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Stratification Pattern and Geochemical Distribution of Gem Mine Sediments in Rathnapura Gem Fields, Sri Lanka

N. Kanthilatha[1], B. A. S. Kumara[2] and R. M. K. G. U. Rathnayaka[3]

[1]Department of Anthropology and International Center for Multidisciplinary Studies, Faculty of Humanities & Social Sciences, University of Sri Jayewardenepura, Sri Lanka, [2]Department of Geography, University of Sri Jayewardenepura, Sri Lanka, [3]Department of Social Statistics, University of Sri Jayewardenepura, Sri Lanka

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*Corresponding author
E-mail address:
nelumyapa@sjp.ac.lk

https://orcid.org/0009-0006-6449-0055

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ABSTRACT

The geomorphic history of Sri Lanka originates in the Precambrian, when the basement rocks were formed, while the much more recent events of subsequent weathering, erosion and sedimentation processes that led to the development of gem-bearing strata. In the hill country, mineral-rich sediments were carried by rivers and streams and deposited in depressions and floodplains, creating favorable conditions for gem concentration. This study investigates the stratification of gem deposits in the Ratnapura region, focusing on how sediment depth, particle size distribution and geochemical signatures reflect long-term geomorphic and climatic dynamics. Ten gem mines were examined to assess vertical and lateral variations in sediment characteristics. Results show that stratigraphic layering corresponds to Quaternary climatic oscillations, with alternating wet and dry phases producing two to three distinct gem-bearing horizons at varying depths. Geochemical analysis indicated relatively stable concentrations of P_2O_5 and CaO, while K_2O, MgO and Fe_2O_3 showed considerable variability. Grain size decreased with depth, with higher clay and silt proportions suggesting deposition in low-energy basins, whereas sandier deposits reflected higher-energy fluvial transport. Variations across sites point to the influence of paleo-river channel shifts and localized geomorphic processes.

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1. Introduction

Sediment movement is a fundamental geomorphic process that shapes landscapes through weathering, erosion, transport and deposition. These processes are influenced not only by natural controls such as rock type, slope, structure, rainfall and vegetation, but also by human activities (Huggett & Shuttleworth, 2022; Wainwright et al., 2015).

In Sri Lanka, major sedimentary deposits occur primarily in the gem-rich zones of Ratnapura and Elahera, situated along the periphery of the central highlands. Both primary and secondary deposits are found, with nearly a quarter of the island's land area considered potentially gem-bearing (Dissanayake & Rupasinghe, 1993). The Highland Complex, composed largely of high-grade metamorphic rocks, is among the world's most significant gem-bearing terrains. Secondary deposits are particularly important and are controlled by geomorphology, bedrock geology, drainage and climate (Dissanayake & Rupasinghe, 1993; Huggett & Shuttleworth, 2022).

Primary gem deposits occur in two main geological settings: (1) Metamorphic deposits, formed in the Highland Complex through skarn reactions between calcitic and silicate rocks or within granulitic gneisses and (2) Magmatic deposits, often associated with pegmatites. Both precious gems (such as corundum and beryl) and semi-precious stones have been documented in these terrains (Dissanayake & Rupasinghe, 1995; Gunaratne & Dissanayake, 1995). Many of these are hosted in crystalline rocks including cordierite gneisses, garnetiferous gneisses and skarn-type marbles (Dahanayake, 1980; Dahanayake and Ranasinghe, 1981; Katz, 1972).

Sediment transport plays a particularly important role in tropical settings such as Sri Lanka, where an extensive river network, over 100 major rivers, facilitates redistribution of mineral-bearing materials. Runoff dynamics, catchment slope, soil properties and rainfall regimes collectively influence sediment movement. Human modifications, such as reservoirs constructed in upper catchments, have altered sedimentation patterns, often leading to reduced reservoir capacity due to accelerated sediment influx (Schleiss et al., 2016; Sidle et al., 2024).

The Kalu Ganga basin, the focus of this study, is underlain by the Proterozoic Highland Complex and overlain by Quaternary alluvial deposits, commonly referred to as the "Ratnapura beds" (Cooray, 1984). This study investigates the following primary research question: How do stratification characteristics and major oxide geochemistry of secondary gem-bearing sediments in the Ratnapura region reveal the influence of past fluvial dynamics and climatic shifts on gem deposition. Despite their economic importance, spatial and stratigraphic variability in soil geochemistry, particularly in relation to major oxides such as P, K, Mg, Ca, and Fe remains insufficiently documented. Addressing this gap is essential for understanding both natural sedimentary processes and their broader archaeological, geomorphic and environmental implications. The present study aims to evaluate the distribution of major chemical elements across different stratigraphic layers in gem mines of the middle catchment of the Kalu Ganga, Ratnapura District, Sri Lanka.

