J.Natn.Sci.Foundation Sri Lanka 2019 47 (2): 221- 234
DOI: http://dx.doi.org/10.4038/jnsfsr.v47i2.9164

RESEARCH ARTICLE

Sedimentary geochemistry of alluvial overburden in the primary gem deposit of Pelmadulla, Sri Lanka

D.T. Jayawardana[1*], R.M.T.D. Madusanka[1], R.M.N.P.K. Jayasinghe[2], A.M.N.M. Adikaram[3] and D.T. Udagedara[4]
[1] *Department of Forestry and Environmental Science, Faculty of Applied Science, University of Sri Jayewardenepura, Nugegoda.*
[2] *Gem and Jewellery Research and Training Institute, Kaduwela.*
[3] *Department of Physical Sciences, Faculty of Applied Sciences, South Eastern University, Samanthurai.*
[4] *Faculty of Science and Technology, Uva Wellassa University, Badulla.*

Submitted: 04 May 2018; Revised: 11 September 2018; Accepted: 30 November 2018

Abstract: This study examined the sedimentology and geochemistry of the alluvial gem-bearing succession in Pelmadulla, Sri Lanka. The major aims were to investigate weathering and climatic influences on the provenance and to study the origin of the alluvial formation. A sedimentological study indicated different layers of sand, clay, and organic matter-rich clay (ORC) in the gem deposit overburden, which indicated hydraulic sedimentary facies by saltation, suspension, and storm-type origin, respectively. Notably, the storm-type deposit was dominant with ORC, which concluded the formation under extreme climatic events. Clay layers of the deposit showed bimodal characteristics while sands showed unimodal nature, reflecting the impacts of chemical weathering on different sources. Clay layers evidenced a higher level of inorganic carbon and a strong sedimentation rate. The major element relationships of alluvial succession reflected the presence of aluminous clay, predominantly formed by the weathering of alkali feldspar. The enrichment of ferromagnesian elements and large cations with rare-earth elements in the sediment layers concluded the presence of heavy minerals such as zircon and garnet, while the Chemical Index Alteration (CIA) indicated uniformly higher values (Avg. CIA: 89). Consequently, a steady-state chemical weathering was dominant in the layers with marked depletion of the labile fraction. The negative correlation between CIA and SiO_2/Al_2O_3 of the layers denotes the impact of grain size and sorting, whereas the relationship between Ga/Rb and K_2O/Al_2O_3 reflects the weathering trend from a dry and cool climatic condition to a warm and humid condition. In contrast, the provenance of sediments concluded quartzose to mafic nature formed under a passive margin condition.

Keywords: Chemical weathering, primary gem, sediment, sedimentary geochemistry.

INTRODUCTION

The geochemical composition of sediments is the product of several processes and their interactions (Johnsson, 1993). Dominant factors influencing the composition include the provenance (McLennan *et al*., 1993), weathering, climate (Nesbitt & Young, 1984; Roy & Roser, 2013), hydrodynamic sorting (Roser, 2000), and tectonic setting of the depositional basin (Bhatia & Crook, 1986). For instance, numerous evidence are preserved in past events regarding sediment chemistry. Thus, geochemical study of the paleo-depositional sedimentary basin is vital to identify past regional processes.

Mineralogical and sedimentological characteristics of sediments under different depositional conditions play a vital role in controlling sediment chemistry (Grizelj *et al*., 2017), and heavy minerals are useful indicators of sediments as they provide crucial information on the provenance (Garzanti & Andò, 2007). The heavy mineral assemblages reflect their parent rock composition. For instance, a particular garnet composition can be related to specific source rocks, with higher MgO-rich garnets in high-grade metamorphic rocks. Most gem minerals

* Corresponding author (daham@sci.sjp.ac.lk; https://orcid.org/0000-0001-9328-2729)

are heavy minerals, hence a compositional study of sediments may reflect the source of different gems.

Twenty-five percent of the total area of Sri Lanka has a potential for gems (Dissanayake & Rupasinghe, 1995). In general, the age of the primary gem deposit in the country is estimated by zircon dating as 560 M.Y. (Herath, 1984). The origin of the gem deposits has been recognised as residual, eluvial, and alluvial. Corundum (ruby and sapphires), alexandrite, topaz, spinel, tourmaline, and garnets are some of the main gem varieties found in the country (Dissanayake & Rupasinghe, 1995). Corundum in gem gravels of Sri Lanka is probably formed by charnockites and meta-sedimentary gneisses (Hapuarachchi, 1998). The Rb, Ba, Sr, and the Ti, Nb, Zr element groups have shown high correlations with the gem occurrences (Ranasinghe *et al*., 2005). In general, discriminant analyses of trace elements and heavy minerals have been used for locating gem deposits (Rupasinghe *et al*., 1994).

Despite the potential value for the provenance and tectonics of sediment successions in alluvial formation in Sri Lanka, studies have only focused on the gem-bearing layer. Alluvial sedimentary sequences possess a clear contrast of past geological history of the origin of the gem-bearing layer. A systematic geochemical investigation of such deposits also reveals paleo-depositional conditions, which is significant to evaluate regional climatic events (Roy & Roser, 2013). Especially, element ratio relationships provide clear evidences on paleo-depositional conditions and provenance. Major element relationships are the most common methods used worldwide (Taylor & McLennan, 1985; Roser & Korsch, 1986;1988). Conversely, trace element relationships have been also utilised during the past (Bhatia & Crook, 1986). Therefore, this study examines the sedimentological and geochemical evidence of alluvial sedimentary formation in the overburden of gem-bearing layers of Pelmadulla, Sri Lanka, with the aim of studying the climatic changes associated with chemical weathering, and the provenance and paleo-tectonism.

Study Area

Physical settings

An initial field survey was carried out in well-known gem-mining fields in Rathnapura, and the popular alluvial gem deposit in Pelmadulla was chosen for this study (Figure 1a). The survey mainly considered the spatial and temporal distribution of mining activities.

Pelmadulla is an active gem-mining area, where valuable gems such as corundum, garnet, and tourmaline are found (Rupasinghe *et al*., 1994; Hapuarachchi, 1998). Paddy fields in the area are demarcated by alluvial deposits that are cultivated with paddy while underground mining continues. Gem mining in the area is usually practiced in deep pits interconnected by a network of underground tunnels called '*Dona*.' The depth of a gem-bearing layer ('*Illama*') varies up to a few meters in the shallow-mining area. Manual mining is the recommended technique proposed by the government authorities, but illegal rapid mining adversely influences the environment.

General geology of the study area

The Precambrian high-grade metamorphic rocks in Sri Lanka belong to three primary litho-tectonic units, i.e., the Highland, Wanni, and Vijayan complexes (Figure 1a). The study sites are located in the Highland complex, which is composed of meta-igneous rocks and concordant meta-sedimentary rocks (Cooray, 1984; 1994). The meta-sedimentary rocks are mostly Proterozoic-Archaean meta-pelites and the meta-igneous rocks comprise granite, charnockite and quartzofeldspathic gneiss (Jayawardena & Carswell, 1976). Major mineral constituents include hypersthene, diopside, hornblende, and biotite, while highly-resistant accessory minerals such as ilmenite, zircon, monazite and garnet are common.

The Highland complex rocks display a marked compositional range between 57 and 62 weight percent of SiO_2, and are characterised by pronounced Fe_2O_3, TiO_2, P_2O_5, MnO, Zr, Pb, Th, Sr, and Nb enrichment, especially in alkaline rocks (Pohl & Emmermann, 1991). Major and trace element trends in charnockites and metabasites suggest the igneous differentiation sequences (Munasinghe & Dissanayake, 1980).

The major rock types present in the area are granitic gneiss, garnet-biotite gneiss and charnockitic gneiss (Figure 1a). In addition, narrow bands of some other rocks are also present. The sampling site is very close to the axis of Kiribatgala Hatella synform. The gem-bearing alluvial formation is located on the garnet-biotite gneiss. According to the maps of the Geological Survey and Mines Bureau (Figure 1a), the sampling area is dominant with some other mineral deposits such as iron and thorium.

