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Application of multi-element relationships in stream sediments to mineral exploration: a case study of Walawe Ganga Basin, Sri Lanka

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Abstract

This study on the application of multi-element relationships in stream sediments to mineral exploration in the Walawe Ganga Basin presents one of the first of its kind in Sri Lanka. In order to determine the nature of these sediments, multi-element analysis of selected grain size (<63 μm , 63–125 μm , 125–177 μm and 177–250 μm) fractions was undertaken. The chemical composition of these fractions were compared with those of the upper continental crust.

Some elements, notably Zr, Hf, Th, U, Ce and La, show very high enrichment factors (e.g. 54 for Zr) as compared to the upper crustal abundance. These are presumably associated with heavy minerals such as zircon, rutile and monazite found in abundance in the stream sediments of the Walawe Ganga Basin.

Principal Component Analysis (PCA) of the geochemical data show that multi-element relationships could be effectively used to delineate target areas for mineral exploration. With the use of PCA, this study reveals that areas with associations of calc-silicate/marble and charnockitic rocks are probable source regions for mineral occurrences, particularly in the axial regions of anticlines. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Sediments in a stream are a sink for elements derived from the surrounding watershed and their composition is more representative of the geochemical characteristics of the area than other sampling media

such as soil, plant and groundwater. Sri Lanka is characterized by a heavy monsoonal and tropical humid climate. Weathering is more intense in these regions because of the extremely high seasonal downpours, and drainage systems in such areas have high sediment yields (Fletcher, 1996). Due to their availability throughout the island, stream sediments have been the most important sampling medium for geochemical mapping in Sri Lanka. Even though Sri Lanka has terrains suitable for mineral exploration surveys using stream sediments, very few attempts have been made to systematically study the geochemis-

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try of stream sediments. Ramakrishna et al. (1985) carried out a reconnaissance survey using panned mineral concentrates from stream sediments and indicated areas with anomalous contents of some elements including U and Au but no further follow-up studies have been carried out. Dissanayake and Rupasinghe

(1992) demonstrated that geochemical analyses of stream sediments combined with heavy mineral analysis could be used as a tool in the exploration of sedimentary gem deposits in Sri Lanka. The main aim of this study on the Walawe Basin is to understand the multi-element relationships of trace metals including