2. Materials and Methods

The study was conducted in the Ratnapura District of Sabaragamuwa Province, situated to the southwest and south of Sri Lanka's central highlands. Geographically, it lies between 6°15′–6°55′ N latitude and 80°10′–80°57′ E longitude. The district exhibits a wide elevation range, from about 30 m in the lowlands to over 2135 m in the central highlands, encompassing diverse landforms such as mountain ranges, isolated peaks, dissected plateaus and escarpments (Coorey, 1984; Katz, 1972; Kumara et al., 2015).

Natural resources in Ratnapura can be broadly categorized into inorganic and organic groups. The distribution of its mineral wealth is closely related to the underlying rock formations, intensity of weathering and depositional environments. Significant mineral resources include a wide variety of gemstones, as well as clay deposits, crystalline limestone, charnockitic gneisses and basic rock types, many of which are also utilized as construction materials (Gislason, et al., 2008; Jayawardana, et al., 2019; Karunanayake & Katupotha, 1990).

For this research, sediment samples were collected from ten gem mines located in the areas of Balangoda, Kahawatta, Niwithigala, Opanayake, and Palmadulla (Figure 1).

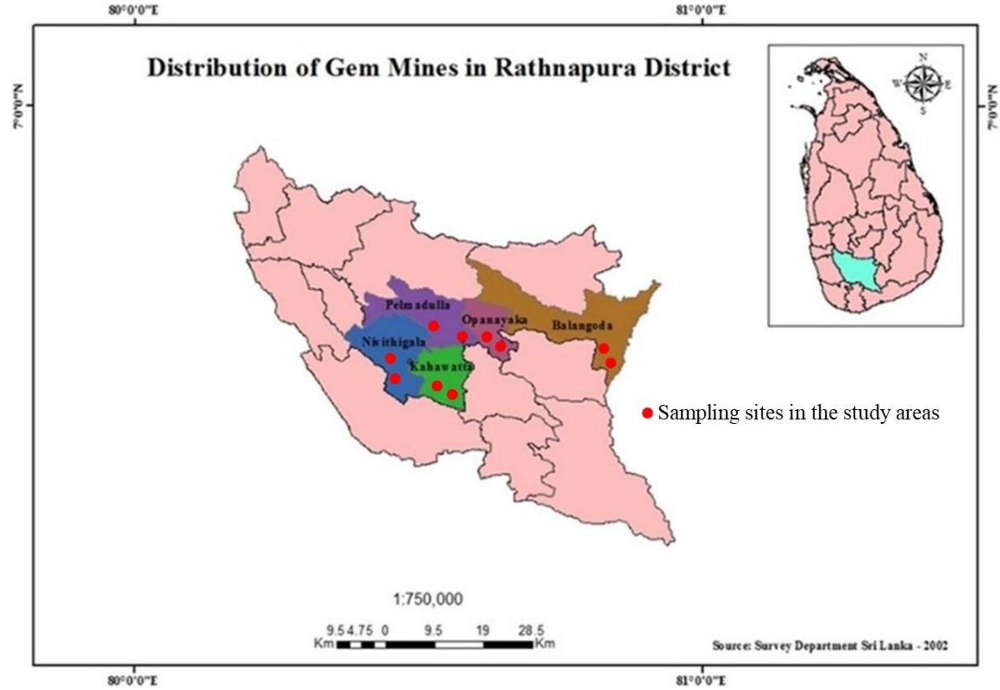


Figure 1. Selected sampling sites at Ratnapura District. Highlighted areas included Nivithigala, Palmadulla, Kahawatta, Opanayaka and Balangoda divisional secretariats.

Samples were obtained from multiple stratigraphic levels within the gem mines, ranging in depth from 0.5 m to 20 m below the surface (Table 1). At each site, information such as the thickness of layers, depth of gem-bearing horizons, mineral variety, gem types, grain shape and particle size distribution was systematically recorded. Local geomorphological conditions and drainage patterns were also noted. From every stratigraphic layer, approximately 300 g of sediment was collected and immediately sealed in labeled plastic containers. Standard field tools including a hammer, PVC coring pipes (2″ diameter, 12″ length), trowels and shovels were used to collect the core samples.

