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Use of indicator minerals in gem exploration: study of a granulitic terrain in Sri Lanka

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Abstract—Electron microprobe analysis of 201 rock samples yielding 435 determinations from the gem-bearing granulite terrain of Sri Lanka shows the potential use of indicator minerals in gem exploration. In view of the indication that Ca-rich rocks could also be probable source rocks of the gem minerals of Sri Lanka, special attention was paid to the Ca- and Mg-rich minerals of the rocks studied. Among the other probable sources are pegmatites and Al-rich high-grade metamorphic rocks. Mg-rich ilmenite, geikielite, Mg-rich spinel, Ca-rich scapolite, Ca–Mg pyroxene (salite), Ca-rich garnet (grossularite) and minerals containing REEs such as sphene, davidite and monazite show promise as good indicator minerals of gems. It is worthy of note that even low-quality corundum and spinels could be considered as indicator minerals.

INTRODUCTION

GEMS such as sapphire, ruby, spinel, garnets and other valuable minerals have been recovered from stream valley sediments in Sri Lanka for centuries. However, the discovery of gem deposits in Sri Lanka is still based on 'hearsay' methods of gem miners. The application of scientific techniques in gem exploration in Sri Lanka needs further development.

Dissanayake *et al.* (1992) applied geochemical methods to gem exploration with emphasis on the use of fluoride geochemistry in locating fluoride-bearing gem minerals. The geochemical mobility of fluorine leaves a geochemical signature that could be effectively used in the exploration for F-rich gem minerals such as topaz, tourmaline and fluorite. Gamage *et al.* (1992) applied the use of Rb/Sr ratios in stream sediments to delineate gem-bearing from non-gem-bearing terrains. It was observed that higher Rb–Sr ratios correspond to high gem potential and even within areas of good potential, barren areas could be delineated using these ratios. Dissanayake and Rupasinghe (1993) compiled a *Gem Prospectors' Guide Map for Sri Lanka*, based on the heavy mineral analyses of sediments of streams draining the Highland Complex, the main gem-bearing formation of Sri Lanka. The gem minerals of Sri Lanka are derived from several sources, e.g. skarns, pegmatites, Al-rich sediments and carbonate rocks (Munasinghe and Dissanayake 1981, Silva and Siriwardena 1988). Among the indicator minerals for gems found in the above-mentioned sources are monazite, davidite, sphene, scapolite, low quality corundum, spinel and zircons. Indicator minerals that are associated with the gem minerals in the alluvial formations very often serve as useful guides in locating gem deposits and this paper discusses the potential use of such minerals. The application of modern scientific techniques to gem exploration in Sri Lanka is now an urgent need and this study forms a part of a larger investigation aimed at developing such methodology.

THE GEM-BEARING TERRAINS OF SRI LANKA

The major gemming areas of Sri Lanka are for the most part underlain by Precambrian metamorphic rocks of the Highland Complex occupying the central part of the island (Fig. 1). The Complex consists of various quartzo-feldspathic gneisses, garnet–sillimanite gneises, basic pyroxene and granulites, marbles and skarns, charnockitic gneisses, cordierite bearing gneisses, quartzites and pegmatites (Cooray 1984, Milisenda *et al.* 1988, Burton and O'Nions 1990, Kroner *et al.* 1991). The main gemming regions are shown in Fig. 1 and Fig. 2 illustrates the metamorphic grades. It can be observed that all of Sri Lanka's gem deposits are located in the central Highland Complex. Those that appear to be found in the Vijayan complex have been transported from the Highland Complex.

The gems occur mainly in alluvial gravels occupying the wide strike valleys into which tributary hillside streams flow, apparently carrying gemstones released from the hilltop or hillside bedrock sources during weathering. The gem-bearing gravel (illam) commonly lies at the base of the alluvium at or near the bedrock surfaces generally 1–10, 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 patches. Hence the location of gem deposits has, up to now, been a matter of chance. The pay gravel apparently occupies palaeochannels in the alluvium. Some gems are recovered directly from present-day stream beds. In other cases, gems are recovered from hillside gravels or old stream terraces into which shallow open pits have been sunk. The gem minerals and the associated heavy minerals are washed and sorted out at a nearby water hole or river. The non-economic gravel is discarded and these contain some of the indicator minerals discussed in this study.

