Sc	1.10	1.36	1.80	1.26	1.50	1.55	1.68	1.63	2.27	1.90	1.52	1.75	1.89	1.92
Cr/Th	4.32	4.55	4.10	5.33	4.81	4.45	3.95	5.14	4.45	5.74	4.30	6.99	5.02	4.69
Eu/Eu*	0.69	0.80	0.73	0.75	0.78	0.75	0.71	0.66	0.83	0.81	0.72	0.67	0.90	0.67
$[La/Yb]_{cn}$	9.47	11.6	13.4	11.7	13.0	11.3	14.8	12.7	9.20	14.2	13.2	14.5	13.6	14.0
$[Gd/Yb]_{cn}$	0.81	0.81	0.89	1.06	0.90	0.94	1.20	1.00	1.08	1.00	0.99	1.11	0.96	1.22

Harnois (1988). Nesbitt and Young (1982) reported a CIA value of nearly 100 for kaolinite and chlorite, and 70 to 75 for average shales, whereas Taylor and McLennan (1985) reported a CIA value of 85 to 100 for residual clays. Condie (1993) reported that most post-Archean shales show moderate losses of Ca, Na, and Sr from source weathering, with CIW values of 80 to 95 and Sr contents of 75 to 200 ppm. In contrast, most Archean shales, show greater losses of all three elements, with CIW of 90 to 98, and Sr contents < 100 ppm. The CIA of the sediments varies between 87 to 96, which is high compared to PAAS, UC, and NASC, but close to that of kaolinite (Table 2). The CIW, which does not include K_2O, ranges between 96 to 99, with Sr contents ranging from 30 to 61

Table 2. (continued)

