Geochemical exploration for gem deposits in Sri Lanka – application of discriminant analysis

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Geochemical Exploration for Gem Deposits in Sri Lanka – Application of Discriminant Analysis

Geochemische Exploration von Edelstein-Lagerstätten in Sri Lanka – Anwendung der „Discriminant Analysis"

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With 8 Figures

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Abstract

Discriminant analysis of geochemical data for stream sediments and bedrock of the drainage basins in 7 localities of Sri Lanka selected as test areas successfully distinguished areas of known high gem potential from those of moderate and low or no potential. Using the discriminant function generated from the data set for the 7 test areas, individual stream sediment samples can be classified as high, moderate, or low potential thereby enabling the preparation of gem potential maps of drainage areas. The quantitative distribution of trace elements in stream sediments reflects the presence of certain heavy minerals that tend to be concentrated along with gems. It is suggested that marbles, skarns, calc-silicate and similar rocks derived by metamorphism of limy and aluminous sediments were the most probable bedrock sources of gems now found in the stream sediments. Gems are also known to occur in pegmatites.

Zusammenfassung

Die Bach- und Flußsedimente, sowie die Gesteine des Grundgebirges von sieben Einzugsgebieten in Sri Lanka wurden geochemisch untersucht. Mit Hilfe der „discriminant analysis" können in den ausgewählten Gebieten ausgewiesene Areale mit hoher Edelsteinführung von denen mit mittlerer oder nicht gegebener Edelstein-Erwartung unterschieden werden. Diese Klassifizierung ermöglicht die Ausarbeitung von Karten zur Edelsteinverteilung für die verschiedenen Einzugsgebiete. Die beobachteten Spurenelemente geben die Verteilung spezifischer Schwerminerale in den Sedimenten wieder, die zusammen mit Skarnen, Kalsilikatfelsen und ähnlichen Gesteinen, die bei der Metamorphose von mergeligen Kalksteinen entstanden sind, die Ausgangsgesteine für die Edelsteine bilden. Das Vorkommen von Edelsteinen in Pegmatiten ist ebenfalls bekannt.

Introduction

Gem minerals such as sapphire, ruby, topaz, spinels, and garnets among others have attracted the attention of mineralogists the world over for their variety and uniqueness.

These minerals have been recovered from stream valley sediments for centuries. However, inspite of the seemingly vast gem mineral resources in the country, there had been no serious attempt to apply scientific exploration techniques for gemstones in Sri Lanka.

Further, recent research has shown that nearly 25% of the total land area of Sri Lanka is potentially gem-bearing, making Sri Lanka the most dense gem-bearing country in the world (DISSANAYAKE, 1991).

The abundance of gem minerals in Sri Lanka is further exemplified by the fact that "hearsay" methods and chance findings still form the commonest method of locating gem deposits. Recently several attempts have been made to adopt a more scientific approach in the exploration for gem deposits in Sri Lanka. GAMAGE et al. (1992) used Rb-Sr ratios with reasonable success in the delineation of gem-bearing from non-gem-bearing regions. DISSANAYAKE and RUPASINGHE (1992) applied rare-earth element and rare element geochemistry in the location of target areas for further detailed gem exploration.

This paper discusses the application of discriminant analysis to delineate and locate gem deposits in high grade metamorphic rocks as exemplified by the Highland and Southwestern Groups of Sri Lanka.

Geological Setting

Ninety percent of Sri Lanka's land is underlain by metamorphic rocks of Precambrian Age. These rocks from three major divisions, namely the Highland Complex, Vijayan Complex and Wanni Complex (KRONER et al., 1991).

The Highland Complex comprises mainly of a suite of metasedimentary and possibly metavolcanic rocks formed under granulite facies conditions. The variety of rock observed in the Highland Complex are described in GAMAGE et al. (1992). It is of interest to note that most of the gem deposits of Sri Lanka are confined to the Highland Complex (fig. 1).

The Vijayan and Wanni Complexes are generally devoid of gem deposits except for those alluvial gems transported from the Highland Complex.

The areas around Ratnapura, Balangoda, Rakwana and Avissawella contain abundant gem deposits and form the largest gem field in Sri Lanka. Residual beds bear gem minerals mostly deposited in-situ, while alluvial beds contain minerals transported along slopes of ridges and deposited away from the parent rock. The alluvial beds on the other hand contain gem minerals transported along streams and deposited at distances away from the parent rock.

Materials and Methods

The gem-bearing gravel (illam) commonly lies at the base of the alluvium at or near the bedrock surface generally 1 to 10 but as much as 30 m below ground level. Mining of these deposits involves sinking pits or shafts through the alluvium and tunnelling to follow the pay gravel (illam). The pay gravel, however, does not form a continuous sheet and rich patches may change abruptly to barren intervals. The pay gravel apparently occupies palaeochannels in the alluvium. Table 1 shows the numbers of samples analyzed.