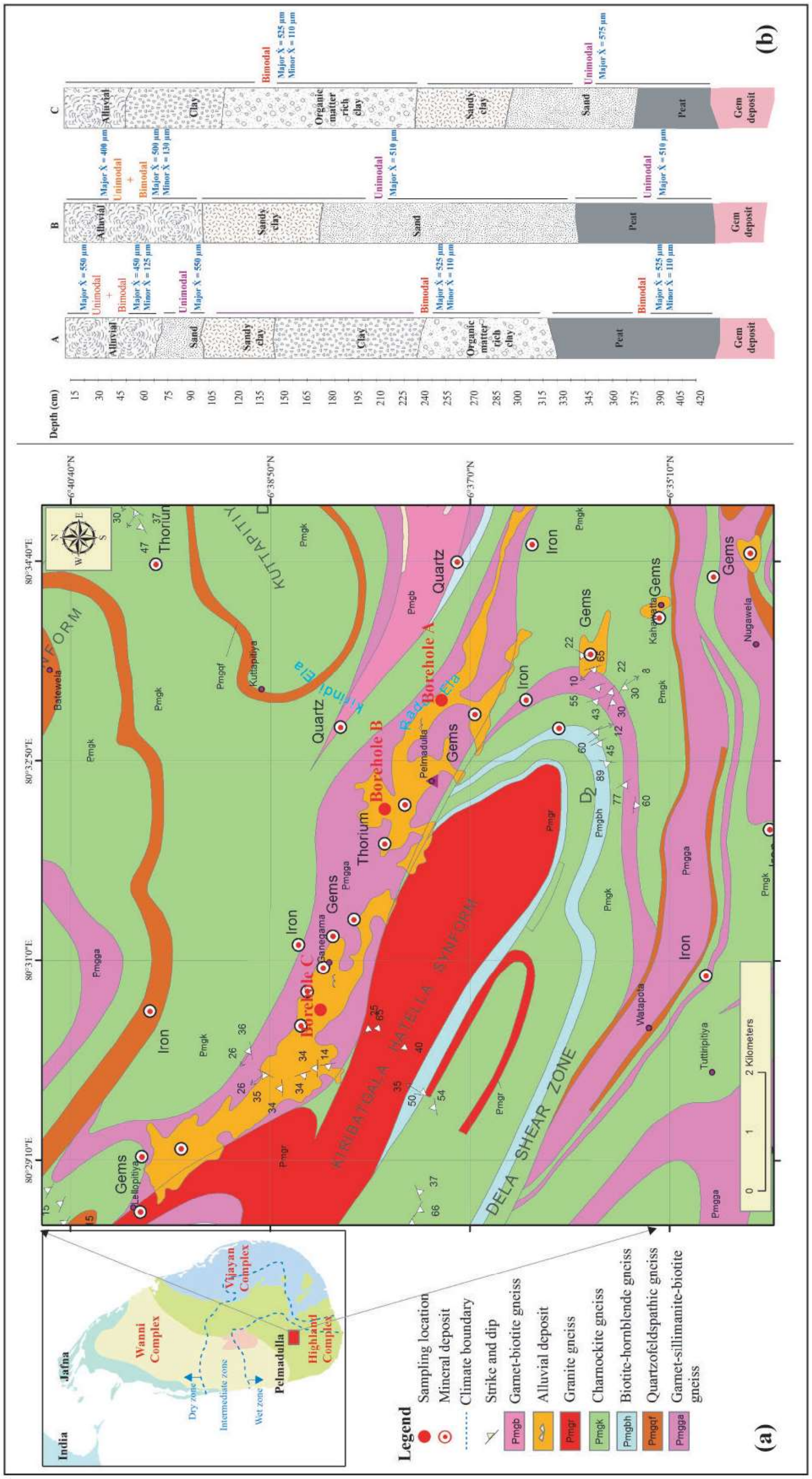

Figure 1: (a) Geology of Pelmadulla sampling area that shows major geological formation and alluvial deposit; (b) schematic description of three different cores of Pelmadulla alluvial formation

METHODOLOGY

Sediment sampling

The standard auger drilling method for sub-surface soil sampling (Cunningham *et al*., 2012) was performed in pristine locations where no prior mining activities have been conducted. Three boreholes were drilled at selected locations using the Eijkelkamp ergonomic hand auger, and the samples were collected into 5 cm-diameter steel casings without any contamination. Composite soil samples were collected at 15 cm intervals through vertical soil profiles of each borehole, and the maximum depth of each borehole was around 415 cm (Figure 1b).

Sediment analysis

The samples were oven-dried at 60 ^oC for 24 h before sieving. By using ¼ phi intervals (ASTM sieves) for 20 min, mechanical sieve analysis was performed with a digital shaker (Retsch AS 200 digit). Grain size distribution (GSD) curves were plotted for each sample and general statistical parameters were obtained using the Minitab software for interpretations.

Organic matter and inorganic carbon content

The loss-on-ignition method involves the sequential thermal oxidation of all organic matter and carbonates present in the soil sample. In this method, a known weight of the sample is heated to 450 ^oC for 12 h to remove all organic matter present in the sample. The inorganic carbon present in the sample is oxidised by heating the sample at 1050 ^oC for 2 h. Methods of sequential weight loss on ignition were used to determine the organic matter and carbonate contents of soils (Heiri *et al*., 2001; Wang *et al*., 2011).

Chemical analysis

The samples were analysed for major and trace elements using X-ray fluorescence spectrometry (RIX 2000) at the National Gem and Jewelry Research and Training Institute, Sri Lanka. Splits of each sample were oven-dried for 48 h at 160 °C. Powdered samples (< 63 μm) were compressed into briquettes under a force of 200 kN for 60 s (Tankersley & Balantyne 2010; Bong *et al*., 2012). Subsequently, the briquettes were analysed for major oxides and trace elements. The relative average error for these elements was less than ± 10 % (Jayawardana *et al*., 2014).