Sample	KITETIKA				NTAWO						SINGO	PAAS	NASC	UC
	KT-L	KT-M	KT-U	KT-V	NT-1	NT-2	NT-3	NT-4	NT-5	NT-6				
SiO₂	64.00	80.51	80.83	77.26	64.65	84.70	82.80	78.77	74.79	70.31	72.65	62.80	64.80	66.00
TiO₂	0.91	0.87	0.81	0.84	1.00	0.82	0.96	1.49	1.44	1.31	0.42	1.00	0.70	0.50
Al₂O₃	19.28	9.96	9.49	11.01	16.14	8.59	7.61	9.38	13.67	16.59	13.33	18.90	16.90	15.20
Fe₂O₃	4.54	2.80	2.40	2.92	7.64	1.46	2.36	1.74	1.88	2.57	2.60	7.22	5.65	5.00
MnO	0.03	0.04	0.10	0.07	0.04	0.04	0.10	0.05	0.04	0.04	0.08	0.11	0.06	0.08
MgO	0.10	—	—	—	0.05	—	—	—	—	0.11	0.60	2.20	2.86	2.20
CaO	0.14	0.05	0.06	0.08	0.13	0.04	0.06	0.10	0.12	0.23	1.09	1.30	3.63	4.20
Na₂O	0.13	0.12	0.10	0.11	0.08	0.04	0.06	0.12	0.11	0.17	3.54	1.20	1.14	3.90
K₂O	0.99	1.09	0.98	0.98	0.69	0.65	0.68	0.99	0.75	1.01	4.87	3.70	3.97	3.40
P₂O₅	0.04	0.03	0.04	0.04	0.10	0.02	0.05	0.06	0.04	0.03	0.13	0.16	0.13	—
LOI	9.72	5.14	5.66	6.71	9.84	4.14	5.42	7.77	7.45	8.24	0.94	6.00	—	—
Total	99.88	100.61	100.47	100.02	100.36	100.50	100.10	100.47	100.29	100.61	100.25	104.59	99.84	100.48
Sc	14.1	7.75	6.37	8.73	11.9	4.10	5.36	7.00	9.64	11.8	8.37	16.0	14.9	11.0
V	110	82	67	83	270	70	64	65	97	138	28	150	130	60
Cr	90.5	65.2	45.4	75.5	85.0	41.4	51.1	50.7	71.0	95.7	27.7	110	125	35.0
Co	8.10	5.40	16.7	8.93	5.97	2.38	7.82	3.64	3.69	6.53	5.81	23.0	25.7	10.0
Ni	28	14	13	17	21	<9	9	10	15	19	11	55	58	20
Cu	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	—	50	—	25
Zn	63.0	26.3	29.5	45.5	46.5	17.1	32.6	32.7	41.1	66.5	40.2	85.0	—	71.0
As	1.05	2.17	0.94	1.40	1.72	0.71	0.79	1.02	0.80	0.27	—	—	28.4	1.50
Rb	95.8	68.2	54.3	76.5	46.9	24.8	24.3	38.7	41.3	53.9	348	160	125	112
Sr	44	34	34	35	36	30	31	48	47	61	103	200	142	350
Y	35	26	25	27	29	10	13	17	22	20	57	27	35	22
Zr	388	485	476	428	454	317	482	688	491	585	159	210	200	190
Nb	54	40	36	42	47	39	40	62	68	63	20	19	13	25
Sb	0.22	0.54	0.15	0.45	0.33	0.21	0.22	0.31	0.36	0.21	0.30	—	2.09	0.2
Cs	5.15	2.74	2.18	3.34	1.98	1.13	0.95	1.38	2.35	2.24	7.09	15	5.16	3.7
Ba	250	266	267	260	190	150	178	225	202	269	552	650	636	550
La	67.9	47.2	39.5	50.9	69.6	22.1	30.2	42.3	66.6	57.0	56.5	38	31.1	30
Ce	100	72.3	66.3	75.2	97.1	23.2	57.5	53.8	79.4	78.7	101	80	66.7	64
Nd	46.8	33.7	32.2	34.7	41.5	11.1	21.8	19.3	36.5	30.0	39.6	32	27.4	26
Sm	6.71	5.17	4.46	5.78	6.56	1.62	3.05	3.90	6.32	5.56	7.43	5.6	5.59	4.5
Eu	1.30	0.86	0.92	0.99	1.14	0.33	0.55	0.75	1.08	1.04	1.30	1.1	1.18	0.88
Gd	3.88	3.85	3.90	3.74	5.13	1.55	2.16	4.19	4.63	4.36	8.56	4.7	—	3.8
Tb	0.78	0.74	0.73	0.72	0.88	0.31	0.49	0.81	0.80	0.79	1.44	0.77	0.85	0.64
Tm	0.42	0.46	0.45	0.47	0.53	0.18	0.31	0.49	0.48	0.45	0.56	0.4	—	0.33
Yb	3.17	3.19	3.17	3.05	3.63	1.41	1.98	3.43	3.41	3.38	5.70	2.8	3.06	2.2
Lu	0.49	0.48	0.48	0.47	0.59	0.23	0.31	0.53	0.56	0.52	0.90	0.43	0.46	0.32
Hf	11.3	13.2	12.8	13.0	13.8	8.10	13.3	17.9	13.9	18.0	5.45	5	6.3	5.8
Ta	3.43	2.27	1.88	2.95	3.21	2.08	2.45	4.10	5.09	4.50	1.87	—	1.12	2.2
Th	23.8	20.4	17.4	21.8	27.3	11.6	15.2	18.9	24.8	25.0	28.8	14.6	12.3	10.7
U	4.41	4.33	3.30	4.57	9.44	2.99	4.93	6.71	9.16	7.82	11.8	3.1	2.66	2.8
CIA	92.6	87.1	87.7	88.8	93.5	91.1	88.9	86.6	91.9	90.2	—	—	—	—
CIW	97.6	97.2	97.2	97.1	97.8	98.4	97.3	96.1	97.2	96.0	—	—	—	—
La/Sc	4.82	6.09	6.20	5.83	5.85	5.39	5.63	6.04	6.91	4.83	6.75	2.38	2.09	2.73
Th/Sc	1.69	2.63	2.73	2.50	2.29	2.83	2.84	2.70	2.57	2.12	3.44	0.91	0.83	0.97
Cr/Th	3.80	3.20	2.61	3.46	3.11	3.57	3.36	2.68	2.86	3.83	0.96	7.53	10.16	3.27
Eu/Eu*	0.78	0.59	0.67	0.65	0.60	0.64	0.66	0.57	0.61	0.65	0.70	0.66	—	0.65
[La/Yb]ₒₙ	14.5	10.0	8.40	11.3	13.0	10.6	10.3	8.30	13.2	11.4	10.7	9.2	6.9	9.2
[Gd/Yb]ₒₙ	0.99	0.98	1.00	0.99	1.15	0.89	0.88	0.99	1.10	1.05	1.22	1.36	—	1.4

Major elements as wt% and trace elements in ppm. Total Fe as Fe_2O_3, CIA = $[Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)] \times 100$ and CIW = $[Al_2O_3/(Al_2O_3 + CaO + Na_2O)] \times 100$ in molecular proportions. CaO in both CIA and CIW is CaO in silicate fraction only and was corrected following the McLennan (1993) method. SINGO = Average Singo granite (data from Nagudi et al., 2000); PAAS = Average Post-Archaean Australian Shale; UC = Upper Crust (data from Taylor and McLennan, 1985) and NASC = Average North American Shale (data from Gromet et al., 1984). $Eu/Eu* = Eu_{cn}/\sqrt{[(Sm_{cn})(Gd_{cn})]}$.

ppm. The CIA and the CIW are both higher than those of average shales, suggesting relatively intense source area weathering. The high CIA and CIW values in the sediments probably reflect the presence of clay minerals and absence of detrital feldspars.