MATERIALS AND METHODS

A total of 201 rock samples from seven different areas was collected and thin sections made. The seven areas, shown in Fig. 1, represent different levels of known (or assumed) gem potential.

1. Areas of known high potential, Opanayake and Hattota Amuna, both of which are underlain by 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. Both areas are also underlain by rocks of the Highland Complex.
3. Areas of low, very low or no potential; Nilambe and Ridigama both underlain by rocks of the Highland Complex. This category also includes an area underlain by the Wanni Complex, assumed to lack potential for gems, e.g. Wariyapola.

Thin sections of some of the rock samples were examined and analyzed with the electron microprobe in order to determine the compositions of specific accessory minerals which might be associated with gem minerals. A total of 435 microprobe determinations was performed, mainly on pyroxenes, garnets, spinel, amphibole, scapolite, titanite and corundum. Some of the noteworthy features in the mineral chemistry are discussed in the following section.

Heavy mineral separations of the medium-grained portion of some stream sediment samples from Opanayake were made. About 15 heavy mineral fractions were further separated with the Franz isodynamic separator. Grain mounts were examined microscopically and material selected for microprobe analysis. All analyses were carried out at Laurentian University, Canada.

RESULTS AND DISCUSSION

Even though a wide variety of relatively unusual minerals have been reported from the stream sediments, gem pits and bedrocks of Sri Lanka (Fernando 1948) only those for which adequate scientific data are avail-

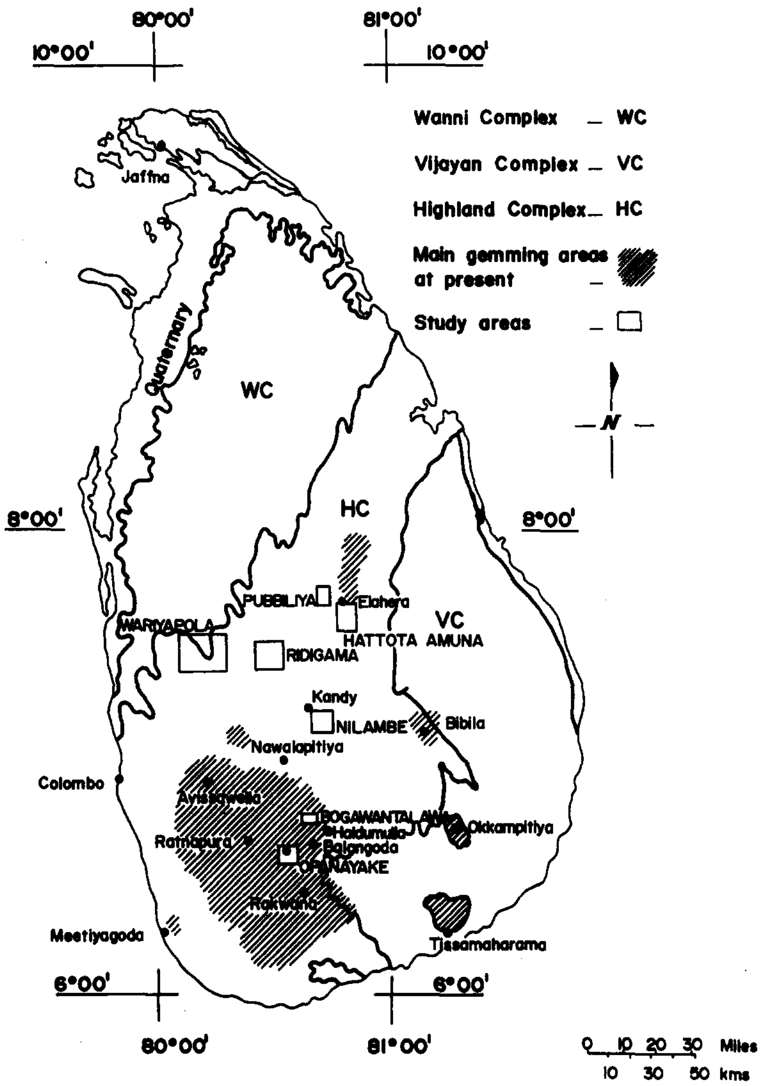

Fig. 1. The main geological groups, sampled areas and the main gem-bearing areas of Sri Lanka.