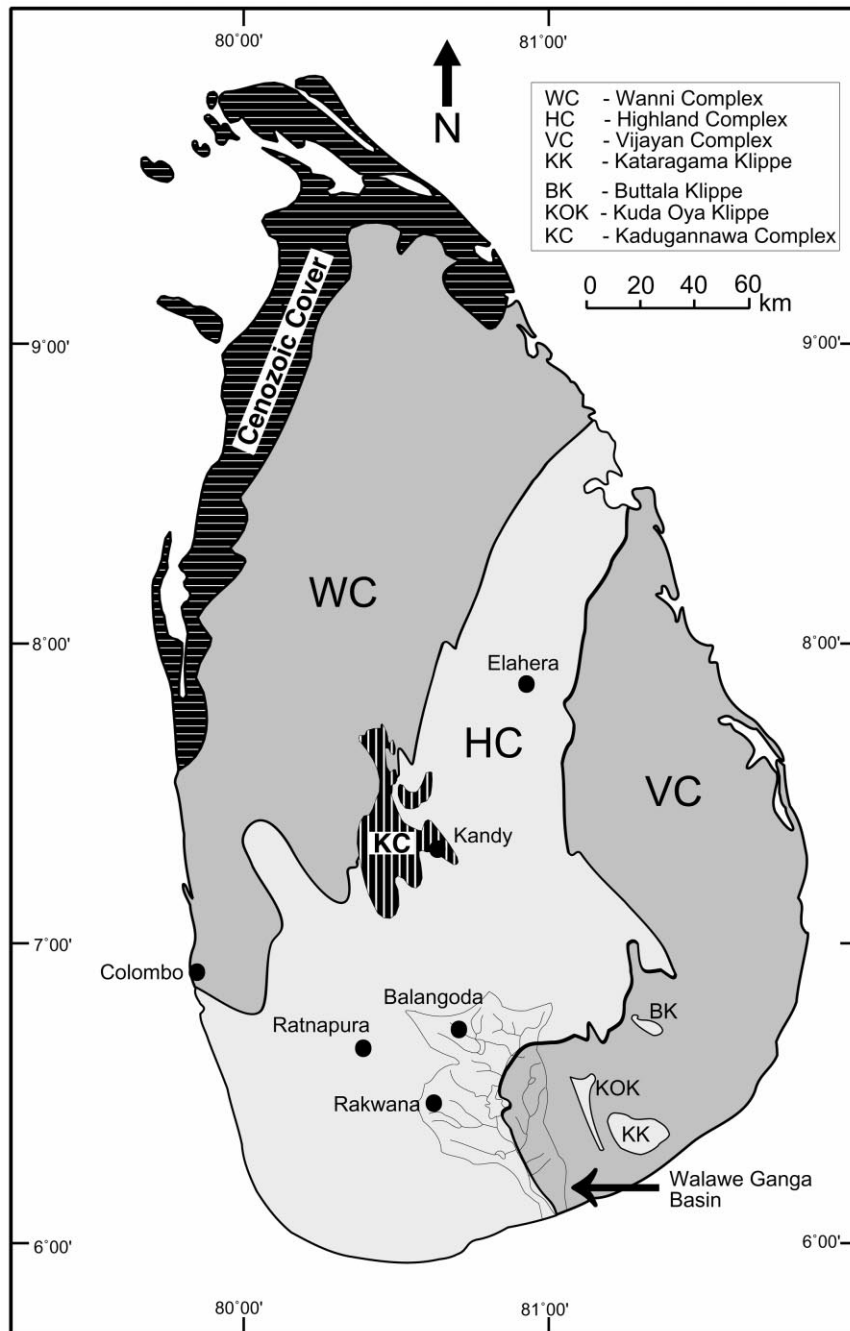


Fig. 1. The location of the Walawe Ganga Basin with respect to the general geology of Sri Lanka.

high field strength elements (HFSE) and to outline areas with anomalous concentrations of elements. Such information will form the basis for future mineral exploration programs in Sri Lanka.

A fundamental problem in relation to sediment chemistry is the selection of a suitable size fraction which best represents the geochemical characteristics of the watershed. The geochemistry of panned heavy mineral concentrates (e.g. Ramakrishna et al., 1985; Bellehumeur and Jébrak, 1993; Bellehumeur et al., 1994) is often used in stream sediment surveys for mineral exploration. However, the material most often used for mineral exploration studies is the minus 170 μm grain size fraction since fine sand, silt and clay fractions of sediments are able to concentrate and transport many elements associated with most types of mineral deposits. Yet, stream sediments can often be transported over long distances from their source and consequently the geochemistry of the sediments changed in the process. Therefore the finer fractions do not always fully represent the geochemical signatures associated with upstream mineralization. On the other hand, most of the heavy minerals, including gem minerals, are harder and more resistant to weathering and they are generally better represented in the coarse fractions of stream sediments. In tropical rain forest areas, finer materials are more rapidly flushed away in suspension but fine-grained heavy minerals lag behind and accumulate on the beds of the streams.

Therefore the selection of a suitable size fraction is an important consideration in an orientation geochemical study and is often an advantage in routine exploration studies in tropical high grade metamorphic terrains such as in Sri Lanka. However, up to now no comprehensive orientation studies have been carried out in Sri Lanka addressing this problem. In this study, several tributaries of the Walawe Ganga (Ganga = river in Sinhalese) (Fig. 1) were selected and several size fractions analysed chemically. The geochemical composition of the selected fractions were interpreted using statistical techniques which will enable the recognition of any additional subtle, though important geochemical patterns that may exist in the study area. This river basin is the third largest fluvial system in Sri Lanka and its river watershed encompasses an area of approximately 2442 km².

2. Geological setting

Over 90% of the island of Sri Lanka is made up of Proterozoic metamorphic rocks and the remainder is covered by sedimentary sequences of Jurassic, Miocene and Holocene ages. The Proterozoic rocks of Sri Lanka are traditionally divided into 3 major lithological units on the basis of rock types and their meta-

morphic grades (Cooray, 1984). Recently Cooray (1994) revised the subdivisions of the Precambrian of Sri Lanka, based mainly on geochronological, petrologic and geochemical data. The recent classification divides the basement complexes of Sri Lanka into 3 main and one subordinate division (Fig. 1) and are named as Highland Complex (including both former Highland Group and Southwest Group), Vijayan Complex (former Eastern Vijayan Complex), Wannu Complex (former Western Vijayan Complex) and the Kadugannawa Complex.

The Highland Complex consists mainly of charnockites, quartzites, marbles, garnetiferous gneisses, and granulites together with a variety of igneous intrusions. The SW part of this complex (or former Southwest Group) is composed predominantly of calciphyres, charnockites and cordierite-bearing gneisses. Kröner et al. (1991) noted that the rocks in this granulite-grade complex are of granitoid composition with ages ranging from 1942 Ma to 650 Ma. The amphibolite grade Vijayan Complex and Wannu Complex show ages ranging between 550 Ma and 1100 Ma (Kröner, 1991). The boundary between the Highland Complex and the Vijayan Complex (Fig. 2) is considered to be a mineralized belt and a convergent plate boundary (Munasinghe and Dissanayake, 1982) as evidenced by the discovery of many mineralizations along its entire length of 400 km (Dissanayake, 1985). Associated with this boundary are: (a) gravity anomalies (Hatherton et al., 1975); (b) a line of hot springs with a maximum temperature of 55°C (Dissanayake and Jayasena, 1988); (c) serpentinite bodies (Dissanayake, 1985); (d) massive Cu–Fe rich sulphides (de Jayawardena, 1982); (e) native S occurrences (Wickramaratne, 1985); (f) diamond occurrences (Dissanayake and Rupasinghe, 1986); and (g) groundwater F⁻ anomalies (Dissanayake and Weersooriya, 1986). The boundary between the Highland Complex and the Vijayan Complex lies in the Walawe Ganga Basin and the lowest segment of the river appears to flow along this boundary.