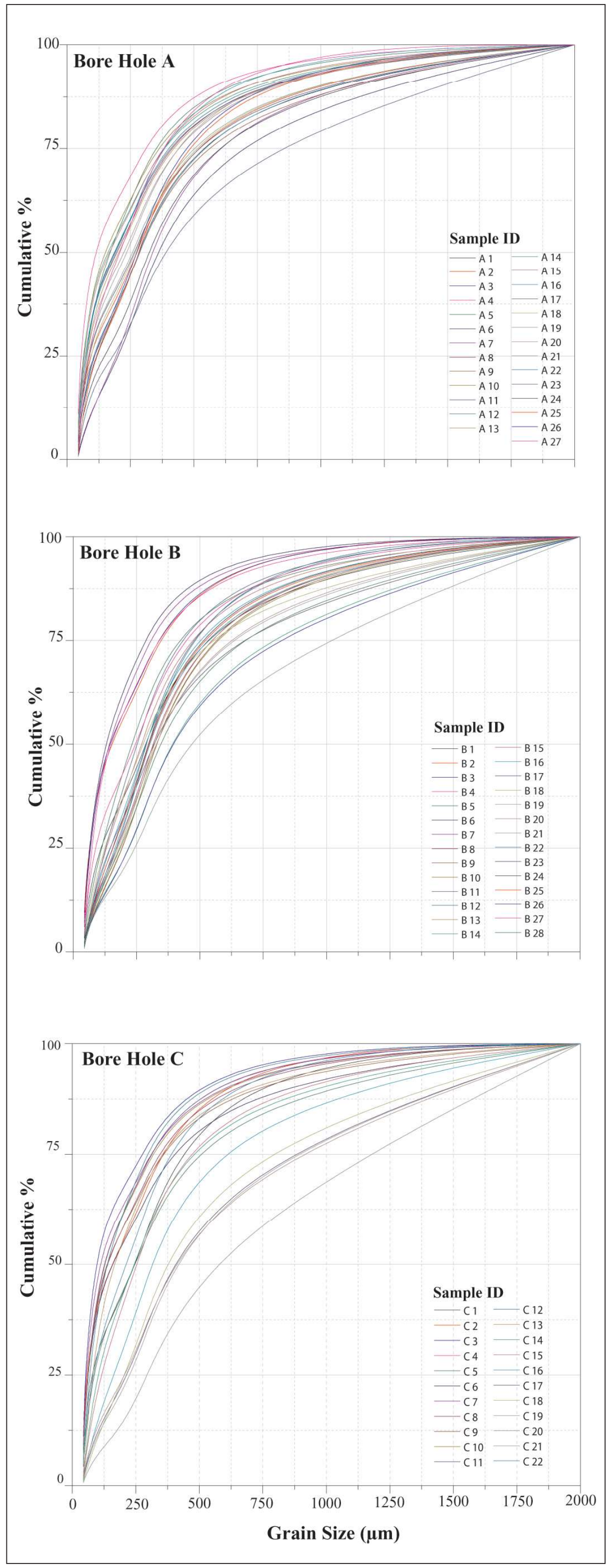

Figure 2: Grain size distribution of alluvial sedimentary formation in Pelmadulla, Sri Lanka

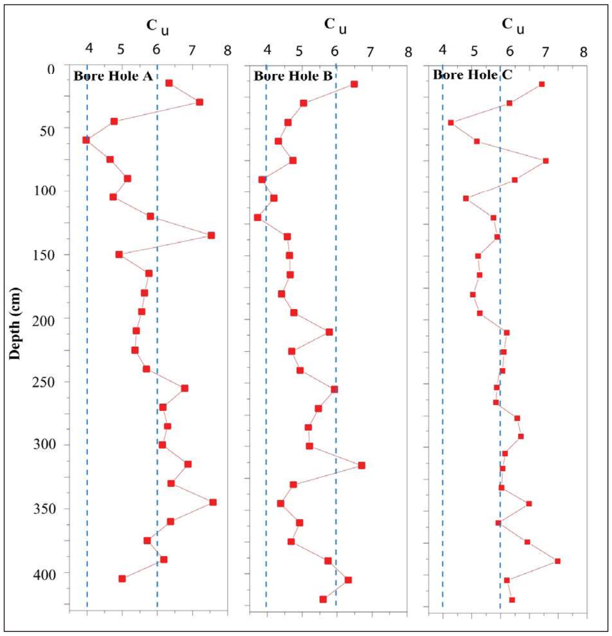

Figure 3: Uniformity coefficient of the sediments for three different cores with respect to depth

RESULTS AND DISCUSSION

Sedimentary contrast of the deposit

The sedimentary deposit in Pelmadulla is characterised by top clay soil, and bottom gem-bearing deposits, '*Illama*' (Figure 1b). *Illama* consists of coarse-grained sand mixed with rock fragments and finer heavy minerals (Dahanayake, 1980). A dominant dark-coloured layer ('*Kolamatta*'), which consists of ORC is present in the gem-bearing layer. Sand and clay sequences are present between the ORC and the topsoil (Figure 1b).

The cumulative frequency analysis revealed sediments with fine to coarse grain texture (Figure 2). Around 50–75 % of total sediments are fine-grained (< 500 µm), and 25–50 % is medium to coarse sediments (500–2000 µm). The grain size analysis evidently represents the enrichment of the fine fraction of the sediments than medium to coarse.

Figure 3 presents the uniformity coefficient of the sediments. The boreholes have a well-graded condition, but the coefficient of gradation for the boreholes further indicates a dominant well-graded condition for clay. The fine-grained and well-graded conditions in the clay layers may reflect the hydraulic sedimentary facies by suspension (Sun *et al*., 2002), whereas sandy sediments show hydraulic sedimentary facies by saltation. Besides, the ORC layer reflects the available condition due to the mixing of fine-sand and clay with the heavy organic matter content, which may indicate the storm deposit.

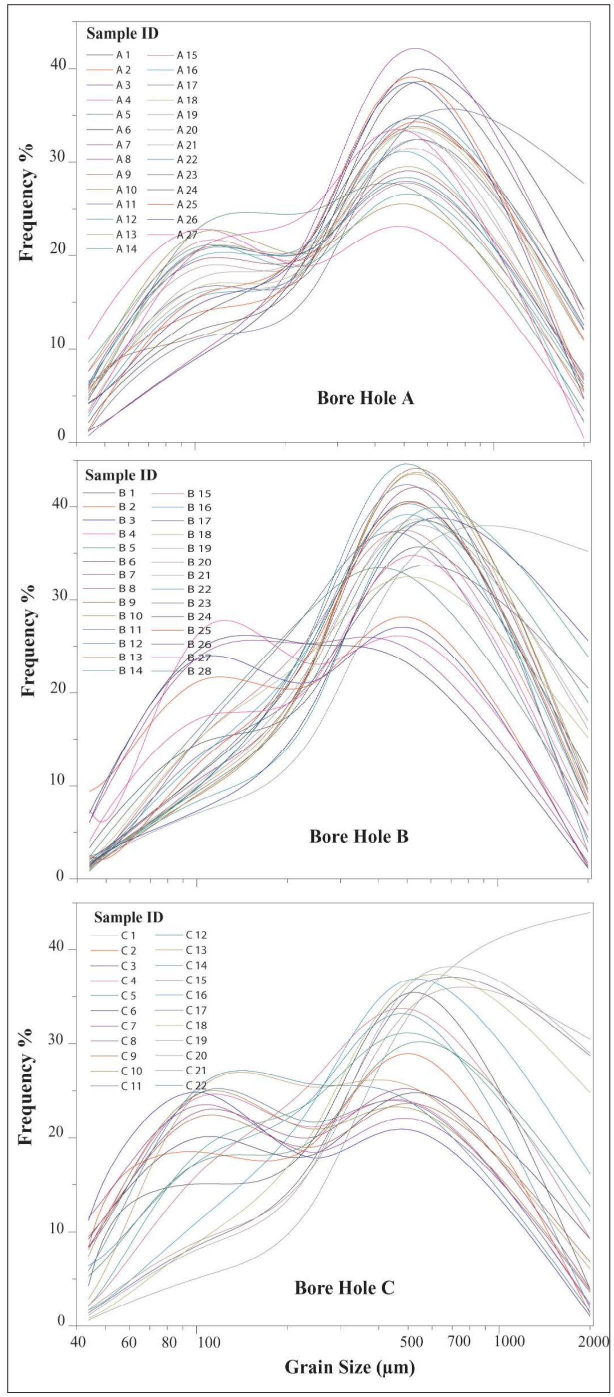

Figure 4: Frequency distribution of grain size for borehole sediment samples which shows different mode of occurrence

Table 1: Organic matter (OM) content and loss on ignition (LOI) values for the different layers of the sediment deposit

	Bore hole 1		Bore hole 2		Bore hole 3	
Depth (cm)	LOI (%)	OM (%)	LOI (%)	OM (%)	LOI (%)	OM (%)
15	14.7	10.0	16.0	10.0	26.7	16.9
30	15.7	10.1	18.5	11.3	27.1	17.3
45	15.2	9.8	15.5	9.3	23.2	13.7
60	14.0	9.3	14.5	9.0	12.7	9.2
75	11.4	8.2	9.2	5.6	13.3	9.6
90	14.0	4.4	11.2	6.6	15.8	10.9
105	14.1	4.9	12.6	7.5	16.8	11.6
120	14.1	8.9	7.0	4.3	15.9	10.8
135	13.5	7.8	5.6	3.2	16.4	11.1
150	13.1	8.3	6.3	3.6	16.1	11.5
165	12.4	7.4	4.5	2.5	15.8	10.9
180	12.2	7.4	6.2	3.5	16.2	11.1
195	12.3	6.9	4.0	2.4	15.6	11.4
210	11.7	6.7	4.5	2.8	15.9	10.9
225	11.1	6.4	3.5	2.2	16.3	11.0
240	13.1	6.9	4.2	3.0	15.0	9.0
255	15.7	8.5	4.7	3.0	14.3	9.1
270	16.5	9.1	4.8	2.5	9.5	6.3
285	16.1	8.5	6.4	4.9	6.8	4.4
300	16.5	8.3	5.4	3.0	7.8	4.9
315	16.8	10.8	6.9	4.0	4.6	2.8
330	17.8	9.5	7.1	4.5	5.7	3.4
345	18.5	10.6	6.4	4.0	8.3	5.7
360	24.0	16.4	15.0	11.2	6.7	5.3
375	22.7	15.5	15.3	11.6	6.1	4.1
390	25.4	17.8	16.1	18.3	23.3	18.1
405	22.4	15.2	22.2	14.4	20.7	16.0
420	-	-	13.9	9.2	45.4	31.0

However, the gem-bearing formation is recognised as the slope-forming material, which is transported to the lower basin due to climatic influences (Dahanayake, 1980).