Mine workers, who possess extensive experiential knowledge of subsurface stratigraphy, classify layers using traditional terminology. These colloquial terms include *Kaboka, Vella, Matta, Thel Matta, Kiri Matta, Kola Matta, Maika Matta, Illama, Malawa, Mala Gala,* and *Maw Pashanaya* (bedrock). The occurrence and depth of these horizons vary considerably between mines, even within the same locality. For example, a unit locally known as *Thel Matta* was identified in a Niwithigala mine (Figure 4) but absent in an adjacent site. Such variability reflects localized geological heterogeneity (Figures 2–6).

2.1 Stratigraphy of the mining sites

Given Sri Lanka's tropical setting, the processes of erosion, fluvial transport and sediment deposition play a central role in landscape development. These processes were particularly pronounced during the Quaternary period, leading to extensive sediment accumulation in lowland basins across the island. The Kalu Ganga basin in Ratnapura is especially significant, as it represents one of the most prominent sedimentation zones in the country (Ampitiyawatta, and Guo, 2009; Kumara et al., 2015).

Sri Lankan gem-bearing sediments can be broadly divided into three categories: as Residual deposits – minerals that remain at or close to their parent source, Eluvial deposits – minerals transported short distances downslope from bedrock and Alluvial deposits – minerals carried by rivers and streams over considerable distances, often concentrated in ancient riverbeds or present-day valleys (Dahanayake et al., 1980; Huggett and Shuttleworth, 2022; Mendis et al., 1993).

Nearly all of Sri Lanka's gem resources are derived from the granulite facies rocks of the Highland Complex, which provided the necessary petrological conditions for gemstone formation (Dissanayake et al., 2000). Sedimentology as a discipline examines the origin, transport, and deposition of sediments, emphasizing both natural processes such as weathering and erosion and post-depositional transformations including compaction, lithification and diagenesis. These processes govern the transition of loose sediment into consolidated rock, with associated physical, chemical and mineralogical changes (Leeder, 2011; Schleiss, et al., 2016; Robert, et al., 1990; Wainwright, et al., 2015).

In this study, stratigraphic sequences were analyzed in ten gem mines across the Ratnapura district, located in Balangoda, Kahawatta, Niwithigala, Opanayake and Palmadulla divisional secretariats (DS) (Figures 2–6).

2.2 Chemical Analysis of Sediments

A total of 44 sediment samples, representing stratigraphic layers from the ten selected sites, were subjected to geochemical analysis to determine the concentrations of phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca) and iron (Fe). Samples were first air-dried, and coarse particles were manually removed. The material was then passed through a 2 mm sieve to ensure uniformity, after which the fine fraction was pulverized using a mortar and pestle.

Elemental analysis was performed using Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES) (Perkin Elmer ELAN DRCe) (precision of 1–3% RSD, accuracy within 90–110% recovery, and an uncertainty range of ±2–5%) at the Geological Survey and Mines Bureau (GSMB) Laboratory, Pitakotte, Colombo. Each measurement was carried out in triplicate and the mean value was used in subsequent interpretation. Particle size distribution was determined using the sieve method. Two representative samples (from the surface and basal layers) were collected from each mining site and analyzed at the Petrology Laboratory at the GSMB.

2.3 Statistical Analysis

To evaluate spatial differences in geochemical composition, a one-way Multivariate Analysis of Variance (MANOVA) was applied. This statistical approach was used to test whether independent sampling sites differed significantly across multiple dependent variables (i.e., the measured chemical elements).

3. Data and Data Analysis

Stratigraphic profiles were drawn for each mine site in the Ratnapura lower catchment to illustrate the layering systems found in different locations. The major strata observed during sampling were labeled with both standard geological terms and the Sinhala terminology commonly used by miners in Sri Lanka. These included: the compact gravel-rich horizon (*Kaboka*), sandy deposits (*Vella*), clay-sand mixes (*Matta*) and fine-textured clay units, which miners distinguish further as *Thel Matta*, *Kiri Matta*, *Kola Matta*, and *Maika Matta*. The gem-bearing stratum was consistently referred to as the *Illama*, with underlying layers known as *Maalawa* or *Maala Gala*, and the final bedrock identified as *Maw Pashanaya*. Once the *Maalawa* was reached, excavation typically ceased, as no gem material is expected below it. Mine depths varied widely, ranging from 35 to 120 feet, reflecting the different depths at which the gem-bearing horizons occur. Figures 3–7 illustrate the stratigraphic distribution at Balangoda, Kahawatta, Niwithigala, Opanayake, and Palmadulla mining sites.