TRACE ELEMENT GEOCHEMISTRY

The behavior of trace elements during sedimentary processes is complex due to factors including weathering, physical sorting, adsorption, provenance, diagenesis, and metamorphism (e.g., Garrels and Mackenzie, 1971; Krönberg *et al*., 1979; Nesbitt *et al*., 1980; Taylor and McLennan, 1985; Wronkiewicz and Condie, 1987). The trace element data show large variations compared to PAAS, NASC, and UC (Table 2). All sediments have similar contents in trace elements and are enriched in Y, Zr, Nb, Hf, Ta, Th, and U. These elements are associated with heavy minerals, such as zircon, which is resistant to weathering. They are preferentially partitioned into melts during crystallization and anatexis (Feng and Kerrich, 1990), and as a result, these elements are enriched in felsic rather than mafic rocks. Thorium and U behave differently during weathering, as U, unlike Th, is chemically mobile as U^{6+} and there is a tendency of the Th/U ratio to be elevated above upper crustal values of 3.5 to 4.0 (McLennan *et al*., 1993). The sediments show Sc, V, Zn, Ni, and Cr, contents similar to, or even above, abundances for PAAS. However, they are depleted in Co, Cu, Rb, Sr, as well as in Cs, and Ba contents. Generally these elements are associated with clay minerals, and their low values could be attributed to the low values in parent rocks and the high quartz content in the sediments (Table 1). This is in agreement with studies by Nesbitt *et al*. (1980) and Wronkiewicz and Condie (1987), in which these authors conclude that small cations, such as Na, Ca, and Sr, are selectively leached and weathered from weathering profiles, whereas cations with relatively large ion radii, such as K, Cs, Rb, and Ba, may be fixed by preferential exchange and adsorption on clays. Therefore, in general, weath-

ering conditions were more intense in the source area before sedimentation, compared to the conditions for PAAS.

Strontium and barium mostly reside in plagioclase and K-feldspar, respectively (Puchelt, 1972). The fractionation of these two elements can result from the selective weathering of these feldspars. Weathering of plagioclase will decrease the Sr content, because plagioclase is more easily weathered than K-feldspar, and Sr is more mobile than Ba. A depletion of Ba could be due to recrystallization of clays and progressive destruction of feldspars. Potassium, Rb, and Cs are mainly hosted in micas and K-feldspar (Heier and Billings, 1970); thus, alteration of these minerals will dominate the fractionation of these elements. Rubidium has a trend comparable to that of Nb and V and is less mobile than K, whose behavior it otherwise follows. Rubidium with respect to K is preferentially retained in weathered illite (Garrels and Christ, 1965). Niobium and V are less mobilized, in agreement with what is known about their behavior during weathering (cf., Middleburg *et al*., 1988). The elements As and Sb are concentrated in samples that are enriched in iron oxides (Fe_2O_3) due to weathering under arid oxidizing conditions.