Figure 4 illustrates the grain size distribution curves for borehole samples. Average grain size variations of the different layers are not significant. Boreholes A and C have dominant bimodal sediments, where the dominant mode is concentrated around 400 – 800 μm (fine sediments) and the minor mode is concentrated around 80 – 120 μm (very fine sediments). However, borehole B mostly reflects a unimodal pattern with the similar major mode with boreholes A and C.

The bimodal characteristics delineate in clay-rich layers while sand layers are unimodal. The bimodal clay-rich sediment is probably a result of the impact of different sources and changes in physical and chemical weathering (Gregory & Sambrook, 1996; Lin, 2016). Especially, clay-rich sediments are formed under wet climatic conditions, which reflect intense weathering. The mineralogical evidence of the bimodal clay-rich sediment also indicates dominant kaolinite formation, which further reflects terminal withering association. In addition, formation of bimodal clay-rich sediment may reflect the weathering on quartz less provenance. The unimodal pattern in sand layers may indicate an identical source. In general, different unimodal and bimodal patterns in sediments may reflect the influences of different climatic conditions on the source (Outridge *et al*., 2017).

Associated characteristics of different layers

Table 1 presents the loss on ignition (LOI), organic matter (OM), and total organic carbon (TOC) contents of the sediment layers. The LOI, OM, and TOC values were very high in the ORC layer, moderately high in the

Table 2: Average major and trace element abundances of the sediment layers in Pelmadulla alluvial formation (n = 84)

	OMR clay	Sandy clay	Sand	Clay	Top soil	UCC
Major element (wt %)						
SiO_2	45.31	38.54	55.52	48.74	41.21	66
TiO_2	0.82	0.91	0.85	0.85	0.99	0.64
Al_2O_3	13.76	16.05	10.70	13.98	15.82	15.4
Fe_2O_3	6.10	8.56	5.06	6.11	9.93	5.04
MnO	0.03	0.01	0.07	0.05	0.02	0.1
MgO	0.32	0.23	0.17	0.15	0.13	2.48
CaO	0.64	0.62	0.55	0.52	0.47	3.59
Na_2O	0.24	0.30	0.30	0.21	0.22	3.27
K_2O	0.86	0.98	0.89	1.00	1.10	2.8
Trace element (mg/kg)						
TS	1920	448	905	399	231	62
V	208	186	145	170	190	97
Cr	256	370	303	290	334	92
Ni	54	52	24	35	43	47
Cu	48	46	27	35	46	28
Zn	123	89	78	75	96	67
Ga	16	19	9	13	16	17
Rb	46	34	23	28	33	84
Sr	64	138	86	106	141	320
Nb	18	13	15	13	16	12
Pb	38	33	14	23	30	17
Th	20	22	11	16	21	10.5
U	10	11	5	6	12	2.7
Zr	2966	3118	3163	3147	3331	193
Rare-earth element (mg/kg)						
Y	43	33	16	23	26	21
Ce	34	31	0	6	0	63
Eu	795	858	653	765	839	1
Gd	250	151	81	132	261	4
Tb	215	58	130	152	32	0.7
Dy	80	105	14	40	72	3.9
Er	13	11	20	10	5	2.3
Tm	25	27	8	15	11	0.3
Yb	7	15	15	13	21	1.9

OMR = organic matter rich clay; UCC = average upper continental crust value; TS = total sulfur

clay or alluvial, and diminished in the sand. The LOI value closely correlates to the carbonate content of the sediments (Heiri *et al*., 2001). Thus, a higher level of LOI in the ORC layer may indicate mixing of carbonate during sedimentation, and higher OM and TOC indicate rich carbon sources. Higher TOC in the ORC layer may reflect a higher sedimentation rate, whereas lower values in clay and sand indicate a slower sedimentation process (Ding *et al*., 2015). Notably, the values of OM may reflect the level of accumulation of organic materials during sedimentation. Perhaps, the presence of OM in all layers is evidence that an organic matter-rich environment forms the sedimentary deposits.

Chemical characteristics

Major and trace element abundance in alluvial succession

Table 2 presents the average abundances of major and trace elements in different layers. Higher values of SiO_2, Al_2O_3 and Fe_2O_3 characterise the sediment successions.

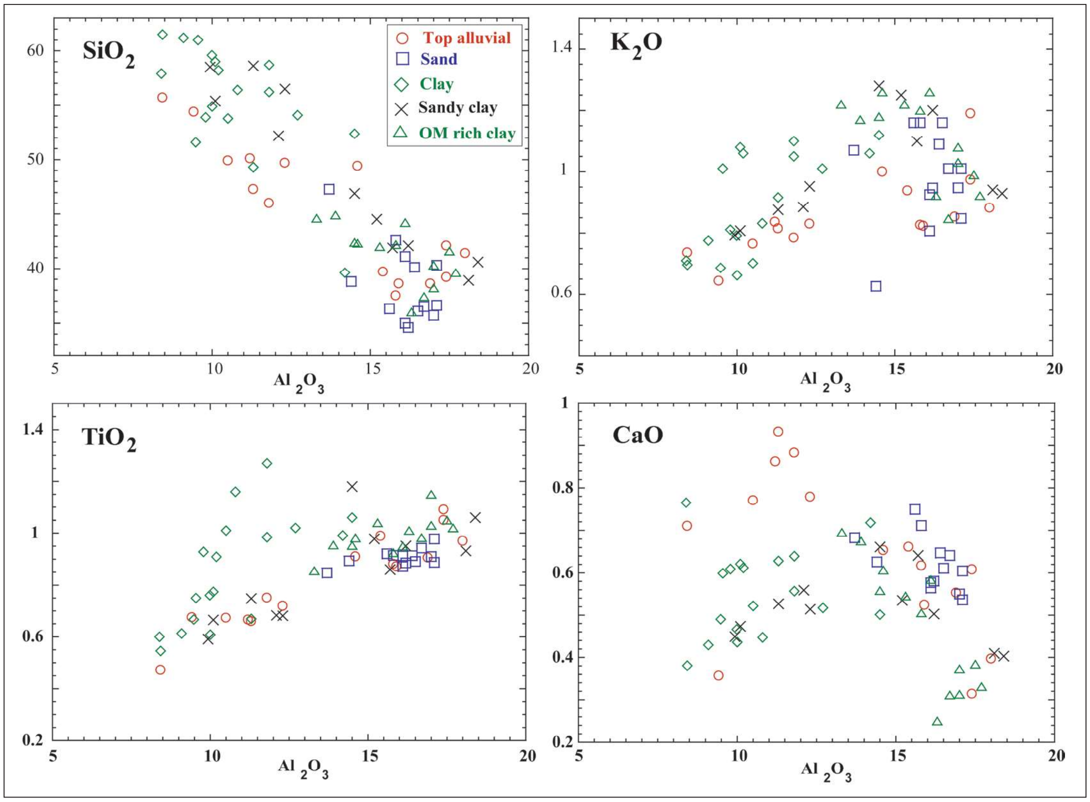

Figure 5: Major element provenance discriminant plot (Roser & Korsch, 1988) for sediment samples from different alluvial formation

The sand layers are differentiated by higher values of SiO_2 while higher values of Al_2O_3 and Fe_2O_3 demarcate the enrichment of clay. The average value of TiO_2 is somewhat high for all layers. However, an abundance of MnO, MgO, CaO, K_2O and Na_2O for the layers have strongly depleted (Table 2). Depletion of MnO may be due to the lower availability in source and higher mobility during chemical weathering. Conversely, MgO, CaO, K_2O and Na_2O are usually depleted in clastic sediments due to strong mobility.