3.1 Balangoda Mining Sites

Two sites in Balangoda DS, located at Gankarawa and Kirillawela Grama Niladhari (GN) Divisions were studied. One shaft reached about 70 feet in depth, while the other extended to approximately 35 feet. The key difference between these mines was that in the deeper site a sandy horizon (*Vella*) appeared above the gem layer, whereas in the shallower site a clay-sandy stratum (*Matta*) was observed directly overlying the *Illama* (Figure 2).

3.2 Kahawatta Mining Sites

Two mines from Kotakethana GN Division in Kahawatta DS were also profiled (Figure 3), each extending to roughly 70 feet. In one mine, two distinct sandy layers as well as two separate gem-bearing horizons (*Illama*) were identified. Local miners confirmed that in certain parts of Kahawatta, more than one gem-bearing layer can occur. In this case, the first *Illama* appeared between two thin sandy strata, with the upper sand lens thinner than the lower one. Similarly, the second *Illama* was noticeably thinner than the first (Figure 3).

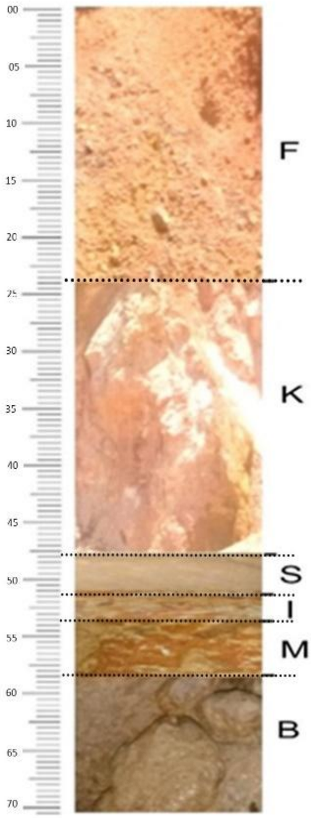
3.3 Niwithigala Mining Sites

Two gem mines were examined in the Niwithigala DS area. The first mine reached approximately 60 feet, while the second extended to about 100 feet. Miners reported that a distinctive feature in some local mines is the presence of two mica layers situated immediately above and below the gem-bearing horizon. Another notable characteristic observed in these shafts was a thin, dark-colored clay layer at the surface (Figure 4).

3.4 Opanayake Mining Sites

Two gem-bearing mines were selected in the Udawela GN area in Opanayake DS, each reaching roughly 60 feet. The soil in these mines was notably drier compared to other sites. A very fine clay layer (*Kiri-Matta*) consistently found directly above the gem-bearing horizon. From top to bottom, the soil texture gradually transitioned through gravel boulders (*Kaboka*), sand, clay and very fine clay until reaching the *Illama* (Figure 5).

Opanayake mines are located at a higher elevation than other study locations, making them well known for their open pits (*Goda Pathal*). A small stream runs close to the first shaft. One key distinction of this site is the thick, compact gravel layer (*Kaboka*) found approximately 15 feet below the surface. Additionally, the sandy (*Vella*), clay-sand (*Matta*) and fine clay (*Kiri-Matta*) layers showed partial mixing. The *Maalawa* layer exhibited a dark yellow hue (Figure 5).



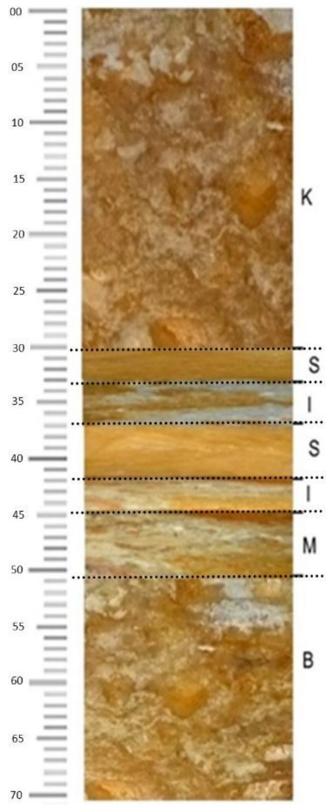


Figure 2. (Left) Stratigraphic layers identified in a Balangoda Mining site
Figure 3. (Right) Stratigraphic layers identified in the Kahawatta Mining sites
(F: in-filled soil layer, K: *Kaboka* (hard gravel boulders), S: sandy layer, I: *illama* (gem baring) layer, M: *Maalawa* (just beneath to the gem bearing layer), B: bedrock (scale 2mm = 1 feet)

3.5 Palmadulla Mining Sites

Two mining shafts were analyzed in the Palmadulla DS region. The first extended to about 50 feet and the second reached 120 feet. Both sites exhibited a black clay-rich soil (*Matta*) within their stratigraphy (Figure 6). The deeper shaft also contained a bluish clay layer with an oily texture (*Thel Matta*) above the gem-bearing horizon.