RARE-EARTH ELEMENT VARIATIONS

The results of the REE analyses are summarized in Fig. 5. All analyzed sediment samples have similar concentrations of the REEs. Chondrite-normalized patterns are typical for shale in general, with an enrichment of the LREEs. All samples have pronounced negative Eu anomalies, ranging from 0.57 to 0.90. The Eu anomaly parallels the depletion in Na_2O and CaO, suggesting that it developed at least partially in response to plagioclase weathering, where most of the Eu is hosted. The Eu anomaly in sedimentary rocks is usually interpreted as being inherited from igneous source rocks (McLennan and Taylor, 1991; Taylor and McLennan, 1985; Awwiller, 1994). Figure 5 illustrates that despite the difference in the absolute abundances, the samples show REE pat-
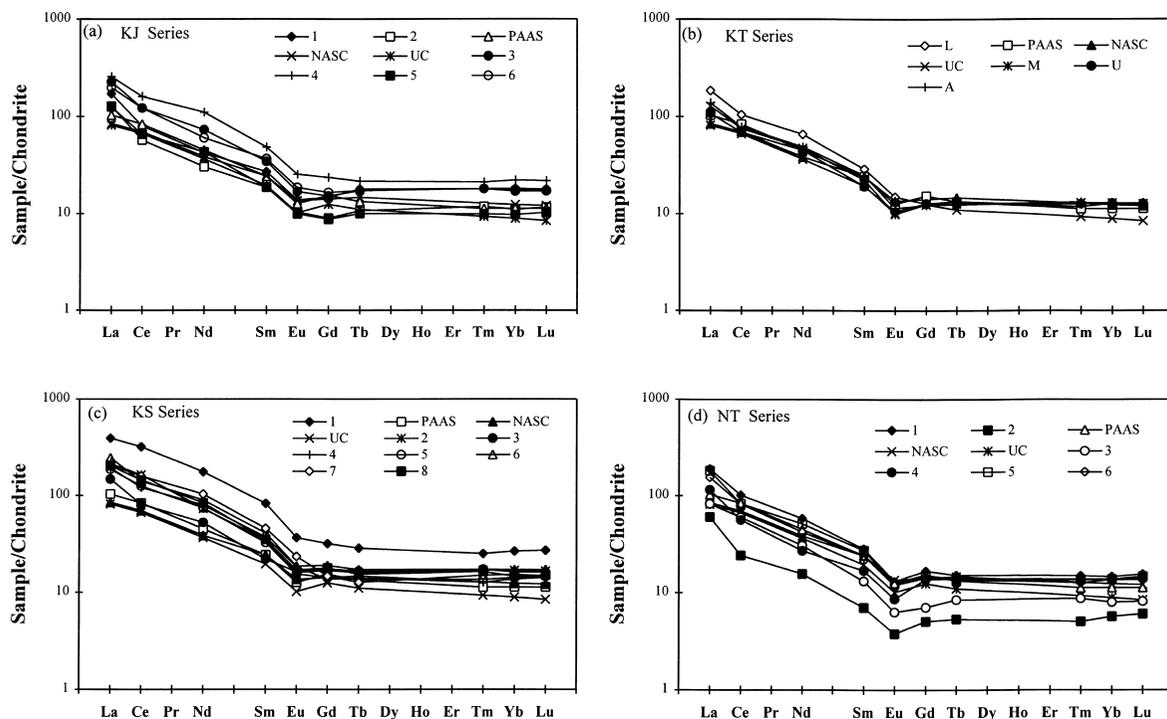
Fig. 5. Rare earth element plots of sediment samples normalized to C1 chondrites after Taylor and McLennan (1985). (a) Kajjansi, (b) Kitetika, (c) Kitiko and (d) Ntawo samples.

terns that are similar to those of NASC and PAAS, but differ in the HREE content compared to the UC. The chondrite-normalized La/Yb ratio ranges from 8.3 to 14.5, with most sediments having slightly higher values than those of PAAS and UC. The relative depletion in the HREEs compared to LREEs may be due to a lower concentration of heavy minerals, for example zircon. The low abundances of Zr in the sediments (Table 2) supports this interpretation.

PROVENANCE

The REEs and high field strength elements (HFSE, including Y, Zr, Ti, Nb, Ta), Th, Sc, Hf, and Co are the most suitable ones for provenance determination, because of their relatively low mobility during weathering, transport, diagenesis, and metamorphism. Ratios of both incompatible and compatible elements are useful for differentiating between felsic and mafic source components.

In addition, the REE patterns have been also used to infer sources of sedimentary rocks, since basic rocks contain low LREE/HREE ratios and no Eu anomalies, whereas more silicic rocks usually contain higher LREE/HREE ratios and negative Eu anomalies (e.g., Cullers and Graf, 1983). Therefore, the REE patterns of the source rocks may be preserved in sedimentary rocks (Taylor and McLennan, 1985; Wronkiewicz and Condie, 1987, 1989).