The contents of ferromagnesian elements (Ni, Cr and V) and large cations (Y, Nb, Zr, Th, U and Sr) tend to be high in most layers with other rare-earth elements (Ce, Eu, Gd, Tb, Dy, Er, Tm and Yb) possibly demarcating the availability of heavy minerals (Table 2). Further, the sediment layers are relatively enriched in chalcophile elements (Pb, Zn and Cu) with more variable contents. The total sulfur content is exceptionally high in the layers, probably due to the accumulation of organic matter and may reflect high salinity levels in the sediments.

Major element relationship in alluvial succession

Major elements were plotted on a Harker variation diagram to assess the control of clay mineral content and overall elemental variations (Figure 5). A negative linear trend is exhibited between Al_2O_3 and SiO_2 in the data (Figure 5a), as it is typical of sedimentary basin dominated by variable contents of aluminous clays (Al_2O_3) and quartz (SiO_2). A strong positive correlation between Al_2O_3 and K_2O in the sediments indicates the control of aluminous clay minerals such as illite and the presence of alkali feldspar (Figure 5b). A strong positive correlation between Al_2O_3 and TiO_2 (Figure 5c) in the samples indicates the association of the residual products of TiO_2- bearing phases with the clay fraction, or with fine-grained Ti-bearing heavy minerals. In contrast, different correlations exist between Al_2O_3 and CaO in different layers, reflecting the lower availability of plagioclase and carbonates (Figure 5d).

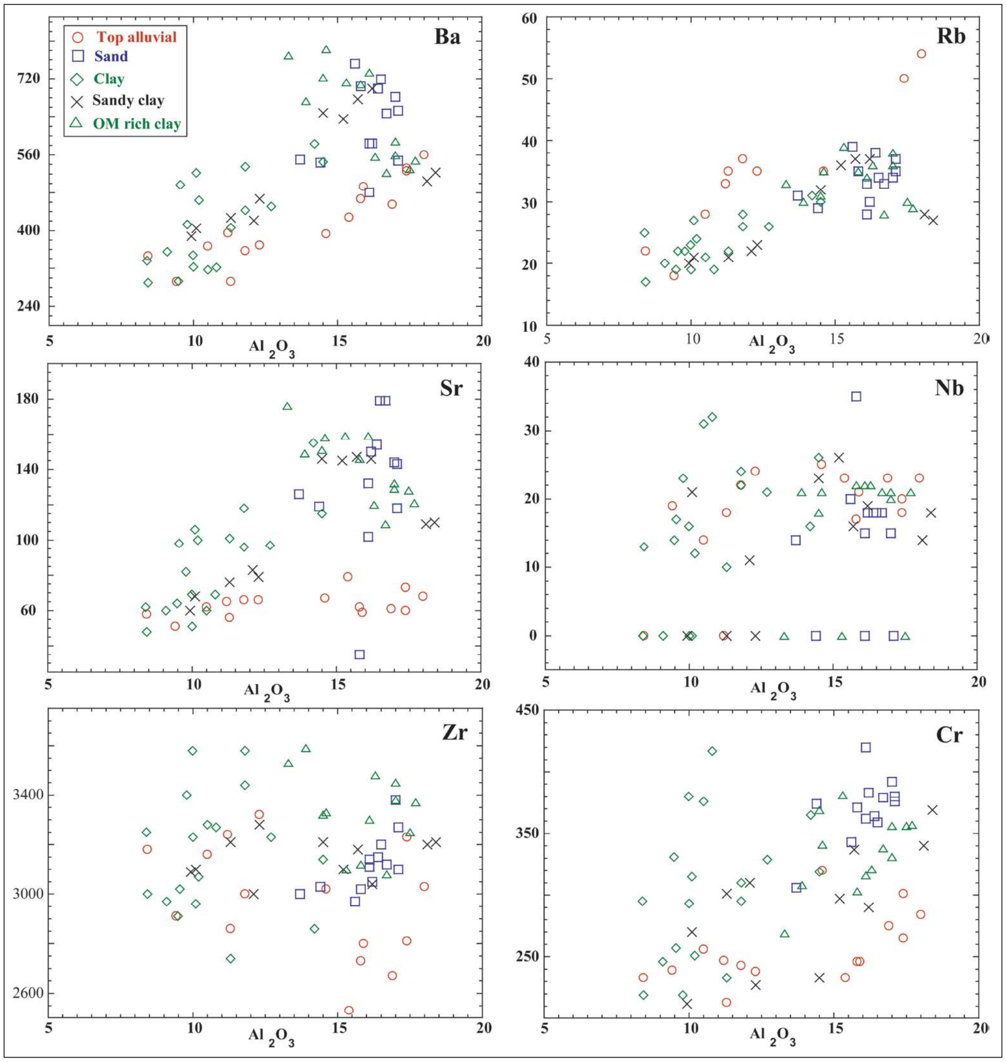

Figure 6: Discriminant function diagram for the Pelmadulla alluvial sediments (Bhatia, 1983)

Trace element relationship in alluvial succession

Most trace elements show correlations with Al_2O_3 of varying strength under different clay and sand contents of the layers (Figure 6). Both Ba and Rb are positively correlated with Al_2O_3 in some layers with a higher clay content in sediment deposit, indicating that the distribution of large-ion lithophile elements is mainly controlled by phyllosilicates (Figures 7a and 7b). A positive correlation exists between Sr and Al_2O_3 (Figure 6c) in most sediment layers, signifying the association of Sr with clay minerals. High field strength elements (HFSE) also denote a considerable variation. Niobium shows a marked positive correlation with Al_2O_3 in most layers, suggesting an association with clay (Figure 6d), while zirconium displays a different pattern with relatively high and uniform concentrations in all layers with no proper correlation with Al_2O_3 (Figure 6e).

Grain size and sorting on sediment composition

Grain size and sorting have a considerable influence on sediment compositions (Kiminami & Fujii, 2007). CIA values were plotted against the SiO_2/Al_2O_3 ratio (Figure 7) to evaluate the effects of grain size and sorting. The different sediment layers are not separated clearly due to high CIA, although SiO_2/Al_2O_3 ratios are overlapped. The SiO_2/Al_2O_3 ratios in sandy sediments are relatively higher by their high SiO_2 contents, and a significant negative correlation between CIA and SiO_2/