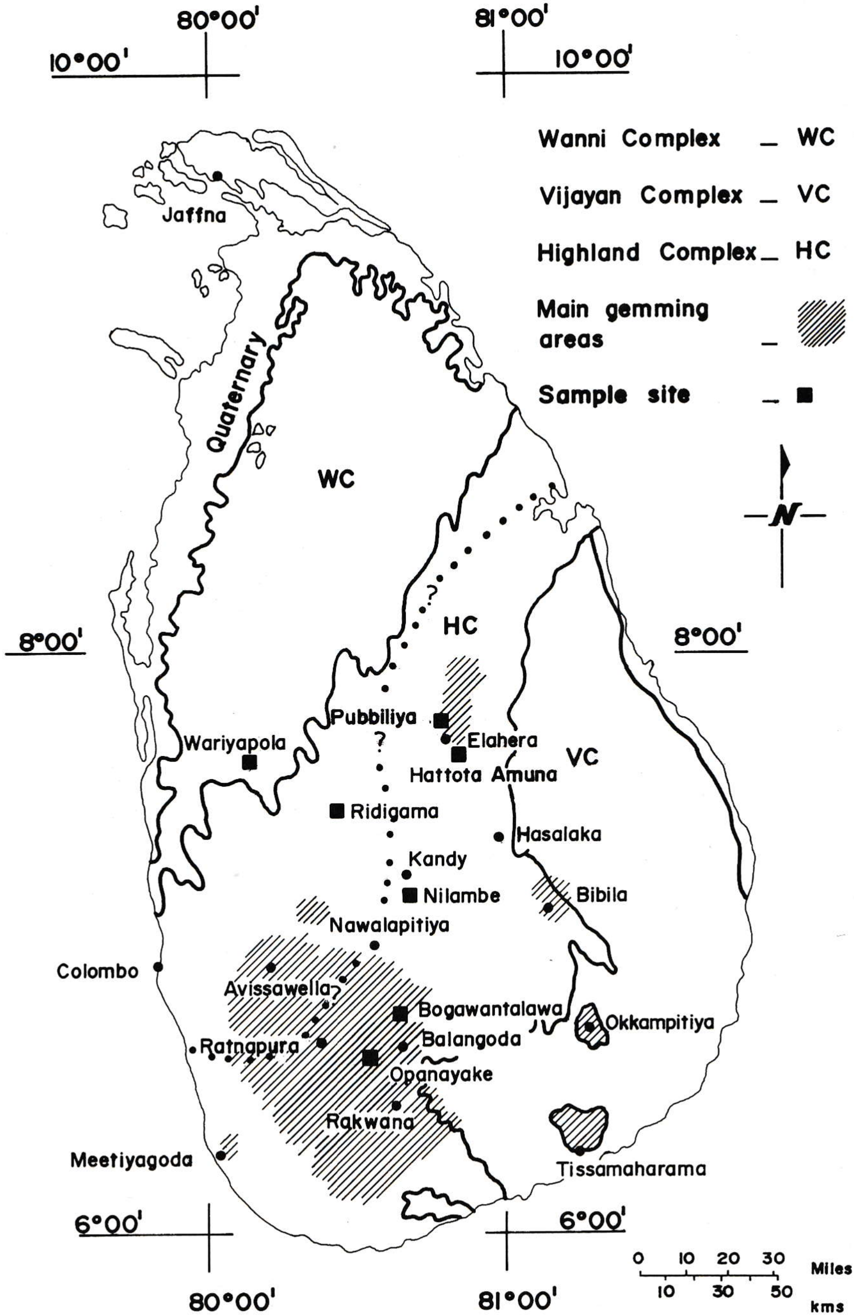

Fig. 1. Map of Sri Lanka showing main geological groups, gem mining areas and sample sites. The dotted line indicating the proposed new boundary of the Wanni Complex is after KRONER et al. 1991.

The basic assumption in the use of stream sediments in gem mineral exploration is that the gem minerals found in stream sediments are derived from adjacent bedrock that form the hillsides of the alluvium-filled valleys. Due to the prevailing topography of hilly areas with adjoining valleys, the effect of heavy monsoonal rainfall is highly marked. Thus, the rocks get easily eroded with concommitant release of weathered materials. Good examples can be seen in the Ratnapura gem fields. Consequently, the mineralogy and chemistry of a particular sediment, gem-bearing or otherwise, should reflect its nearby provenance and the processes of weathering, erosion, solution, transportation and deposition that resulted in the sediment. Therefore, gem-bearing sediments should be characterized chemically and mineralogically permitting them to be distinguished from those with low potential for gems. It is also desirable to characterize the types of bedrock from which sediments of high, moderate, and low gem potential have been derived.

A total of 676 samples from 7 different areas was collected and analyzed by X-ray fluorescence spectrometry at Laurentian University, Canada. Sampling involved both stream sediments and bedrock. The seven areas, shown in Figure 1, represent different levels of known (or assumed) gem potential, as follows:

1) Areas of known high potential; Opanayake and Hattota Amuna. Both areas are underlain with rocks of the Highland Complex. Extensive gem production in these areas is derived from stream sediments.

2) Areas of moderate potential from which some gem occurrences have been reported, but in which no significant production has taken place; e.g., Bogawantalawa and Pubbiliya. These areas are also underlain with rocks of the Highland Complex.

3. Areas of low, very low or no potential; Nilambe and Ridigama. Both areas are underlain with rocks of the Highland Complex. This category also includes Wariyapola, an area underlain with rocks of the Wanni Complex, assumed to lack potential for gems.

In the Opanayake area, a prolific gem-bearing region with extensive production of sapphire, the bedrock consists dominantly garnet sillimanite gneiss, quartzite and marble. Bedrock sampled during the present study included a variety of garnetiferous gneisses containing pyroxene, hornblende or biotite, granulites, acid charnockites, pegmatites, marble and pyroxenite.