3.6 Chemical Analysis of Sediment Layers

Sediment samples were collected from a total of ten gem mines to determine the concentrations of key chemical compounds, including P_2O_5, K_2O, MgO, CaO and Fe_2O_3. The sampling strategy targeted different stratigraphic layers across the study sites located in the Kalu Ganga River Basin to capture representative variation. The number of samples per location was as follows: Palmadulla (8 samples, Pal), Opanayake (10 samples, Opa), Kahawatta (10 samples, Kah), Balangoda (8 samples, Bal), and Niwithigala (8 samples, Niv) (Table 1). These analyses provide a detailed understanding of the chemical composition of each layer, contributing to interpretations of mineral distribution within the gem-bearing horizons.

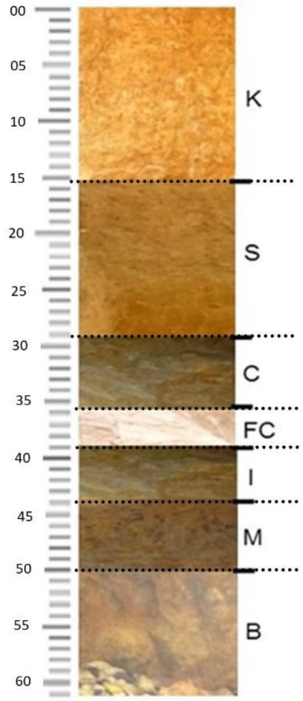


Figure 5. Stratigraphic identified in Niwithigala Mining sites

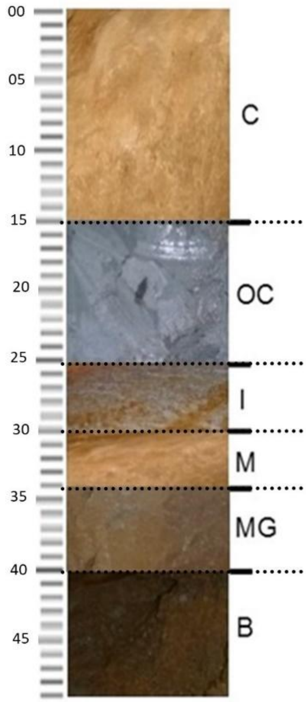


Figure 6. Stratigraphic layers identified in Opanayake site

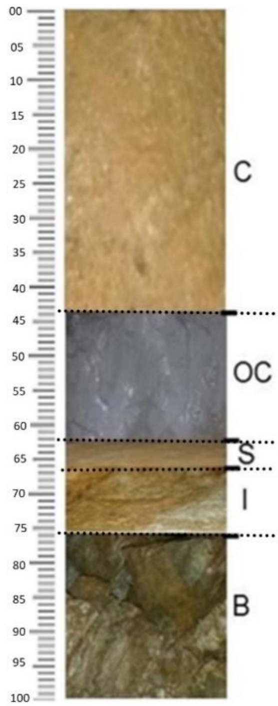


Figure 7. Layers identified in Palmadulla site

(C: clayey soil layer, OC: oily clay layer, S: sandy layer, I: gem baring layer (*illama*), K: hard gravel boulders (*Kabok*), S: sandy layer, C: clay-sandy layer (*matta*); FC: very-fine clay layer (*kiri-matta*) I: gem baring layer (*illama*), M: just beneath to the gem bearing layer (*Maalawa*), MG: hard gravel layer (*Maala gala*), B: bedrock. (scale 1mm = 1 feet)

Table 1. Percentage of basic chemical elements in soil layers

Sample ID (Site-Site No-Layer No)	Depth (~ feet)	P_2O_5 (%)	K_2O (%)	MgO (%)	CaO (%)	Fe_2O_3 (%)
Pal-1-1	10	0.23	1.33	3.93	0.35	4.89
Pal-1-2	20	0.17	0.05	0.07	0.04	1.85
Pal-1-3	30	0.02	0.07	0.06	0.10	0.50
Pal-1-4	35	0.10	0.05	0.04	0.09	2.05
Pal-2-1	10	0.06	2.64	5.92	0.14	2.87
Pal-2-2	20	0.10	3.45	10.69	0.14	8.26
Pal-2-3	30	0.14	0.02	0.02	0.05	2.95
Pal-2-4	35	0.08	0.08	0.15	0.12	0.29