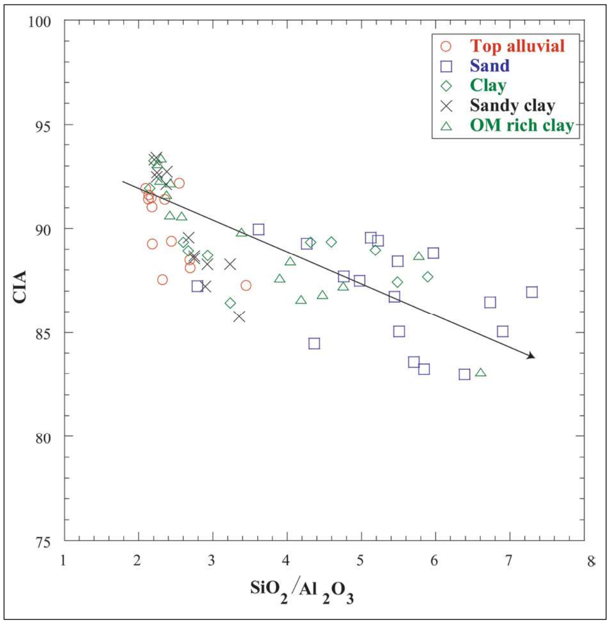

Figure 7: A-CN-K (Al_2O_3-CaO+Na_2O-K_2O) diagram for mineralogical and compositional variations in alluvial sediment samples (Nesbitt & Young, 1984). The dotted line parallel to the A-CN edge is the ideal weathering trend (IWT). Ideal mineral compositions: Ka (kaolinite), Gb (gibbsite), Chl (chlorite), Mu (muscovite), Sm (smectite), Pl (plagioclase), Ksp (K-feldspar) and illite

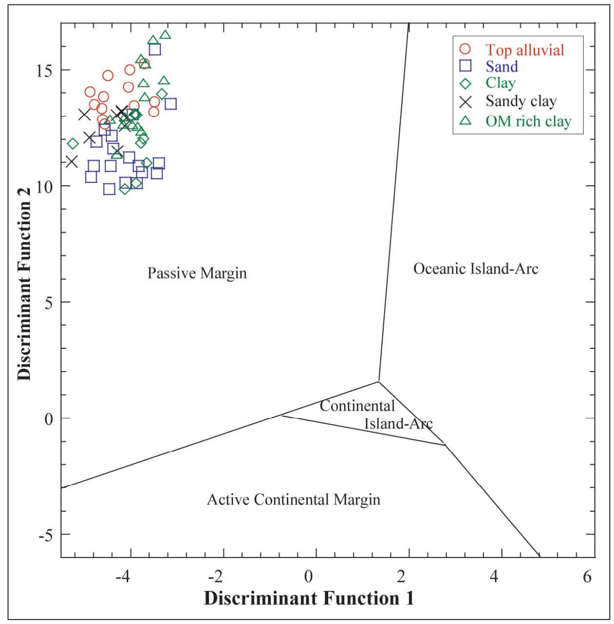

Figure 8: Element ratio plot of Ga/Rb-K_2O/Al_2O_3 for sediment samples from different alluvial formations

Al_2O_3 in the succession indicates that the variation in CIA is due to varying grain size and sorting. However, the different alluvial formations in Pelmadulla have

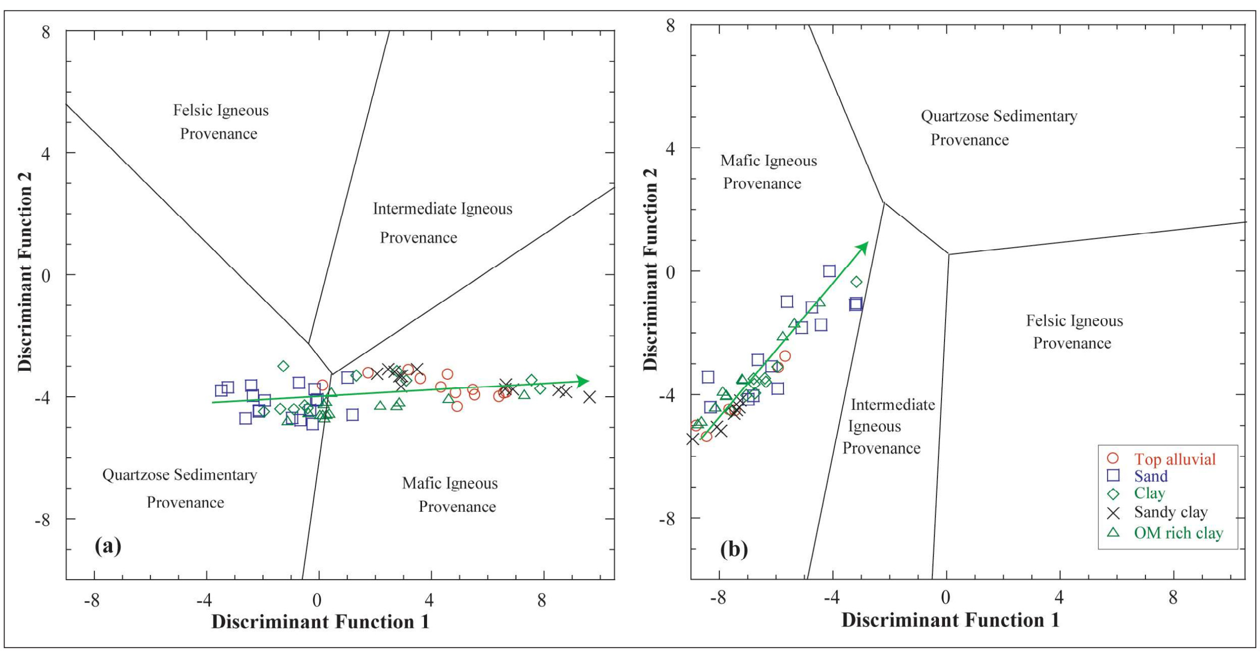

Figure 9: a and b: Major element provenance discriminant plot (Roser and korsch, 1988)

uniformly high CIA ratios (range 83 – 93; average 89), which further concludes that the accumulation of gem minerals in the deposit is effectively controlled with strong chemical weathering.

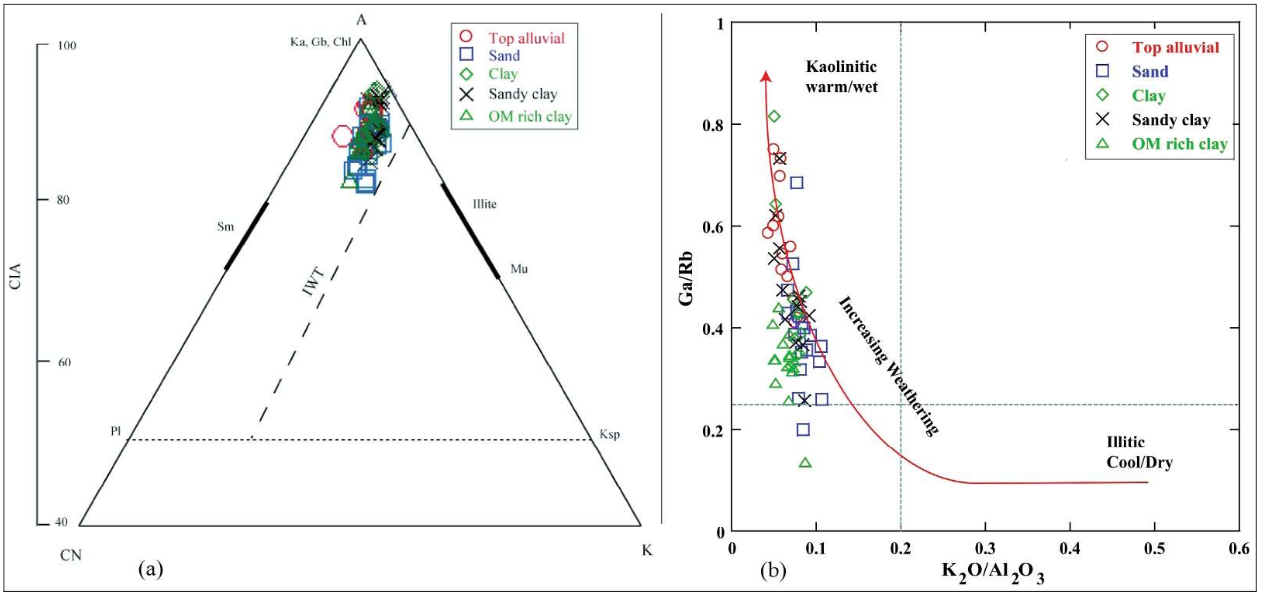

Figure 10: (a) Selected major element-Al_2O_3 variation diagram and; (b) selected trace element-Al_2O_3 variation diagram for the Pelmadulla alluvial sediments