Mineralogical maturity of the sediments indicated by the proportion of compositionally mature alumina-rich minerals such as kaolinite is consistent with having a felsic or reworked sedimentary source (e.g., Cullers et al., 1975, 1987). The CIA, which varies from 87 to 96, and the CIW values (96 to 99) point towards a more felsic source and may indicate sediment recycling processes (Nesbitt et al., 1980). The sediments have fractionated REE patterns, with $(La/Yb)_{cn}$ varying from 8.3 to 14.5, and a negative Eu anomaly
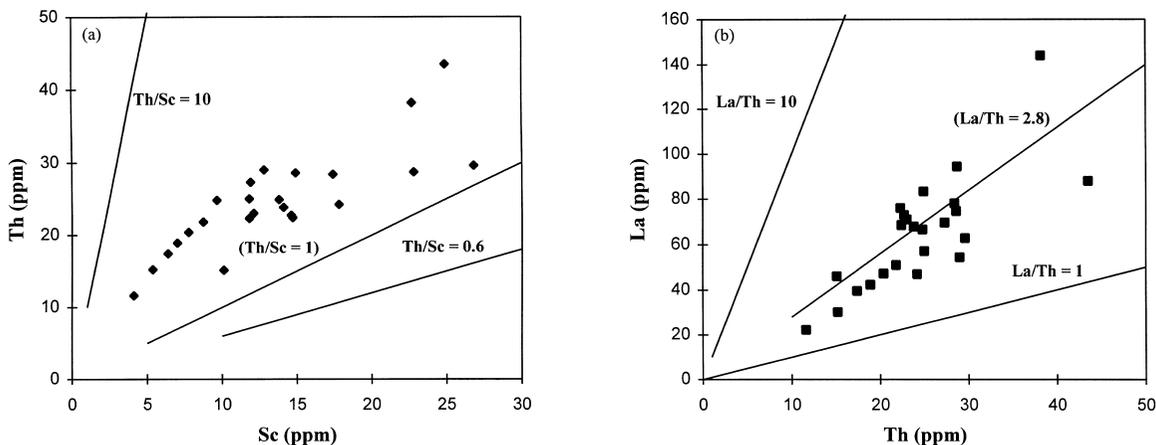
Fig. 6. (a) Th versus Sc for sediment samples. Th/Sc = 1 ratio is that of the upper continental crust (UC) (b) La versus Th for the sediment samples. The La/Th = 2.8 ratio is that of upper continental crust (data from Taylor and McLennan, 1985).

(0.57 to 0.90). The LREEs are enriched and the HREE patterns are almost flat, with $(Gd/Yb)_{cn}$ varying from 0.81 to 1.36. These characteristics indicate that the original source area was felsic and the negative Eu anomaly is regarded as evidence for a differentiated source, similar to granite (McLennan, 1989; McLennan et al., 1993; Taylor and McLennan, 1985, 1995). The relative enrichments of (normally) incompatible elements (e.g., LREE, Th) over compatible elements (e.g., Sc, Co) in the sediments, indicate relatively felsic average provenance compositions and a relatively severe weathering regime (McLennan et al., 1993). The slight differences among the REE patterns probably do not reflect changes in source area composition, but are likely due to variations in mineral sorting and weathering.

The immobile elements La and Th are more abundant in felsic than in basic rocks, whereas Sc and Co are more concentrated in basic rocks than in felsic rocks (Taylor and McLennan, 1985; Wronkiewicz and Condie, 1987). It has been shown that ratios, such as La/Sc, Th/Sc, Co/Th, Cr/Th, and Eu/Eu*, in siliciclastic sediments, allow to place constraints on the average provenance composition (e.g., Cullers et al., 1988; Cullers, 1994b, 1995; Wronkiewicz and Condie, 1987, 1989, 1990; Cox et al., 1995). Thus, the concen-

tration of these elements and the corresponding elemental ratios in sediments may be useful for provenance determination. The geochemical differences between elements such as Th and La (indicative of a felsic source) and Sc and Cr (indicative of a mafic source) have been exploited to distinguish between felsic and mafic provenance by various authors (e.g., McLennan, 1989; McLennan and Taylor, 1991; McLennan et al., 1980; Wronkiewicz and Condie, 1990). The Th versus Sc plot (Fig. 6(a)) shows that the sediment data scatter above the Th/Sc = 1 line with most samples that have Sc contents below 15 ppm indicating a more felsic component. The Th/Sc values are higher than that of UC. On the La/Th plot (Fig. 6(b)), the sediment data fall into the range of UC, with most samples having a significant felsic component. This indicates that the sediments did not have a uniform provenance. The ratios of Th/Sc range from 1.1 to 2.84 and La/Th from 1.87 to 3.35, also suggesting a mixed source of sediments.