The underlying lithology of the study region comprises of rocks of granulite facies grade, notably charnockitic rocks, quartzites, calc-silicate rocks and sillimanite- and garnet-bearing gneisses (Fig. 2). The Upper Basin tributaries of the study region are prime target areas for gem mining. Some rare gem varieties such as Ekanite, Alexandrite cat's eye and Aquamarine have been reported in the upper part of the Rakwana Ganga tributary (Rupasinghe, 1995). Gold nuggets and flakes also have been reported in several areas in this river basin (Dissanayake and Nawaratne, 1981). The heavy minerals of the study area of the Walawe Ganga Basin are dominantly metamorphic and the mineralogy is fairly simple. The weight percentage of the content of heavy minerals in sediments varied from

10% (in the <63 μm fraction) to 49% (in the fraction 63–125 μm). In contrast the minus 63 μm fraction contains lesser amounts of heavy minerals compared to the 63–125 μm and the 125–177 μm fractions. Zircon, garnet, monazite, ilmenite, sphene, allanite, magnetite, rutile and ferromagnesian minerals are among the heavy minerals found in the heavy fractions of the stream sediments (Chandrajith, 1999).

3. Methodology

A total of 38 sediment samples of 5–10 kg in size were collected from some selected tributaries located in the western part of the Walawe Ganga (Fig. 2). Samples were dried at 50°C and screened into 4 size fractions <63 μm , 63–125 μm , 125–177 μm and 177–250 μm . Part of the samples were finely ground using an agate swing mill.

The chemical analyses were carried out by an X-ray fluorescence (XRF) technique using fused glass discs.

1,000 g aliquots were weighed accurately and ignited in a clean ceramic crucible at 1030°C for at least 12 h in a muffle furnace to constant weight. The samples were mixed with 1:2.5:2.5 (by weight) of spectroscopic grade Li tetraborate and Li metaborate flux, previously dried at 400°C for 4 h. Mixing was done directly in the crucible with a small glass pestle. A few mg of I_2O_5 was added as a non-wetting agent. The mixture was then fused in Pt (95%)–Au (5%) crucibles for 10 min, the fusion being carried out with a Oxiflux[®] burner system. During the fusion, the crucible was regularly rotated to ensure thorough mixing of the melt while keeping an oxidising atmosphere during fusion. The molten mixture was then poured into a Pt (95%)–Au (5%) mould heated red-hot with a gas burner and allowed to solidify. The mould was cooled by a stream of air thus allowing easy handling.

The precision and accuracy of the preparation and the instrumental performances were checked using international reference samples, JSd-1, JSd-2, Jlk-1, SARM-46, SARM-52, JB-2, JGb-2 and IAEA-SL-1,