The Hattota Amuna area, an area of proven potential for gem quality corundum and garnet, is underlain with garnetiferous gneisses (some of which are graphitic), granulites and charnockites, marble, skarn and pegmatite. Gem-quality garnets appear to be associated mainly with garnet-graphitic gneisses rather than with garnet gneisses lacking graphite. High-quality corundum appears to be restricted to areas of massive, medium- to coarse-grained crystalline limestone.

At Bogawantalawa, an area from which some gems have been reported and which is considered to be of moderate potential, charnockites, charnockitic gneiss and a variety of garnetiferous gneisses were observed. At Pubbiliya, the bedrock consists largely of garnet gneisses, some of which are graphitic. Like Bogawantalawa, Pubbliliya is considered to be an area of moderate potential.

The Nilambe and Ridigama areas, assumed to be of low potential, are underlain with garnetiferous gneisses. The western part of the Ridigama area is underlain with rocks of the Wanni Complex where no gems have been found. These areas were included in the present study for comparison with the areas underlain with rocks of the Highland Complex. Stream sediments were collected by auger or shovel and were dried, desegregated and sieved. The fine fraction (< 65 mesh) was ground further to < 250 mesh, and this material was pressed into powder pellets for analysis by X-ray fluorescence spectrometry.

Discriminant analysis was applied to the geochemical data in order to determine whether significant differences existed between areas of high gem potential, and areas of assumed moderate gem potential. The analysis was performed using the statistical package SYSTAT.

Statistical Methods

This section is intended to show how geochemical variations as observed by discriminant analysis could demarkate samples obtained from different geologic and geographic terrains into clearly defined groups. This would enable one to classify areas into gem-bearing and low non-gem-bearing areas. Due to the compositional differences between sediments from the rapidly-flowing hillside (slope) streams and those of the flat alluvium-filled valleys, samples from these two groups of sediments were treated separately as "slope" samples and "flat" samples.

It was first necessary to determine which particular elements of the 26 analyzed would result in the separation between the three groups of samples (high, moderate and low potential).

This was achieved through a series of analyses of variance (ANOVA) where, by calculating for each element the between-group and, within-group variances, the F ratios and probability (P) that the differences between within-group and between-group variances were due to chance was estimated.

Table 2 presents the F ratios and probabilities (P) for those elements which discriminate between the 3 groups of samples. The differences in F ratios of individual elements in the "slope" and "flat" categories provide further justification for separating stream sediments into those two categories. However, it should be mentioned that the numerical value of the F ratio indicates nothing about the relative quantity of a particular element in slope and flat samples. Such information is only provided in Table 3 which shows the mean element content for slope, flat and rock samples from high, moderate and low-potential areas. Discriminant functions were generated using elements listed in Table 2. The exercise consists in combining the variables so as to yield linear functions that provide the best separation between the previously defined groups of high, moderate and low potential. Separate functions are required for slope, flat and rock samples. The operations were performed using Multivariate General Linear Hypothesis procedures of SYSTAT which procedures plots of individual samples in discriminant space.

The data for rocks were treated somewhat differently from those for the stream sediments. When the rock samples were classified by the discriminant function, it was found that many fell into categories other than those to which they had been assigned in order to generate the discriminate function. This was not surprising since it is probable that only certain rock types with compositions distinctly different from other rock types contribute to the discrimination. Common rock types occurring in areas of high and low potential on the otherhand, would contribute little to, or might even dilute, the ability of the function to discriminate. Furthermore, it is almost certain that in gem producing areas not all rock types are bedrock sources for the gems found in the stream-bearing sediments.

The rock samples which were misclassified by an initial analysis were removed from the data set and only the remaining samples were used in the second discriminant analysis. The average element content of rocks shown in Table 3 are for the 117 samples used in the second discriminant analysis. This provides a greatly improved separation of high, moderate and low potential samples (Fig. 5).

Stream Sediment Discriminant Diagrams

Figures 2, 3 and 4 are the discriminant diagrams for stream sediments based on the elements listed in Table 3. Figure 2 represents results of slope samples obtained from tributary and headwater streams flowing over bedrock of the sediment. Since no slope samples were obtained from Hattota Amuna and Pubbiliya they do not appear in Figure 2.

Due to the crowding of symbols, the results for flat samples are presented on two diagrams Figs. 3 and 4. Figure 3 includes two areas of high potential and two of

Table 1. Numbers and types of samples analyzed.

Area	Sediments	Rock	Total
Opanayke	106	31	137
Bogawantalawa	59	24	83
Hattota Amuna	50	25	75
Pubbiliya	49	27	76
Nilambe	56	24	80
Kurunegala-Ridigama	99	42	141
Wariayapola	56	28	84
Total	475	201	676

Table 2. F ratios and probabilities for slope, flat sediment sample and rock samples.