Tectonic discrimination of alluvial formation

Different tectonism, weathering, and chemical modification during sediment transport are common phenomena, and the tectonism of depositional systems can influence the geochemical compositions of sediments (Johnsson, 1993; Roser, 2000). Figure 8 presents the tectonic discrimination for gem-bearing sedimentary deposit. Different sediment layers in Pelmadulla are laid on passive continental margin (Roser & Korsch, 1986), which indicates that rock assemblage deposits may be formed in a cratonic basin and the formation of mature gem-bearing clastic sediments. However, this may need further clarification by a detailed study. The sediments dominantly show mafic igneous provenance with a trend towards quartzose sedimentary provenance (Figure 9). This concludes that the gems belonging to mafic rocks could be expected in the alluvial gems in the region. Thus, the mafic provenance was evidenced by the common gem minerals found in the region such as corundum, chrysoberyl, spinel, garnet, and tourmaline. These minerals are predominantly enriched with mafic ferromagnesian elements (Fe, Mg, Ni, Cr, V, and Ti). However, the quartzose-dominant trend may reflect the enrichment of mineral quartz in the source rocks and the intensive chemical weathering during transportation (Figure 9).

The climatic impact on alluvial formation of overburden in gem-bearing deposit

The CIA values can be plotted graphically in the A-CN-K diagram in a more accurate assessment of weathering trends and conditions (Nesbitt & Young, 1984). In this plot, all sediment layers of Pelmadulla were laid in a tight cluster near the A apex and above to the ideal weathering line (IWT; Figure 10a). However, a slight upward weathering trend of sediments was noted from the IWT line to the apex, which may discriminate the sand and clay layers. The uniform CIA values of the sediments and their clustering in A-CN-K suggest a steady-state weathering condition on their sources. This leads to intense weathering signalled by the marked depletion of labile elements relative to UCC (Table 2). Conversely, stable elements are enriched in the system compared to UCC, and those elements are the major components for gems. Especially, all sediment layers are strongly enriched with the element Zr and REE, indicating the mineral zircon, while the enrichment of V and Cr may reflect the availability of garnet (Jayawardana *et al*., 2015).

Fine-grained aluminosilicate fractions are mainly associated with the elements Al and Ga and enriched in kaolinite associated with strong chemical weathering under a warm and humid climate (Ratcliffe *et al*., 2010). Elements K and Rb are associated with illite, reflecting dry and cool climatic conditions. Consequently, sediments rich in kaolinite should have high Ga/Rb and low K_2O/Al_2O_3 ratios, whereas those rich in illite will have low Ga/Rb and high K_2O/Al_2O_3 ratios. Figure 10b presents the combination of this ratio for the Pelmadulla sediments in a Ga/Rb-K_2O/Al_2O_3 binary plot (Roy & Roser, 2013). In contrast, Ga/Rb ratios in Pelmadulla sediments are in a wide range (~0.15–0.8) and low K_2O/Al_2O_3 (< 0.1), suggesting a preponderance of kaolinite produced during an increased chemical weathering process under warm and humid climatic conditions.

CONCLUSIONS

The sedimentological study of alluvial successions in Pelmadulla, Sri Lanka, covers different layers of sand, clay and ORC in the gem deposit overburden. These layers indicate hydraulic sedimentary facies by saltation, suspension and storm-type origins. Storm-type deposit is dominant with ORC, which concluded the formation under an extreme climatic event, and the bimodal and unimodal characteristics of clay and sand determined chemical weathering impacts on different sources. Analyses of clay deposits concluded a higher sedimentation rate with the enrichment of inorganic carbon, which may indicate a sudden event. Major element relationships for different layers resolved the formation of aluminous clay by alkali feldspar. Enrichment of ferromagnesian elements and large cations with rare-earth elements in the sediment layers indicate the presence of heavy minerals such as zircon and garnet. A steady-state chemical weathering is dominant in the layers with marked depletion of the labile fraction, while a negative correlation between CIA and SiO_2/Al_2O_3 concluded the impact of grain size and sorting. The relationship between Ga/Rb and K_2O/Al_2O_3 concluded the trend of weathering from a dry and cool climatic condition to a warm and humid climate. In contrast, the provenance of sediments fulfilled the quartzose to mafic nature, formed under a passive margin condition.

Acknowledgement

The authors thank the Centre for Forestry and Environment, Faculty of Applied Science, University of Sri Jayewardenepura, the staff members in National Gem and Jewelry Research Training Institute, Sri Lanka for the support in sample collection and analyses and the staff of the Department of Forestry and Environmental Sciences.

REFERENCES

Bertaux J., Frohlich, F. & Ildefonse P. (1998). Multicomponent analysis of FTIR spectra: quantification of amorphous and crystallized mineral phases in synthetic and natural sediments. *Journal of Sedimentary Research* **68**: 440–447. DOI: https://doi.org/10.2110/jsr.68.440

Bhatia M.R. (1983). Plate tectonics and geochemical composition of sandstones. *Journal of Geology* **91**: 611–627. DOI: http://dx.doi.org/10.1086/628815

Bhatia M.R. & Crook K.A.W. (1986). Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. *Contributions to Mineralogy and Petrology* **92**: 181–193. DOI: https://doi.org/10.1007/BF00375292

Bong W.S.K., Nakai I., Furuya S., Suzuki H., Abe Y., Osaka K., Matsumoto T., Itou M., Imai N. & Ninomiya T. (2012). Development of heavy mineral and heavy element database of soil sediments in Japan using synchrotron radiation X-ray powder diffraction and high-energy (116 keV) X-ray fluorescence analysis: 1. Case study of Kofu and Chiba region. *Forensic Science International* **220**: 33–49. DOI: https://doi.org/10.1016/j.forsciint.2012.01.024

Cooray P.G. (1984). *An introduction to the geology of Sri Lanka (Ceylon)*. 2nd edition, pp. 81–104, 256–259, 289. National Museums of Sri Lanka, Colombo, Sri Lanka. DOI: https://trove.nla.gov.au/version/21201966

Cooray P.G. (1994). The Precambrian of Sri Lanka: a historical review. *Precambrian Research* **66**: 3–18. DOI: https://doi.org/10.1016/0301-9268(94)90041-8

Dahanayake K., Liyanage A.N. & Ranasinghe A.P. (1980). Genesis of sedimentary gem deposits in Sri Lanka. *Sedimentary Geology* **25**: 105–115. DOI: https://doi.org/10.1016/0037-0738(80)90056-1

Ding X., Liu G., Zha M., Huang Z., Gao C., Lu X., Sun M., Chen Z. & Liuzhuang X. (2015). Relationship between total organic carbon content and sedimentation rate in ancient lacustrine sediments, a case study of Erlian basin, northern China. *Journal of Geochemical Exploration* **149**: 22–29. DOI: https://doi.org/10.1016/j.gexplo.2014.11.004

Dissanayake C.B. & Rupasinghe M.S. (1995). Classification of gem deposits of Sri Lanka. *Geologie en Mijnbouw* **74**: 79–88.