Opa-1-1	10	0.04	0.05	0.04	0.05	2.10
Opa-1-2	20	0.05	0.06	0.02	0.02	3.51
Opa-1-3	30	0.07	0.05	0.03	0.04	2.84
Opa-1-4	40	0.02	0.03	0.03	0.04	2.21
Opa-1-5	45	0.11	0.08	0.02	0.01	9.23
Opa-2-1	10	0.04	0.03	0.02	0.03	0.56
Opa-2-2	20	0.05	0.05	0.03	0.02	4.76
Opa-2-3	30	0.05	0.07	0.03	0.05	2.61
Opa-2-4	40	0.06	0.04	0.03	0.04	6.29
Opa-2-5	45	0.06	0.06	0.03	0.01	8.38
Kah-1-1	15	0.15	3.93	11.36	0.01	3.39
Kah-1-2	35	0.36	0.68	12.67	0.02	12.08
Kah-1-3	45	0.09	0.02	0.02	0.02	2.41
Kah-1-4	50	0.30	0.02	0.02	0.02	6.85
Kah-1-5	60	0.03	0.05	0.03	0.05	0.76
Kah-2-1	15	0.08	2.93	9.44	0.34	0.01
Kah-2-2	35	0.03	0.05	0.06	0.04	0.62
Kah-2-3	45	0.17	0.06	0.06	0.05	1.64
Kah-2-4	50	0.06	0.06	0.05	0.08	1.37
Kah-2-5	60	0.34	0.03	0.15	0.14	12.05
Bal-1-1	15	0.10	0.04	0.07	0.05	12.90
Bal-1-2	35	0.20	0.04	0.02	0.03	6.95
Bal-1-3	45	0.05	0.03	0.02	0.03	2.76
Bal-1-4	50	0.13	0.04	0.02	0.03	3.70
Bal-2-1	05	0.34	0.05	0.04	0.05	14.57
Bal-2-2	15	0.13	0.03	0.03	0.03	6.87
Bal-2-3	20	0.08	0.04	0.02	0.04	3.58
Bal-2-4	25	0.09	0.06	0.02	0.04	3.75
Niw-1-1	20	0.07	0.05	0.05	0.16	1.28
Niw-1-2	50	0.09	0.08	0.11	0.16	2.36
Niw-1-3	70	0.07	0.06	0.07	0.11	2.33
Niw-1-4	75	0.11	0.04	0.07	0.16	2.48
Niw-2-1	15	0.08	0.05	0.04	0.10	0.60
Niw-2-2	30	0.06	0.08	0.08	0.13	0.98
Niw-2-3	40	0.05	0.02	0.03	0.06	1.42
Niw-2-4	50	0.07	0.02	0.05	0.11	3.92

The multivariate analysis of variance (MANOVA) indicated that the chemical composition of soils differs significantly across the study sites when all measured variables are considered simultaneously. These results suggest that local geological and geomorphological factors strongly influence the geochemical profiles of the sediments, potentially contributing to the observed stratigraphic variation in gem-bearing layers. Subsequent multiple comparisons using the Tukey HSD test assessed site-specific differences in soil geochemistry, including P_2O_5, K_2O, MgO, CaO and Fe_2O_3, across the stratified layers of each mining area.

Most pairwise comparisons did not show statistical significance, indicating that P_2O_5 concentrations remain relatively uniform across the majority of layers and sites. However, localized variability was evident: a significant difference was observed between Layer 2 and Layer 3 (mean difference = –0.1060, $p = 0.036$), particularly at Opanayake (Site 2) and Kahawatta (Site 3), where phosphorus enrichment was more pronounced in Kahawatta soils. Potassium (K_2O) content appeared consistent throughout both the soil profiles and across sites, with no significant pairwise differences ($p > 0.05$). Similarly, magnesium oxide (MgO) exhibited stability across stratigraphic layers and sites, reinforcing the relatively uniform distribution of these oxides.

In contrast, calcium oxide (CaO) displayed distinct spatial and vertical variability. Significant differences were observed between Layer 1 and Layer 2 (mean difference = 0.0977, $p = 0.025$) and between Layer 2 and Layer 5 (mean difference = –0.0928, $p = 0.037$), patterns that aligned with site-specific contrasts—most notably between Palmadulla (Site 1) and Opanayake (Site 2), and between Opanayake (Site 2) and Niwithigala (Site 5). A marginal difference between Palmadulla (Site 1) and Balangoda (Site 4) ($p = 0.060$) further highlights spatial heterogeneity in calcium distribution. For Fe_2O_3, a significant increase was identified between Layer 4 and Layer 5 (mean difference = 4.9638, $p = 0.048$), consistent with the site-level difference observed between Balangoda (Site 4) and Niwithigala (Site 5), where Balangoda soils showed elevated iron oxide content.