Rock			Slope			Flat		
Element	F	P	Element	F	P	Element	F	P
P	38.967	0.000	Ni	134.669	0.000	Al	81.595	0.000
Ca	31.867	0.000	Cr	63.307	0.000	Sr	81.208	0.000
Zr	30.413	0.000	Y	59.410	0.000	Ca	77.499	0.000
Ti	18.175	0.000	Sr	28.260	0.000	Zn	58.502	0.000
Ba	17.72	0.000	Zn	26.795	0.000	P	54.281	0.000
Y	8.945	0.000	K	24.397	0.000	Zr	53.081	0.000
Zn	8.513	0.000	Ca	24.358	0.000	Ti	45.078	0.000
Cr	7.865	0.001	Ba	22.432	0.000	Cu	37.235	0.000
Ni	6.543	0.002	P	22.273	0.000	Rb	34.140	0.000
K			Rb	16.027	0.000	Ni	29.695	0.000
Co			Al	12.273	0.000	Co	22.358	0.000
Sr			Zr	6.665	0.002	Cr	15.990	0.000
Al			Cu	4.087	0.018	K	10.307	0.000
Rb			Co			Y	3.528	0.030
Cu			Ti			Ba		

moderate; both figures include results from all three low potential areas. The discriminant diagrams for slope and flat samples reveal excellent separation between areas of high, moderate and low potential (Figs. 2, 3 and 4). The programme also classifies each sample individually, revealing whihc samples were misclassified. Except for some stream sediments in areas of high potential very few samples were misclassified (Table 4). This is also apparent in Figs. 2, 3 and 4 where there is little overlap between the 3 groups. Individual stream sediment samples, properly classified, were then plotted on separate gem potential maps for each of the areas studied. This can now be done for areas of unknown potential for which samples could be collected.

For the areas tested, the separation into three categories of high, moderate and low potential is excellent. Figure 2 contains samples from 3 widely separate areas

Table 3. Mean element content and standard deviations of sediment and rock used in discriminant analysis. All elements in ppm, except K, Al, Ca, Ti, P in %. Rocks (N = 117)
Average element content of sediment and rock used in defining the discriminant functions K, Al, Ca, Ti, P in wt%; remainder in ppm.

Group Potential	K	Al	Ca	Ti	P	Cr	Ni	Co	Cu	Zn	Y	Zr	Rb	Sr	Ba
High (N=30)			12	0.33	0.03	157	35			89	29	136			430
Moderate (N=24)			3	0.75	0.19	30	16			103	44	393			1402
Low (N=63)			2	0.28	0.04	36	21			55	21	186			787
Stream Sediments, Slopes (N=168)															
High (N=62)	1.71	8.28	1.33		0.04	709	57		43	108	17	934	62	277	857
Moderate (N=35	0.71	7.29	0.35		0.06	160	30		35	178	21	1266	35	69	474
Low (N=71)	1.04	6.47	0.93		0.03	173	26		29	108	31	1246	51	102	570
Stream Sediments, Flats (N=307)															
High (N=94)	2.04	9.42	0.93	3.0	0.04	320	39	115	40	121	30	1016	82	161	
Moderate (N=73)	1.61	6.96	1.18	6.0	0.06	228	24	91	20	163	36	2145	52	207	
Low (N=140)	1.66	5.94	2.29	1.94	0.03	129	22	147	26	75	32	883	54	337	

Table 4. Classification of stream sediment samples

	Total	Misclassified	Recognition rate (%)
Slope Samples			
High Potential	62	5	92
Moderate Potential	35	1	97
Low Potential	71	1	98
Flat Samples			
High Potential	94	21	78
Moderate Potential	73	8	89
Low Potential	140	3	98

categorized a priori as low potential, viz. Nilambe, Ridigama and Wariyapola. It is particularly noteworthy that samples from all 3 areas plot within the same cluster on Fig. 2.

The low potential flat samples fall in the lower quadrants of the discriminant diagrams. Similarly, the high potential and moderate potential samples fall mainly on the upper quadrants. However, a comparison of Figures 3 and 4 (because of crowding of symbols the results for flat samples are presented on two diagrams Figures 3 und 4), Figure 2 reveals that the high potential flat samples (Figs. 3 and 4) plot in the northeast quadrant, whereas the high potential slope samples (Fig. 2) plot in the northwest quadrant; the moderate potential flat and slope samples are similarly transposed. This results from the fact that some of the elements used in the function for flat samples differ from those in the function for slope samples (see Tables 2 and 3). Consequently, linear functions for flat samples define lines with different orientations from those separating slope samples.

On Figures 3 and 4, the low potential samples display little or no overlap with high and moderate potential samples. There is or no overlap with high and moderate potential samples. There is minor overlap between the high and moderate potential clusters, suggesting misclassification of some samples. This is not unexpected since

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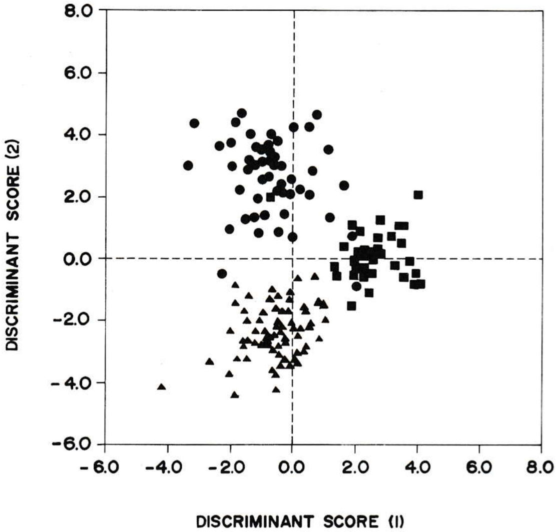