In a La-Th-Sc diagram (Fig. 7), which is used to discriminate felsic and basic provenance of fine-grained sediments (e.g., Cullers, 1994a, b), the sediment data fall in a region that indicates a predominantly felsic source, but does not exclude an intermediate source or possible mixing between felsic and basic source rocks. The clustering of
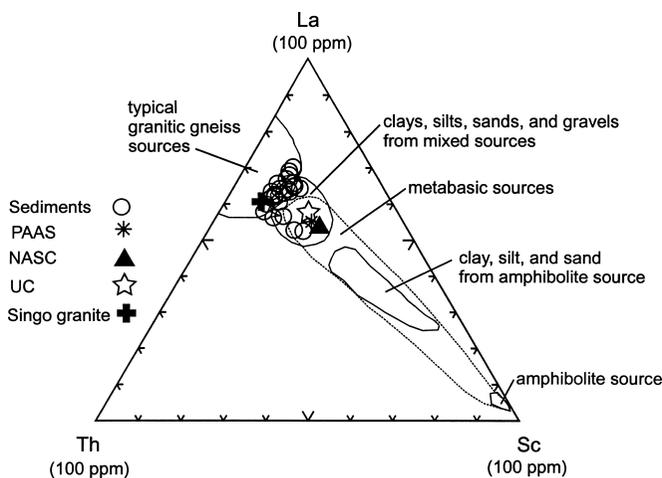
Fig. 7. Ternary plot of La-Th-Sc for the sediment samples after Cullers (1994a) compared with Singo granite (data after Nagudi et al., 2000); Post-Archean Average Shale, Upper Crust (data from Taylor and McLennan, 1985), and North American Shale Composite (data from Gromet et al., 1984).

sediment data more or less around the Singo granite value suggest that the sediments are mainly derived from a source with a composition similar to that of the Singo granite. The sediment data show a cluster along the La-Th edge, at a position closer to La than to Th. The fact that all the sediment data plot close to the values for UC, NASC, and PAAS indicates that, despite the intense weathering experienced by the sediments, La, Th, and Sc have remained immobile. The sediments have low contents of Sc, Fe, and Cr (and Co), high concentrations of the REE, Th, Hf, high La/Sc, Th/Sc, La/Cr, Th/Cr, and Ba/Sc ratios, which indicates that they were derived mainly from felsic rocks (cf., Cullers *et al.*, 1987, 1988; Cullers, 1988). It can be concluded that the sediments were derived from predominantly felsic sources, rather than from basic rocks. The sediments with a basic component were most likely derived from metasedimentary rocks, such as muscovite-biotite schists, which are characteristic of the Buganda-Toro System rocks, while the felsic sediments are derivatives of granitoid rocks of the basement. Thus, on the basis of chemical composition, the sediments are derived locally, mainly from highly acidic rocks, with minor contributions from basic rocks.

SUMMARY

We analyzed 24 sediment samples from Kajjansi, Kitiko, Kitetika, and Ntawo, central Uganda, in order to determine their mineralogical and chemical compositions, REE characteristics, and their provenance. XRD analyses show that the sediments are dominated by kaolinite and quartz, with minor smectite, chlorite, and illite/muscovite. From the weathering diagrams (Figs. 3 and 4), it is possible to infer that the samples underwent a relatively high degree of weathering. Weathering has proceeded to a stage where a major part of the alkali and alkali earth elements were removed. The low CaO contents in sediments indicate their maturity relative to most typical post-Archean shales, such as PAAS and NASC. The sediments are depleted in Ca, Na, and Sr compared to Archean shale compositions (Condie, 1993). CIW values of around 98, and variations in CIA values from 87 to 96, indicate that the sediments contain residual clays rich in kaolinite (Taylor and McLennan, 1985).

The low contents of Sc, Fe, and Cr (and Co), and high abundances of the REE, Th, Hf, high La/Sc, Th/Sc, La/Cr, Th/Cr, and Ba/Sc ratios in

the sediments, all indicate that the sediments were derived from granitic rocks. This also agrees with the general shape of the chondrite-normalized REE patterns (including a negative Eu anomaly), which suggests that the granites—the likely source rocks—were derived by inter-crustal melting. The slight increase in the LREE is probably a source area effect. Mineralogical and geochemical data here reported suggest that the provenance of the sediments was dominated by felsic sources. The basic component in the sediments was most likely derived from metasedimentary rocks, such as muscovite-biotite schists, which are characteristic of the Buganda-Toro System rocks, while the felsic sediments are derivatives of granitoid rocks of the basement. We find that, despite intense weathering, which affected the contents of most elements, the REE, Th, and Sc remained immobile; this observation can be considered as one of the most important geochemical results of the present study.

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