Garzanti E. & Andò S. (2007). Heavy mineral concentration in modern sands: implications for provenance interpretation. *Heavy Mineral in Use* (eds. M.A. Mange & D.T. Wright), pp. 517–545. Milano, Italy.
DOI: https://doi.org/10.1016/S0070-4571(07)58020-9

Gregory H. & Sambrook S. (1996). Bimodal fluvial bed sediments: origin, spatial extent and processes. *Progress in Physical Geography* **20**: 402–417.
DOI: https://doi.org/10.1177/030913339602000402

Grizelj A., Peh Z., Tibljaš D., Kovačić M. & Kurečić T. (2017). Mineralogical and geochemical characteristics of Miocene pelitic sedimentary rocks from the south-western part of the Pannonian Basin System (Croatia): Implications for provenance studies. *Geoscience Frontiers* **9**: 65–80.
DOI: https://doi.org/10.1016/j.gsf.2015.11.009

Hapuarachchi D.J.A.C. (1998). Corundum in the gem gravels of Sri Lanka. *Gondwana Research* **1**: 415–416.
DOI: https://doi.org/10.1016/S1342-937X(05)70861-3

Heiri O., Lotter A.F. & Lemcke G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* **25**: 101–110.
DOI: https://doi.org/10.1023/A:1008119611481

Herath J.W. (1984). Geology and occurrences of gems in Sri Lanka. *Journal of the National Research Council of Sri Lanka* **12**: 257–271.
DOI: http://doi.org/10.4038/jnsfsr.v12i2.8364

Jayawardena D.E. de. S. & Carswell D.A. (1976). The geochemistry of charnockites and their constituent minerals from the Precambrian of southeast Sri Lanka. *Mineralogical Magazine* **40**: 541–554.
DOI: https://doi.org/10.1180/minmag.1976.040.314.01

Jayawardena D.T., Pitawala H.M.T.G.A. & Ishiga H. (2014). Assessment of soil geochemistry around some selected agricultural sites of Sri Lanka. *Environmental Earth Science* **71**: 4097–4106.
DOI: https://doi.org/10.1007/s12665-013-2798-9

Jayawardena D.T., Pitawala H.M.T.G.A. & Ishiga H. (2015). Geochemical evidence for the accumulation of vanadium in soils of chronic kidney disease areas in Sri Lanka. *Environmental Earth Science* **73**: 5415–5424.
DOI: https://doi.org/10.1007/s12665-014-3796-2

Johnsson M.J. (1993). The system controlling the composition of clastic sediments. *Processes Controlling the Composition of Clastic Sediments* (eds. M.J. Johnsson & A. Basu A.), pp. 1–19. Geological Society of America, USA.
DOI: https://doi.org/10.1130/SPE284-p1

Jolliffe I.T. (2002). *Principal Component Analysis*, 2nd edition, pp. 487, 547. Springer, New York, USA.
DOI: https://doi.org/10.1007/b98835

Kiminami K. & Fujii K. (2007). The relationship between major element concentrations within sandstones from four turbidite sequences in Japan. *Sedimentary Geology* **195**: 203–215.
DOI: https://doi.org/10.1016/j.sedgeo.2006.08.002

Lin Y., Mu G., Xu L. & Zhao X. (2016). The origin of bimodal grain-size distribution for aeolian deposits. *Aeolian Research* **20**: 80–88.
DOI: https://doi.org/10.1016/j.aeolia.2015.12.001

Madejova J. (2003). FTIR techniques in clay mineral studies. *Vibrational Spectroscopy* **31**: 1–10.
DOI: https://doi.org/10.1016/S0924-2031(02)00065-6

McLennan S.M., Hemming S., McDaniel D.K. & Hanson G.N. (1993). Geochemical approaches to sedimentation provenance and tectonics. *Processes Controlling the Composition of Clastic Sediment* (eds. M.J Johnsson & A. Basu), volume 284, pp. 21–40. Geological Society of America, USA.
DOI: http://dx.doi.org/10.1130/SPE284-p21

Munasinghe T. & Dissanayake C.B. (1980). Are charnockites metamorphosed Archean volcanic rocks? A case study from Sri Lanka. *Precambrian Research* **12**: 459–470.
DOI: https://doi.org/10.1016/0301-9268(80)90040-6

Nesbitt H. W. & Young G. M. (1984). Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic consideration. *Geochimica et Cosmochimica Acta* **48**: 1523–1534.
DOI: https://doi.org/10.1016/0016-7037(84)90408-3

Outridge P.M., Sanei H., Mustaphi C.J.C. & Gajewski K. (2017). Holocene climate change influences on trace metal and organic matter geochemistry in the sediments of an Arctic lake over 7,000 years. *Applied Geochemistry* **78**: 35–48.
DOI: https://doi.org/10.1016/j.apgeochem.2016.11.018

Pohl J.R. & Emmermann R. (1991). Chemical composition of the Sri Lankan Precambrian basement. *The Crystalline Crust of Sri Lanka Part 1*, Summary of Research of the German-Sri Lankan Consortium (ed. A. Kroner), Paper 7, pp. 94–124. Geological Survey Department of Sri Lanka.

Ranasinghe P.N., Dissanayake C.B. & Rupasinghe M.S. (2005). Application of geochemical ratios for delineating gem-bearing areas in high grade metamorphic terrains. *Applied Geochemistry* **20**: 1489–1495.
DOI: https://doi.org/10.1016/j.apgeochem.2005.02.009

Ratcliffe K.T., Wright A.M., Montgomery P., Palfrey A., Vonk A., Vermeulen J. & Barrett M. (2010). Application of chemostratigraphy to the Mungaroo Formation, the Gorgon field, offshore northwest Australia. *Australian Petroleum Production and Exploration Association Journal* **50**(1): 371–388.
DOI: https://doi.org/10.1071/AJ09022

Roser B.P. (2000). Whole-rock geochemical studies of clastic sedimentary suites. *Memoirs of the Geological Society of Japan* **57**: 73–89.

Roser B.P. & Korsch R.J. (1986). Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. *Journal of Geology* **94**: 635–650.
DOI: https://www.jstor.org/stable/30078330

Roser B.P. & Korsch R.J. (1988). Provenance signatures of sandstone-mudstone suites determined using discrimination function analysis of major-element data. *Chemical Geology* **67**: 119–139.
DOI: https://doi.org/10.1016/0009-2541(88)90010-1

Roy D.K. & Roser B.P. (2013). Climatic control on the composition of Carboniferous-Permian Gondwana sediments, Khalaspir basin, Bangladesh. *Gondwana Research* **23**: 1163–1171.
DOI: https://doi.org/10.1016/j.gr.2012.07.006

Rupasinghe M.S., Dissanayake C.B. & Mendis D.P.J. (1994). Use of indicator minerals in gem exploration: study of a granulitic terrain in Sri Lanka. *Journal of Southeast Asian Earth Sciences* **9**: 249–254.
DOI: https://doi.org/10.1016/0743-9547(94)90032-9

Srasra E., Bergaya F. & Fripiat J.J. (1994). Infrared spectroscopy study of tetrahedral and octahedral substitutions in an interstratified illite-smectite clay. *Clays Clay Minerals* **42**: 237–241.
DOI: https://doi.org/10.1346/CCMN.1994.0420301

Sun D., Bloemendal J., Rea D.K., Vandenberghe J., Jiang F., An Z. & Su R. (2002). Grain-size distribution function of polymodal sediments in hydraulic and aeolian environments, and numerical partitioning of the sedimentary components. *Sedimentary Geology* **152**: 263–277.
DOI: https://doi.org/10.1016/S0037-0738(02)00082-9

Tankersley K.B. & Balantyne M.R., (2010). X-ray powder diffraction analysis of Late Holocene reservoir sediments. *Journal of Archaeological Science* **37**: 133–138.
DOI: https://doi.org/10.1016/j.jas.2009.09.023

Taylor S.R. & McLennan S.M. (1985). *The Continental Crust: its Composition and Evolution*, pp. 45–51. Blackwell, Oxford, UK.
DOI: https://doi.org/10.1016/B0-08-043751-6/03016-4

Udvardi B. *et al*. (11 authors) (2014). Application of attenuated total reflectance Fourier transform infrared spectroscopy in the mineralogical study of a landslide area, Hungary. *Sedimentary Geology* **313**: 1–14.
DOI: https://doi.org/10.1016/j.sedgeo.2014.08.005

Wang Q., Li Y. & Wang Y. (2011). Optimizing the weight loss on ignition methodology to quantify organic and carbonate carbon of sediments from diverse sources. *Environment Monitoring and Assessment* **174**: 241–257.
DOI: https://doi.org/10.1007/s10661-010-1454-z