Fig. 2. Discriminant diagram of "SLOPE" stream sediment samples, area of high, moderate and low gem potential.
● High potential area (Opanayake)
■ Moderate potential area (Bogawantalawa)
▲ Low/no potential areas (Nilambe, Wariyapola)

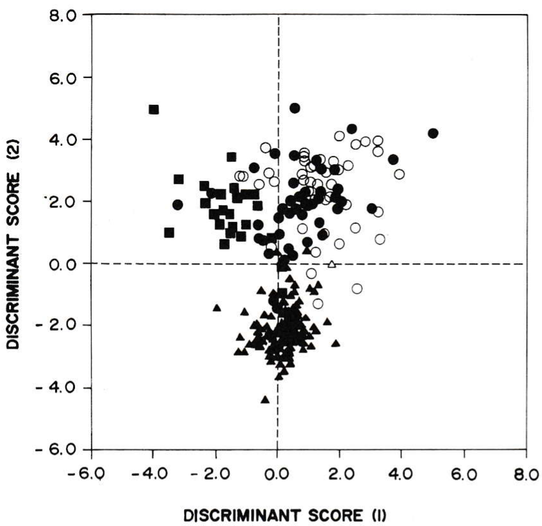


Fig. 3. Discriminant diagram of "FLAT" stream sediment samples, area of high, moderate and low gem potential.
● High potential area (Opanayake)
○ High potential area (Hattota Amuna)
■ Moderate potential area (Bogawantalawa)
▲ Low/no potential areas (Ridigama, Kurunegala Wariyapola)

stream sediment samples from an area of high potential, for example, will have a wide range in chemical composition and as a consequence are likely to overlap with those from moderate potential areas which also have a wide range in composition.

More important is the fact that the flat samples from the two high potential areas (Opanayake and Hattota Amuna) plot in the same clusters (Fig. 3) as do the flat samples from the two moderate potential area (Bogawantalawa and Pubbiliya Fig. 4). The fact that results for both slope and flat sediments from two high potential, two

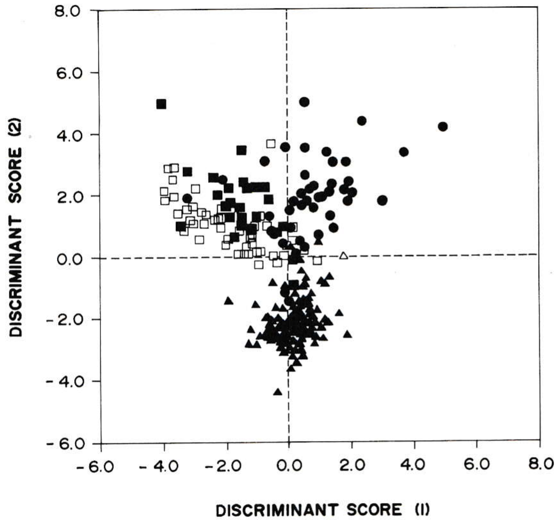


Fig. 4. Discriminant diagram of "FLAT" stream sediment samples, area of high, moderate and low gem potential.
● High potential area (Opanayake)
■ Moderate potential area (Bogawantalawa)
□ Moderate potential area (Pubbiliya)
▲ Low/no gem potential areas (Ridigama, Kurunegala Wariyapola)

moderate potential and three low potential areas are consistent strongly suggest that the a priori classification of the 7 areas as high, moderate and low potential was valid and that fundamental geochemical differences exist between gem-bearing and non gem-bearing sediments of Sri Lanka.

Rock Discriminant Diagram

The discriminant diagram for rock samples (Fig. 5) displays the same degree of separation between high, moderate and low potential areas as the diagrams for stream sediments. As in the case of stream sediments, rocks from the low potential areas cluster in the lower quadrants and those from the high and moderate potential areas cluster in the upper quadrants. It is also apparent that samples from the two high potential areas occupy the same cluster; samples from two moderate potential areas also cluster together. This clearly indicates fundamental geochemical differences in bedrock from areas of high, moderate and low potential.

The high F ratios for Ba, P and Zr for rocks (Table 2) and differences in the means for these elements in areas of high, moderate and low potential (Table 3) suggests Ba feldspar, apatite and zircon as sources of these discriminatory elements. It is notes that all these elements are highest in rocks from areas of moderate potential.

The high F ratios for Ca and the high average content of Ca in rocks from areas of high potential suggest the presence of marbles or skarns in those areas, a suggestion in accord with field observations. The correlation of Ba, P and Zr with a particular rock type is less certain.