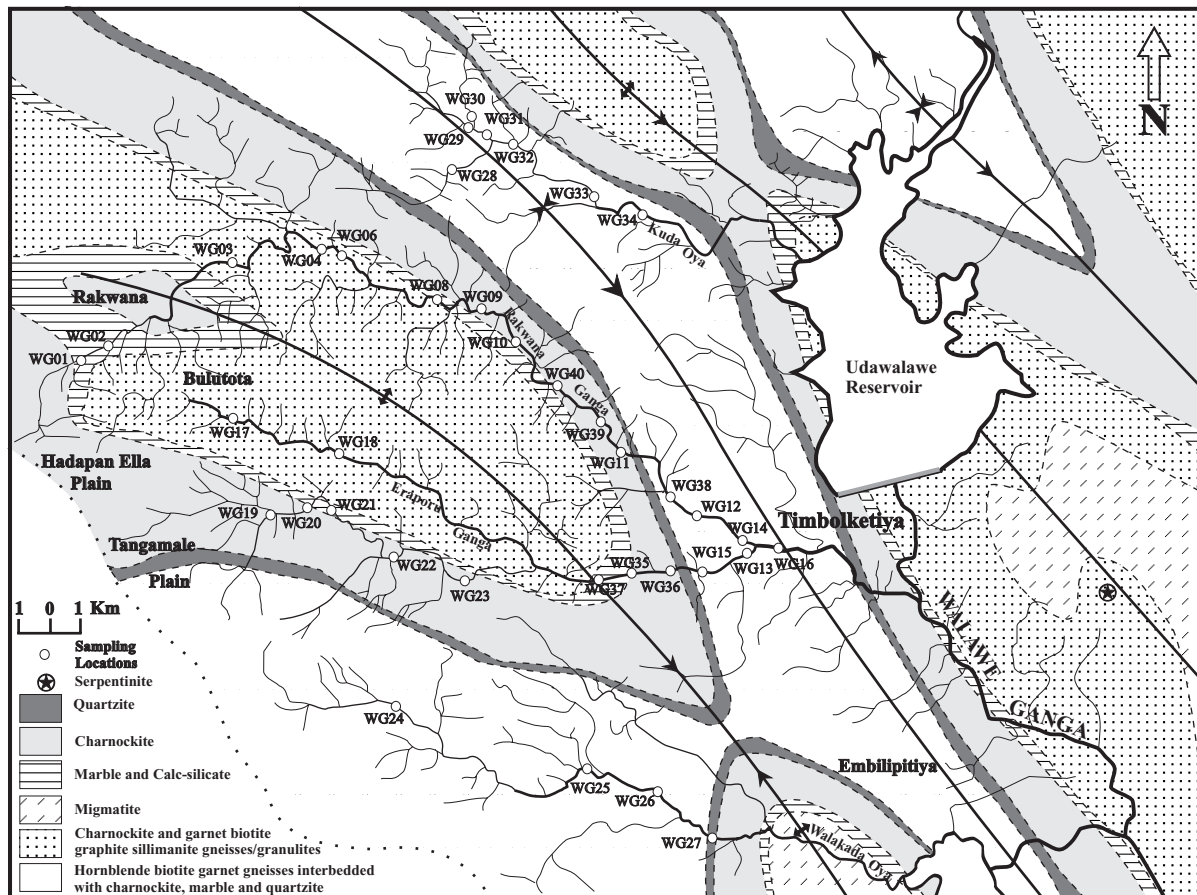


Fig. 2. The geology and sampling locations of the Walawe Ganga Basin. The geology map has been modified after Silva et al. (1987).

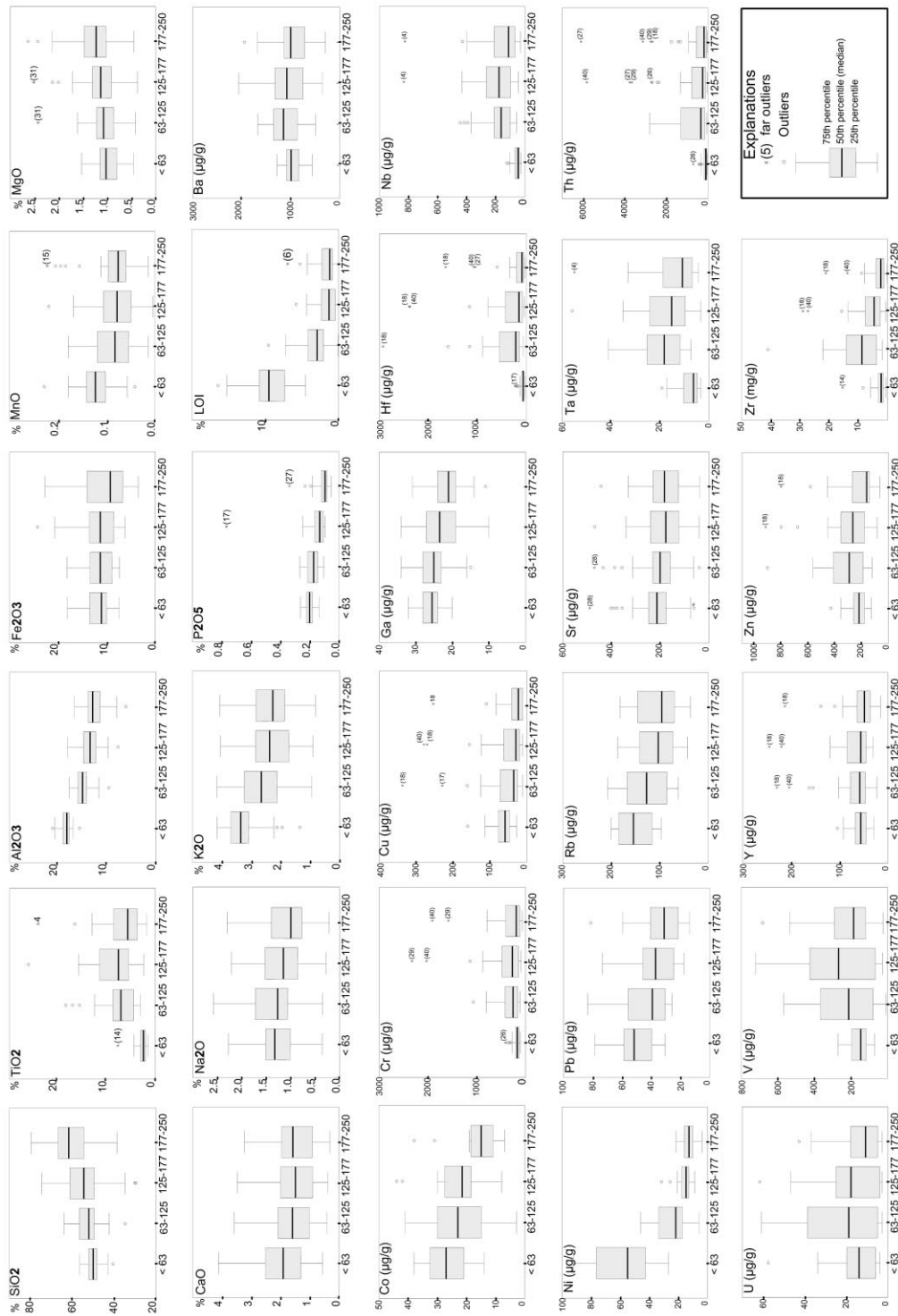


Fig. 3. Box and whisker plots for selected major and trace elements in the <63 μm, 63–125 μm, 125–177 μm and 177–250 μm fractions (all oxides and LOI given in percentages).

which are measured as ‘unknowns’ with samples and sample duplicates. With few exceptions there were no discrepancies between the measurements and consensus data in international reference samples. The percentage recoveries vary up to $\pm 12\%$ for most elements depending on the reference sample. Replicate analyses of samples yielded RSD $< 1\%$ for Si, Ti, Al, Fe, K and U; nearly 1% for Mg, Sr and Zr; nearly 2% for Mn, Na, P, Ba, Cr, Nb, Rb, and Zn; and between 2 and 8% for Ce, Pb, La, Th, W and Y.