3.7 Grain Size of the Sediments

For grain size analysis, two samples were selected from each of the five mines, representing the topmost and lowermost layers of the sediment profile. Table 2 presents the proportion of sand relative to the combined silt and clay fractions for ten sediment samples collected across the study sites (Palmadulla – Pal, Opanayake – Opa, Kahawatta – Kah, Balangoda – Bal, and Niwithigala – Niw). Soil texture is a critical factor, as it affects sediment deposition patterns, water drainage, nutrient retention and the potential formation of gem-bearing horizons within these geological contexts.

Table 2. Grain size analysis of soil

Sample ID	Sand (%)	Silt and Clay (%)
Pal-1-1	46.4	53.59
Pal-1-4	34.4	65.59
Opa-1-1	58.76	41.23
Opa-1-5	9.32	90.67
Kah-1-1	51.02	48.97
Kah-1-5	31.16	68.83
Bal-1-1	13.08	86.91
Bal-1-4	44.83	55.16
Niw-1-1	42.84	57.15
Niw-1-4	37.55	62.44

The analysis of grain size reveals distinct differences between sand-dominated and clay-dominated layers at the various sites, reflecting variations in depositional energy and environmental conditions. Finer-grained strata, characterized by lower sand content and higher proportions of silt and clay are especially important as they may correspond to potential gem-bearing horizons. In contrast, layers with higher sand content indicate periods of more energetic sediment deposition (Kabata-Pendias and Pendias, 2001; Leeder, 2011; Sparks, 1995; Wainwright, et al., 2015).

3. Results and Discussion

The Kalu Ganga basin is a major river system in Sri Lanka, characterized by high rainfall and substantial river discharge. The lower floodplain is prone to seasonal flooding due to the basin's hydrological and topographical features. Sediments from lakes and floodplains act as natural archives, recording environmental and climatic changes over millennia. These records can be reconstructed through analysis of mineralogical, chemical and physical properties of sediments, which generally comprise mineral particles of various sizes, organic matter and biogenically derived inorganic components. This study focused on both chemical composition and particle size variation within gem-bearing layers.

4.1 Geochemical Composition

Analysis of major oxides revealed that phosphorus, calcium and iron are commonly present in most soil layers (Table 2). Elevated P_2O_5 concentrations were noted at Kahawatta (35–60 ft depth) and Balangoda (5 ft depth), while other locations showed relatively uniform distributions. Phosphorus may reflect agricultural or residential inputs, though no clear depth trends were observed. Surface layers at Palmadulla-1 and Kahawatta-2 exhibited higher CaO than underlying layers, reflecting calcium mobility through exchangeable cations or leaching.

Iron (Fe_2O_3) displayed the broadest concentration range (0.01–14.57%), with most samples falling between 2–5%. Iron is primarily present as fine-grained oxyhydroxides coating clay, silt and sand particles, which enhances cation adsorption. Maximum Fe_2O_3 concentrations at intermediate depths suggest redistribution via downward migration, potentially aided by organo-iron complexes. Potassium (K_2O) and magnesium (MgO) were mainly concentrated in upper layers at Palmadulla and Kahawatta, while other layers contained trace amounts (<0.07%), likely due to leaching in sandy soils with high water permeability (Kanthilatha, et al., 2017; Kabata-Pendias and Pendias, 2001; Robertnand Chamley, 1990; Senbayram et al., 2015; Sparks, 1995).

Stratigraphic analysis indicated relative stability of P_2O_5, K_2O and MgO across layers, whereas CaO and Fe_2O_3 varied significantly, suggesting selective mobility influenced by stratigraphic position and paleoclimatic factors, which may have contributed to the formation of gem-bearing horizons.

4.2 Sedimentation and Grain Size

Grain size analysis revealed contrasts between sand-rich and fine-grained layers, reflecting variable depositional energy. Sand-dominated layers, such as Opa-1-1 (58.76% sand) and Kah-1-1 (51.02% sand), indicate deposition under high-energy conditions, typically near active river channels. Fine-grained layers (high silt and clay content), such as Opa-1-5 (90.67% silt/clay) and Bal-1-1 (86.91% silt/clay), represent low-energy environments conducive to gem accumulation. Intermediate textures suggest moderate depositional energy and balanced sediment transport.