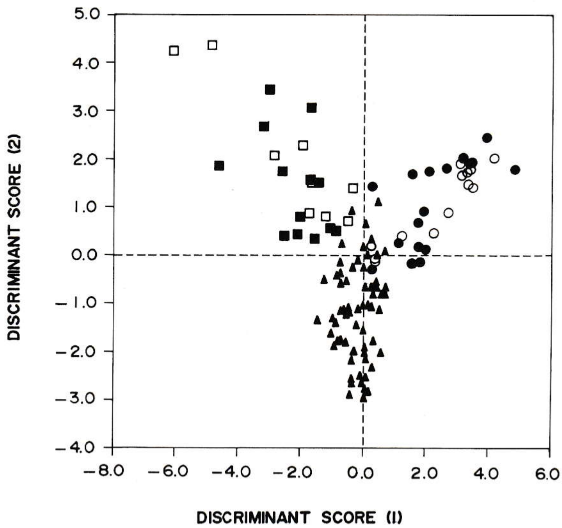


Fig. 5. Discriminant diagram of "ROCK" samples, area of high, moderate and low gem potential.
● High potential area (Opanayake)
○ High potential area (Hattota Amuna)
■ Moderate potential area (Bogawantalawa)
□ Moderate potential area (Pubbiliya)
▲ Low/no potential areas (Nilambe, Ridigama, Wariyapola)

Stream Sediment Gem Potential Maps

The classified slope samples, along with similarly classified flat samples could be presented as gem potential maps (eg: Fig. 6) showing individual stream sediment samples as high, moderate or low potential.

Due to crowding of samples and sample numbers the location of gem pits are not shown in Fig. 6. In the Opanayake area one of the sites of gem mining is at the location of samples 110–116, 125–129 and 131–132, west of Opanayake (Fig. 6). This site marks the location where the steeper south-flowing hillside stream, laden with high potential sediment, enters the broad, flat valley where it changes to a slower eastward-flowing stream.

The gem potential map will also illustrate the presence of low and moderate potential samples in areas of generally high potential and, conversely, the presence of a few high potential samples in areas of moderate and low potential.

However, one or two isolated high potential sites in an area of generally low potential should be viewed with caution as even they may be misclassified and do not necessarily indicate a high probability of the presence of gems. It is also possible that these observations contain anomalous concentrations of element (in a background area) as a result of inhomogeneity of the sampled material, rather than poor performance of the discriminant functions. A number of closely spaced high potential samples in an area of generally low potential may offer greater promise, bearing in mind that this is an exercise in probability.

Rock gem potential map

Figure 7 illustrates the rock gem potential map for Opanayake prepared by the use of the discriminant function generated after screening out the samples that had been misclassified by the initial trial analysis. The samples that were removed were not

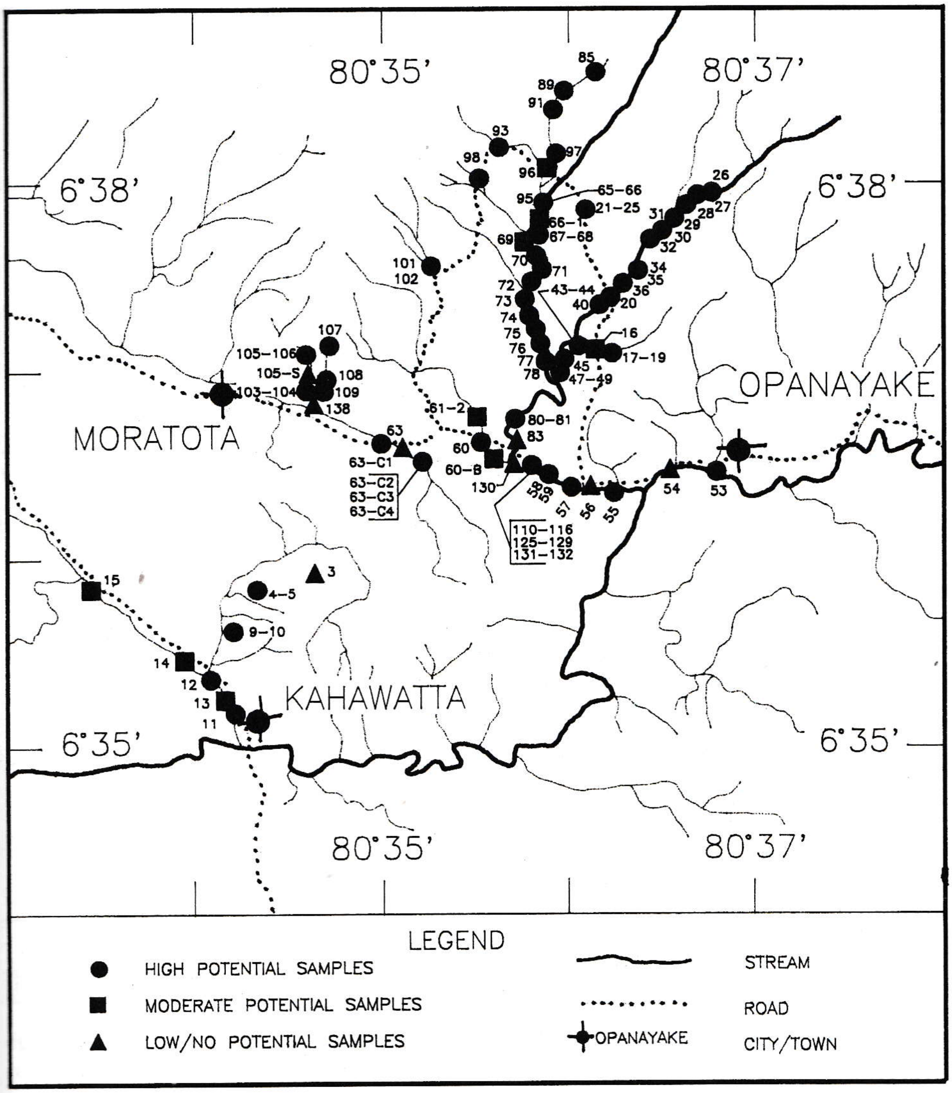


Fig. 6. Stream sediment gem potential map around Opanayake.

classified by the second analyses and are shown as unclassified on the gem potential map. The separation of unclassified samples from those with a high probability of belonging to the class to which they were assigned permit ready identification of those specific rock types most likely to bedrock sources for gems.