4. Results and discussions

4.1. Relative concentrations and enrichment of elements

The contents of studied major and trace elements including High Field Strength Elements (HFSE) are displayed as box and whisker plots in Fig. 3. These plots show that there are often significant differences in the elemental concentrations between different size fractions. However Sr, Ba, Cr, Y, and Th show very similar median concentrations in all 4-size fractions. In

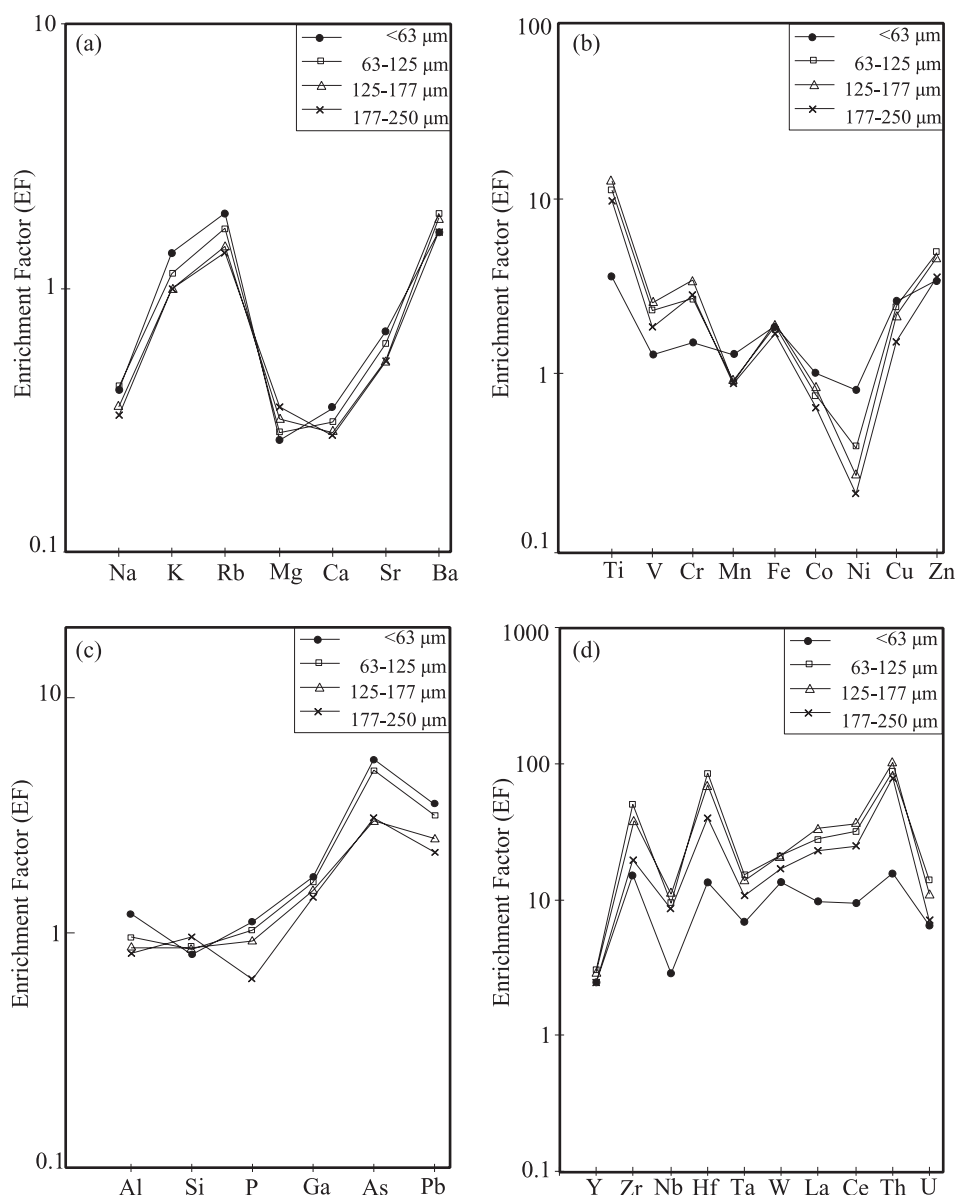


Fig. 4. The Enrichment Factors (EF) for the elements in the 4 size fractions $< 63 \mu\text{m}$, $63\text{--}125 \mu\text{m}$, $125\text{--}177 \mu\text{m}$ and $177\text{--}250 \mu\text{m}$. The EF is calculated as the ratio of the average elemental abundance to the average crustal abundance of Wedepohl (1995).

the Walawe Ganga sediments major elements and most of the transition group elements (e.g. Ni, Co, Cu) show significant lowering of the concentrations in coarser fractions whereas the HFSE are enriched in the 63–125 μm and 125–177 μm fractions compared to the other fractions. The 177–250 μm fraction generally shows the lowest median values for most studied elements.