Across all sites, silt–clay content generally increased with depth, consistent with natural sorting during transport. The depth of gem-bearing layers corresponds with historical river activity, with cycles of flooding, erosion and sediment deposition shaping the observed stratigraphy (Dissanayake, et al., 2000; Gislason, et al., 2008; Huggett and Shuttleworth, 2022; Robert and Chamley, 1990).

4.3 Paleoenvironmental Implications

The alternation of sand-rich and clay-silt layers in the Kalu Ganga basin reflects

Quaternary climatic fluctuations. Periods of intense monsoonal rainfall promoted high-energy sediment transport and deposition of coarse sand near river channels, while more stable, humid intervals allowed fine-grained sediments to settle in floodplains and basins. Such alternations of sandy and clay–silt layers in the gem-bearing profiles represent sedimentary imprints of Quaternary climatic fluctuations. These patterns are consistent with paleoclimatic reconstructions of Sri Lanka, which highlight oscillations between humid and relatively drier phases during the middle to late Quaternary. Variations in chemical composition, particularly selective mobility of CaO and Fe_2O_3 indicate the influence of rainfall, waterlogging and redox conditions on soil chemistry over time (Deraniyagala, 1992; Dissanayake, et al., 2000; Kanthilatha, et al., 2020; Premathilake, 2007; Premathilake & Risberg, 2003; Sparks, 1995; Wainwright, et al., 2015).

These sediments act as paleoenvironmental archives, capturing both hydrological dynamics and broader climatic trends during the middle to late Quaternary. Particle size distributions further support this interpretation, with coarse fractions representing stronger flow conditions and fine fractions indicating more humid, low-energy environments. Similar findings from South Asian Lake and floodplain records also emphasize the role of monsoon variability in controlling sediment geochemistry and depositional environments (Giosan et al., 2012; Kanthilatha et al., 2017; Sinha et al., 2011; Wainwright, et al., 2015). Therefore, the sediments of the Kalu Ganga basin can be regarded as paleoenvironmental archives, recording both the hydrological dynamics of the river system and the broader paleoclimatic shifts that governed erosion, transport, and soil chemical evolution across the region.

Statistical comparisons confirmed significant site-level differences in mean concentrations of P_2O_5, CaO and Fe_2O_3. Notably:

- P_2O_5 differed significantly between Opanayake and Kahawatta ($p < 0.036$)
- CaO varied between Palmadulla and Opanayake ($p < 0.025$) and between Palmadulla and Balangoda ($p < 0.060$)
- Fe_2O_3 differed between Balangoda and Niwithigala ($p < 0.048$)

These results highlight spatial heterogeneity in chemical composition across mining sites, shaped by depositional history, hydrology and post-depositional elemental mobility.

4. Conclusion and Recommendations

The Ratnapura District, particularly within the Kalu Ganga basin, contains Sri Lanka's richest gem-bearing deposits. The formation of these gem-rich sediments is a result of a long and complex interplay between fluvial processes, weathering dynamics and climatic oscillations over Quaternary timescales. By examining both textural and chemical properties of the sediments, it becomes possible to reconstruct the depositional history and environmental conditions that governed gem formation and concentration.

Grain size analysis shows a general increase in silt–clay content with depth, with finer fractions dominating deeper layers. Variation in gem layer depths reflects historical river dynamics, including shifts in channel position and flow intensity, influenced by geological, geomorphological and climatic factors. Geochemical patterns indicate relative stability of P_2O_5 and CaO, while K_2O, MgO and Fe_2O_3 show notable variation, reflecting leaching, redox processes and sedimentary redistribution. Periods of intense rainfall correspond to phases of strong river flow and sediment transport, redistributing gem-bearing gravels downstream. Conversely, during prolonged dry periods, river energy declined, allowing fine-grained deposition and the concentration of heavy minerals, including gemstones, within alluvial traps and paleochannels. These alternating wet–dry cycles resulted in multiple episodes of sediment reworking, producing two or more distinct gem-bearing horizons within the basin. Thus, the gem-bearing deposits serve as archives of past hydrological and climatic regimes, recording the influence of tropical monsoon variability on sediment dynamics and mineral concentration.

Gem extraction in the region remains largely traditional, highlighting the importance of systematic exploration to predict gem distribution accurately. Integrating sedimentological, geochemical and paleoenvironmental analyses provides a robust framework for understanding the genesis of gem-bearing layers. Future studies incorporating microfossils, chronological dating and high-resolution stratigraphic profiling will further clarify past environmental and climatic conditions, supporting sustainable gem exploration and resource management in Sri Lanka.

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