In the Opanayake area (Fig. 7), the highest potential bedrock sources are marbles and skarns (51, 58) pegmatite (52, 94), garnetiferous and graphitic gneisses (2, 104, 105, 718, 723, 726) some of which were almost certainly derived from carbonate-bearing sediments, and charnockitic gneisses (RUPASINGHE and DISSANAYAKE, 1985).

In the Hattota Amuna area, the favourable rock types include marbles, skarns and

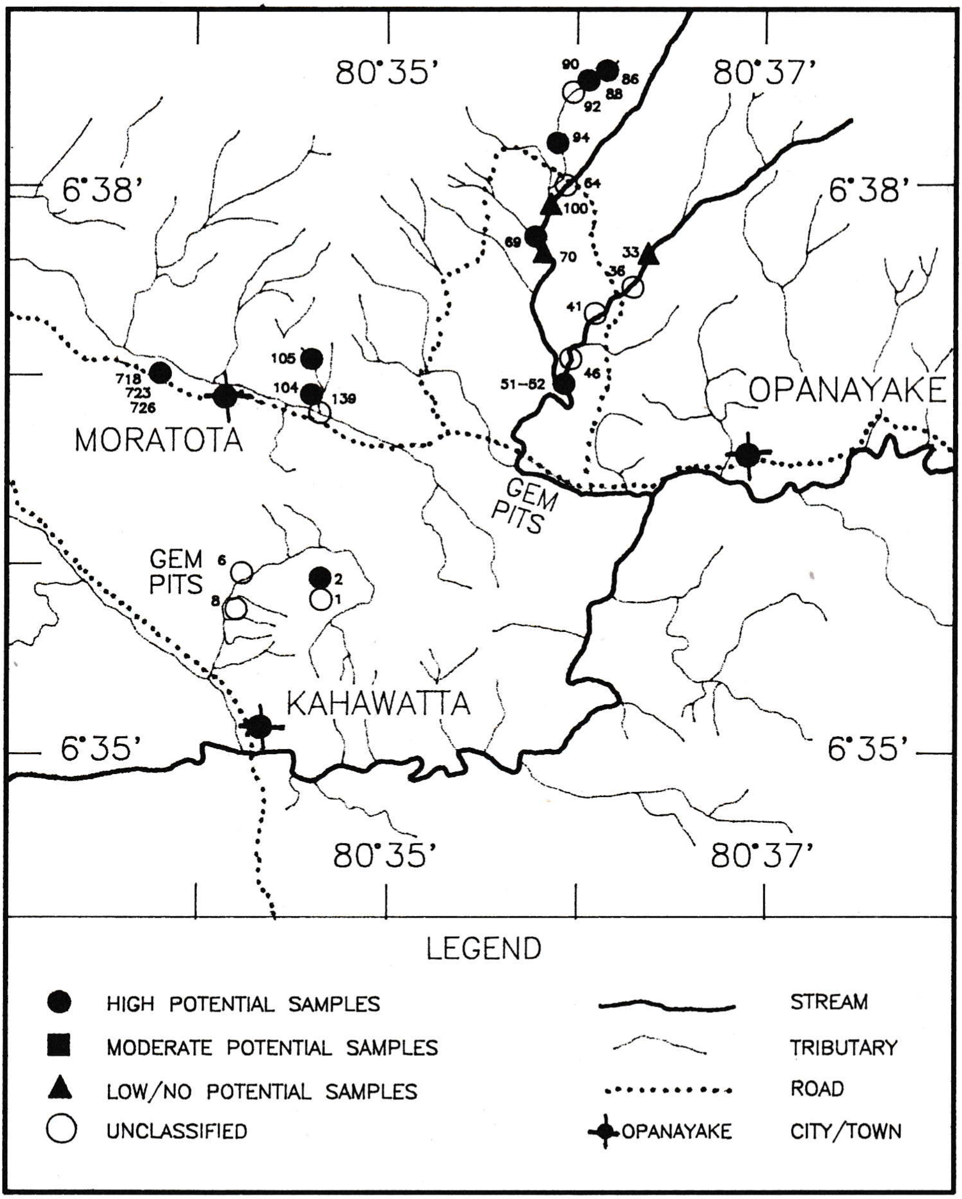
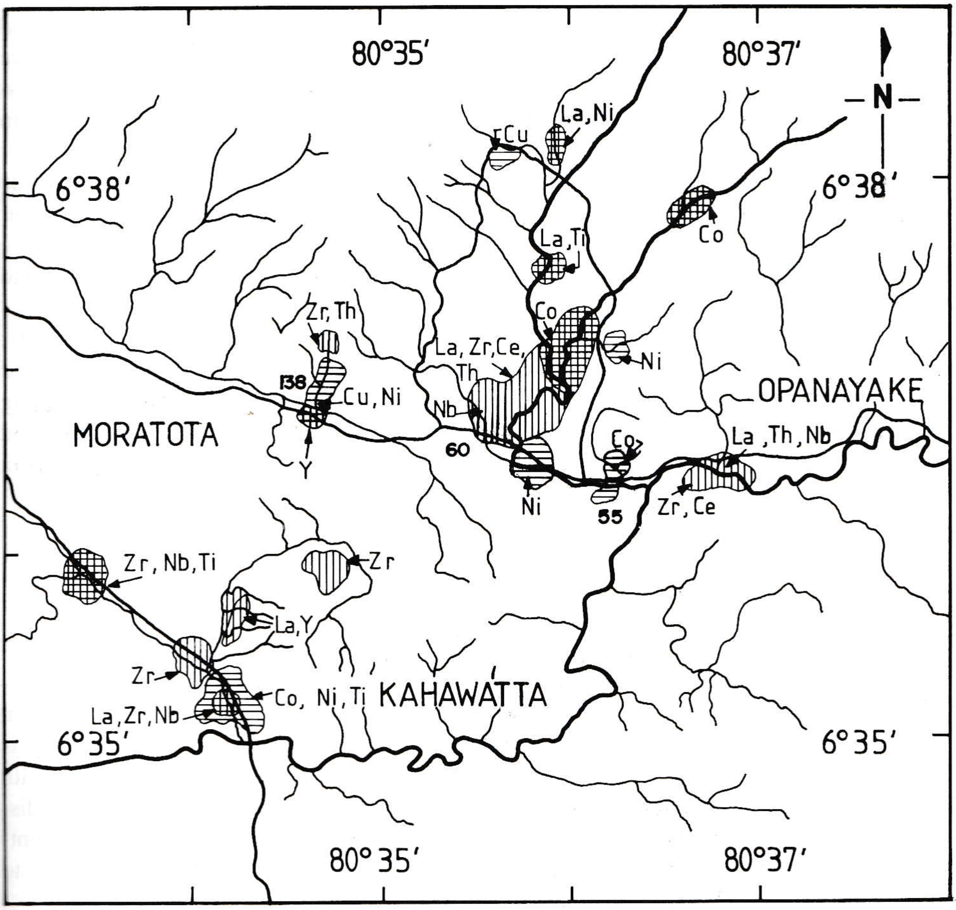