Since sediment background values are not available, the major and trace element levels in different size fractions were normalized to the abundance values for the Average Upper Continental Crustal (AUCC) (Wedepohl, 1995). The derived Enrichment Factor (EF) allows a more detailed comparison of major and trace element levels between the different sieve fractions and typical crustal abundances. It is apparent that the HFSE and related trace elements are highly enriched in comparison to the average continental crustal values.

4.1.1. Alkali and alkaline earth elements

For the Walawe Ganga sediments, alkali and alkaline earths (Fig. 4a) are depleted or slightly enriched against the average crustal levels. Potassium, Rb and Ba are slightly enriched against the AUCC values compared to other elements in the same group. However, all the alkali group elements studied show their highest enrichments in the minus 63 μm fraction except for Mg and Ba. It is well known that these elements are mobile in the weathering process, owing to their high hydration energies (e.g. Nesbitt et al., 1980; Kronberg et al., 1987; Cullers, 1988). Therefore generally these elements tend to accumulate in the dissolved phase rather than in the solid bed loads. Wronkiewicz and Condie (1987) showed that larger cations (Rb and Ba) are often fixed in weathering profiles by preferential exchange and adsorption onto clays whilst smaller cations (Na, Ca and Sr) are more readily leached from the weathering profiles. The behaviour of Mg is different from that of Ca, Sr and Ba (Kronberg et al., 1987) since Mg is a major constituent of common minerals such as pyroxene, amphiboles and biotite which are found in high-grade granulite facies rocks. These minerals most probably control the Mg content in all size fractions within the sampled sediments.

4.1.2. Transition group elements

The Walawe Ganga sediments do not show significant enrichments ($\text{EF} < 5$) for the transition group elements relative to their AUCC abundance except for Ti (Fig. 4b). Titanium shows a marked enrichment by factors of 11, 12 and 9 in the fractions 63–125, 125–177 and 177–250 μm , respectively. It is worth noting that quadrivalent Ti also belongs to the high field strength group of elements. When compared to other elements of the transition group, Mn, Co, Ni and Cu

are more enriched in the minus 63 μm fraction whereas other transition elements are enriched in the 63–125 μm size fraction. Nickel shows a negative anomaly and is largely enriched in the minus 63 μm fraction. It was not found in detectable concentrations in fractions larger than 63 μm , and this probably reflects its affinity for selective adsorption by clay minerals along with Mn, Co and Cu. The enrichment of Ti, V and Fe in coarser fractions compared to the minus 63 μm fractions is due to the existence of high amounts of ilmenite, rutile, garnet and spinel in river bed sediments. These minerals are common accessory minerals in high grade rocks in Sri Lanka.

4.1.3. Al, Ga, Si, Pb, P, and As

These elements do not show marked enrichments (generally $\text{EF} < 5$), in studied fractions, against average crustal abundance (Fig. 4c). Except for Si, all elements in this group show their maximum enrichment in the minus 63 μm sediment fraction. The content of Si is much higher in the 177–250 μm fraction indicating the dilution effect of sediments with quartz. The positive anomaly of As is probably due to the presence of sulphide minerals (e.g. pyrite, arsenopyrite) in finer fractions. Most of the trace elements in this group (Ga, As, Pb) tend to accumulate with clay minerals or to get adsorbed on to Fe-oxide particles in the 63 μm fraction.

4.1.4. High Field Strength Elements (HFSE)

This group of elements figures prominently in the sediment geochemistry of the Walawe Ganga Basin. They are generally found in low concentrations in most river sediments except in sediments from highly mineralized regions. Zirconium is strongly enriched in the Walawe Ganga sediments and has averages of 3094 $\mu\text{g/g}$, 10,050 $\mu\text{g/g}$, 6791 $\mu\text{g/g}$ and 3962 $\mu\text{g/g}$ in fractions $< 63 \mu\text{m}$, 63–125 μm , 125–177 μm and 177–250 μm , respectively. The average Zr content of the exposed upper continental crust is about 190 $\mu\text{g/g}$ and typical shales contain $200 \pm 100 \mu\text{g/g}$ Zr (Taylor and McLennan, 1985). The upper crust normalized plot (Fig. 4d) indicates positive anomalies for Zr, Hf and Th. When compared with AUCC, Zr shows the highest EF in fractions 63–125 μm ($\text{EF} = 50$) and 125–177 μm ($\text{EF} = 45$). Rupasinghe and Dissanayake (1985) found that Zr is highly enriched against average shale in some gem sediments from Ratnapura. Hafnium is also highly enriched in fractions 63–125 μm ($\text{EF} = 85$) and 125–177 μm ($\text{EF} = 70$) compared to other fractions. Thorium is another element that shows markedly high enrichment in all grain sizes. Other elements such as Nb, Ta, W, Th, U, La and Ce also show higher EFs as against the AUCC, specially in fractions 63–125 μm and 125–177 μm . However, W and U values are based on a lower number of samples since in others the con-

tents are below their detection limits. Among tributaries of the Walawe Ganga Basin, Rakwana Ganga sediments are relatively enriched in W and U. However Y does not show a significant enrichment ($EF < 3$) in the sediment fraction studied. The rare earth elements Ce and La are also highly enriched compared to the AUCC values. The average content of Ce and La in the 63–125 μm and 125–177 μm fractions are 1890 $\mu\text{g/g}$ and 2145 $\mu\text{g/g}$ for Ce and 847 $\mu\text{g/g}$ and 991 $\mu\text{g/g}$ for La, respectively.

The most significant feature of this group is the higher EFs in fractions 63–125 μm and 125–177 μm as compared to fractions $< 63 \mu\text{m}$ and 177–250 μm . The heavy minerals such as zircon, garnets, monazite, ilmenite, etc. which are found abundantly in the 63–125 μm and 125–177 μm fraction control the content of HFSE. For instance the Hf levels are influenced by zircon whereas ilmenite, monazite, apatite and sphene influence the other HFSE. Therefore in the sediments of Walawe Ganga, mineralogical control would be of great importance in the fractionation and enrichment of HFSE in the size fractions 63–125 μm and 125–177 μm .

4.2. Dependence of chemical composition on grain size

The present study in the Walawe Ganga Basin shows that the different size fractions of stream sediments carry different geochemical information. Taking into account the considerations of element distribution and their enrichment against AUCC, the abundance of alkali, alkaline earth and transition elements in the grain size fractions less than 63 μm can be better understood. However, most of the high field strength and related trace elements such as Zr, U, and Th are more enriched in fractions greater than 63 μm . It is apparent that these elevated contents are generally observed in the 63–125 and 125–177 μm fraction. This may be related to the occurrence of resistant phases such as zircon, ilmenite, garnet and spinel, which have higher contents in the sand-sized fractions. In contrast, the size fractions less than 177 μm are found to be a preferable fraction for stream sediment geochemical exploration surveys in high-grade tropical terrains of Sri Lanka.

4.3. Multi-elemental relations

In order to explain the interrelationship of the abundances of elements in the Walawe Ganga sediments multivariate principal component analysis (PCA) was used. PCA is one of the most widely used statistical treatments and is useful in evaluating multi-element geochemical data of various types (Bellehumeur and Jebrak, 1993; Bellehumeur et al., 1994; Weber and Davis, 1990). This technique attempts to reveal the

correlation structure of the variables allowing interpretation of geological processes affecting the geochemical data. The PCA method assumes symmetrical population. This was ensured by removing the extreme tails (far-outliers) of the concentration distribution rather than by natural logarithm transformation. Although each sample was analysed for 32 elements in this study, certain elements in some samples are found in amounts below the detection limits of the analytical procedure. These observations are set to a two-thirds value of the detection limit (e.g. Fordyce et al., 1998). Analytical replicate results and field duplicate results were removed from the data set prior to statistical processing. The components (PC) were extracted using the correlation matrix and rotated to an orthogonal simple structure using the variance maximizing (Varimax) criterion. The PCA were performed on fractions $< 63 \mu\text{m}$, 63–125 μm and 125–177 μm . Since the fraction 177–250 μm does not provide significant information of the element content levels, it was not included in the PCA. However, since the extracted factor components are nearly similar in fraction $< 63 \mu\text{m}$ and 125–177 μm , only fractions $< 63 \mu\text{m}$ and 63–125 μm were considered in the discussion. In this analysis, 5 components were extracted which explain 82% and 89% of the total data variability of fractions $< 63 \mu\text{m}$ and 63–125 μm , respectively. The most noteworthy observation in PCA is that whatever the size fraction, the same element groups are associated together in the components (e.g. Na–Mg–Ca–Sr and K–Rb).

4.4. PCA for $< 63 \mu\text{m}$ fraction of stream sediments

Table 1 gives the results of the PCA factor loading for the size fraction $< 63 \mu\text{m}$. The extracted components PC-1, PC-2, PC-3, PC-4 and PC-5 represent 27%, 27%, 15%, 7% and 6% of the total variance of the geochemical data, respectively. For these fractions, the first component (PC-1) explains the dispersion of negatively correlated Na–Mg–Ca–Sr–Ba and positively correlated Ga–Pb–Al and their association with clay and mica group minerals. The Na–Mg–Ca–Sr combination again appears in the PC-3 in the 63–125 μm fraction. Both components highlight the lithological backgrounds of the study area. It appears likely that the marble/calc-silicate rock association may have contributed strongly to these factors.

The second component (PC-2) extracted from the stream sediment geochemical analysis represents the Ce–Hf–La–Th and Mn–Co–Ni associations. The Mn–Co–Ni association indicates the co-precipitation of Mn oxides in the fine fraction. The Ce–Hf–La–Th and perhaps Ti association indicates the occurrence of heavy minerals such as apatite and/or monazite and ilmenite mixed with clay minerals.

The positive weights of Ta–U–V–W–Zr in PC-3 and

Cu–Nb–Y–Zn in PC-5 has to be ascribed to mineralization in the drainage basin. It is also observed that from among the studied tributaries, the Rakwana Ganga contains higher amounts of W (9–25 µg/g) and Mo (2–21 µg/g) in the minus 63 µm fraction whereas in the other streams, these elements are found in very low concentrations. Some other elements such as Cu, Zn, Cr, Zr, Hf, Nb, Ta, and Y are also higher in the Rakwana Ganga tributary compared to other streams. This may be related to mineralization in the tributary basin. The fourth component of the minus 63 µm fraction and fifth component of the 63–125 µm fractions represents the K–Rb association in the sediments. This association indicates the presence of K-feldspar, probably of magmatic origin, in the sediments.