Fig. 7. Rock gem potential map around Opanayake.

garnetiferous or charnockitic gneisses. Although no pegmatites from Hattota Amuna were analyzed, that rock type and graphitic gneisses are also known sources of corundum in the area.

One samples (953) was classified as high potential in the Kurunegala-Ridigama area, an area considered to be of low potential. A single high potential sample will not



Elements concentrated areas

Fig. 8. Distribution of the occurrence of the high concentrations of elements in stream sediments around Opanayake.

warrant change of the designation, low potential for the area in general. However, it is interesting to note that sample 953 is a scapolite-bearing calc-silicate apparently derived from a carbonate rock. In this respect it is similar to the marbles, skarns and graphitic gneisses, all of which are high potential rocks in the Opanayake and Hattota Amuna districts.

Uses of element distribution maps

The trace element data for all areas were contoured. Figure 8 illustrates the occurrence of the highest concentration of elements in stream sediments at Opanayake. The element distribution maps (all of them not presented here) were obtained by projecting the highest element values in each contour into a single map for each area.

As shown in Fig. 8, there are anomalously high values of Zr, La and Ce around locality 60. Close to locality 55, anomalously high values of the same elements were again observed. Mining for gems around these localities is being carried out successfully. Further, the highest values of K, Ba, Al and Mg were found together close to locality 138.

La, Ce, Nb, Y and Zr contents in sediments of the southwardflowing hillside streams increase downstream towards the main valley in which the gem pits occur near Opanayake in the Ratnapura District. The trends in La, Ce, Nb, Y and Zr are probably related to the concentrations of minerals such as monazite, rutile, zircon and other heavy minerals which may be diagnostic of gemming areas.

It should be stated that the high concentrations of REE and other elements (Th, U, Ce, La, Nb, Zr) are found even in areas where no gems are found. It is therefore of extreme importance that this criterion should not be used by itself when delineating gem-bearing areas from non gem-bearing areas. Other factors such as lithology, and geology and whether the terrain concerned is in the Highland Complex or Vijayan Complex should also be considered.

Conclusions

Using the statistical package SYSTAT, discriminant analysis was applied to stream sediment and rock geochemical data in order to determine whether significant differences existed between areas of high gem potential, areas of assumed moderate gem potential and ares of low or no gem potential. The application of discriminant analysis to areas representing the three levels of gem potential showed good results. With additional information obtained by the study of bedrock structures, quantitative distribution of trace elements, correlation of known gem-bearing sites with local concentrations of trace elements, Rb/Sr ratios, and heavy mineral data, it is possible to delineate areas of high gem potential from others.

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Refereces

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Announcement

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Workshop: Scanning Probe Microscopy of Clays, organized by Kathryn Nagy and Alex Blum.
Field trip: Potash mine shaft and Tertiary and Cretaceous clays of the Western Interior Basin in southern Saskatchewan, led by Dr. B. Shreiner.
Contact: Dr. Ahmet R. Mermut, Dept. of Soil Science, Saskatchewan Institute of Pedology, University of Saskatchewan, Saskatoon S7N 0W0, Canada. Telephone: 306-966-6839; fax: 306-966-6881; E-mail: MERMUT@SASK.USASK.CA.

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