4.5. PCA for 63–125 µm fraction of stream sediments

For the 63–125 µm size fraction in which factor loadings are given in Table 2 extracted components

PC-1, PC-2, PC-3, PC-4 and PC-5 represent 36%, 32%, 11%, 6% and 4% of the total variance of the geochemical data, respectively. The first component reflects the distribution of different rock types and also mineralization. The positive factor scores point to a close relationship with the terrain in which charnockites and hornblende–garnet bearing gneisses are prominently associated. Likewise the negative factor scores relate to the terrain in which charnockites and marble/calsilicate rocks are associated. The negatively loaded elements represent the mineralization in the terrain. The second component (PC-2) with high positive loadings in Fe–Cu–Hf–Y–Zn–Zr is consistent with the occurrence of heavy minerals such as garnets and zircon which are likely host minerals. The factor loading for component 4 (PC-4) contains high positive contributions by P–Th–Ce–La. This component reflects the relative abundance of monazite and apatite in the stream sediment samples. The heavy mineral separate

Table 1
Principal component analysis for the <63 µm fraction of the sediments

Component (% variation)	PC-1 (26.91)	PC-2 (26.52)	PC-3 (15.45)	PC-4 (7.01)	PC-5 (6.12)
SiO ₂	–0.54	0.57			
TiO ₂		0.62	0.63		
Al ₂ O ₃	0.64	–0.40			
Fe ₂ O ₃	0.48	–0.57			0.46
MnO		–0.75			
MgO	–0.80				
CaO	–0.84				
Na ₂ O	–0.87				
K ₂ O	–0.42			0.86	
P ₂ O ₅	0.48				0.47
As	0.57	–0.64			
Ba	–0.86				
Ce		0.90			
Co		–0.81			
Cr	–0.52			–0.49	
Cu	0.51				0.66
Ga	0.70				
Hf		0.76			0.55
La		0.87			
Nb		0.57			0.75
Ni		–0.70			
Pb	0.70				
Rb				0.89	
Sr	–0.86				
Ta			0.77		
Th		0.89			
U			0.98		
V		–0.41	0.81		
W			0.89		
Y					0.78
Zn	0.40				0.74
Zr		0.51	0.72		0.40

of this fraction contains 2–8% of monazite and 0.2–3% of apatite.

5. Conclusions

The elevated concentrations of base metals and HFSE in stream sediment samples from certain parts of the study region indicate possible mineralization. However up-to-now no major deposits have been recorded except for gem minerals. The enrichment of some elements, especially HFSE and related trace elements appear to be associated with monazite and Zr- or Ti-bearing minerals such as zircon, rutile, sphene and ilmenite. However, most of the HFSE are often associated with F-rich granitic rocks (Pollard et al., 1987; Congdon and Nash, 1991; Keppler, 1993). During the formation of igneous rocks, enrichment of Zr, Nb, Hf, Ta, Th, U and REE is controlled by volatile phases such as F (Keppler, 1993). The Walawe

Ganga Basin is located very close to the boundary between the Highland and Vijayan Complexes (see Fig. 1) which is considered a mineralized belt (Dissanayake, 1985). A sharp increase of the groundwater F^- anomaly as well as relative enrichments of base metals at the boundary between the Highland and Vijayan Complexes were also reported by Dissanayake and Weersooriya (1986). It can be concluded that there may have been exhalations of F^- along this deep-seated rift or mini-plate boundary. In addition, the area is structurally controlled and the serpentinite body of Udawalwe is located in one of the synclinal axial regions.

Since most of the HFSE and related trace element contents are higher, it is apparent that the axial regions of anticlines as shown in Fig. 2 have a marked influence on the location of mineralized zone in the study area. Further the close lithological and genetic relationships of calc-silicates and marbles with those of charnockitic rocks appear to indicate probable source

Table 2
Principal component analysis for the 63–125 μm fraction of the sediments

Component (% variation)	PC-1 (36.46)	PC-2 (32.28)	PC-3 (10.90)	PC-4 (5.63)	PC-5 (4.25)
SiO ₂		-0.75		-0.40	
TiO ₂	-0.68	0.45		0.44	
Al ₂ O ₃		-0.62	-0.59		
Fe ₂ O ₃	-0.57	0.70			
MnO	-0.88				
MgO			-0.80		
CaO			-0.94		
Na ₂ O			-0.82		
K ₂ O		-0.43			-0.79
P ₂ O ₅		0.48		0.78	
As	-0.90				
Ba	0.71			0.54	
Ce	0.43	0.57		0.66	
Co	-0.96				
Cr				0.56	0.55
Cu		0.82			
Ga	0.68	-0.46			
Hf		0.86			
La		0.47		0.77	
Nb	-0.66	0.56			
Ni	-0.72				
Pb	0.58			0.56	
Rb	0.44				-0.86
Sr			-0.76		
Ta	0.74	0.42			
Th	0.44			0.78	
U	-0.97				
V	-0.97				
W	-0.96				
Y		0.88			
Zn		0.86			
Zr		0.88			

regions and loci for mineralization. The concentration of anomalous values of indicator elements in such regions further points to the conclusion that these may be target areas for detailed mineral exploration.

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