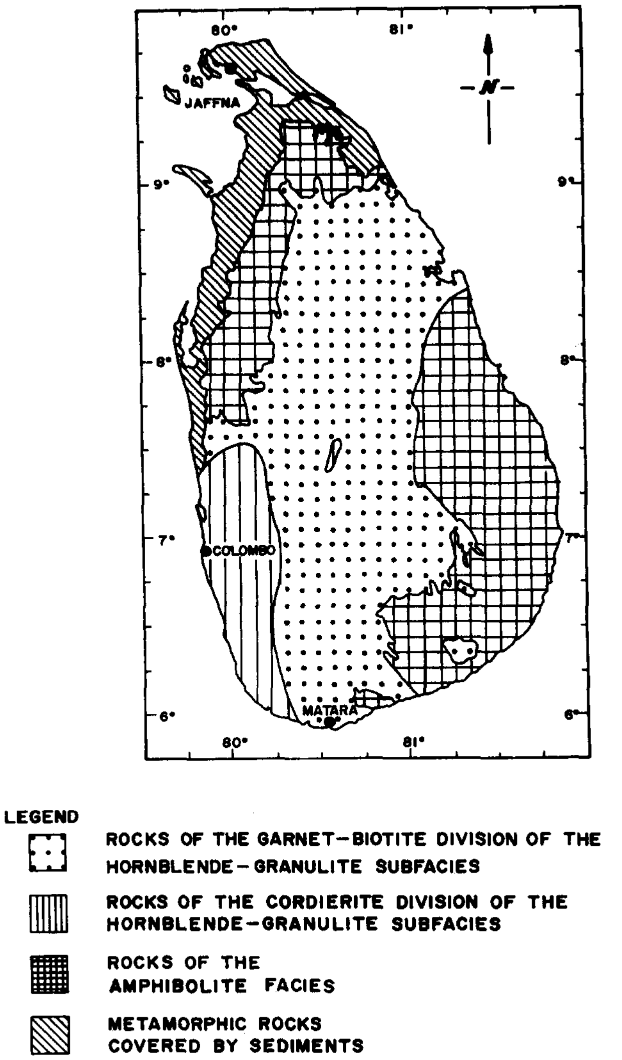

Fig. 2. The metamorphic map of Sri Lanka. (Source: Geological Survey Department of Sri Lanka.)

able will be discussed here. Many of these minerals discussed here are of fairly common occurrence but a few have unusual chemical compositions. As index minerals these are probably superior to rare mineralogical curiosities which, precisely because they are rare, would hardly serve as useful index minerals.

Ilmenite–geikielite

Geikielite ($MgTiO_3$) is probably the Mg-end member of a continuous series with ilmenite, $FeTiO_3$, but is of much less common occurrence than ilmenite. It has been known to occur at Rakwana and Balangoda (Palache *et al.* 1944). Mg-rich ilmenites and geikielites have been identified from the gem gravels at Hattota Amuna. These have Mg^{2+}/Fe^{2+} ratios between 1.1 and 1.8. In the two areas of moderate potential, on the other hand, the ilmenites have Mg^{2+}/Fe^{2+} ratios of 0.2 (Bogawantalawa) and between 0.05 and 0.1 (Pubbiliya). The Mg-rich ilmenite and geikielite may, therefore be indicative of gem-bearing gravels.

Sphene (titanite) and davidite

The only sphene analyzed was from Ridigama, an area designated as low potential. The location in question is underlain by calc gneiss enclosing bands of vein quartz, pegmatitic material and granitic segregations. The calc gneiss also contains dark bands, a few centimeters wide, in which concentrations of dark minerals, including sphene, are found. The sphene contains between 0 and 0.3 wt% La and 0.82 to 1.36% Ce and have La/Ce ratios between 0 and 0.3, well below the crustal average of 0.5 (Taylor 1964).

The sphene crystals contain minute inclusions of Ti and rare-earth element oxide davidite in which La/Ce ratios vary from 0.18 to 0.40, again below the crustal average (Fig. 3). These low ratios are very unusual since davidite generally contains La in excess of Ce (Fleischer 1965). The davidite contains about 11 wt% rare earth elements.

Monazite

Only semi-quantitative data were obtained for monazite, all samples of which were from the gem-bearing Opanayake area. They display rather large variations in rare-earth element and Th contents. One grain displayed distinct zoning with the rim containing ThO_2 30.91%, La_2O_3 11.93% and Ce_2O_3 23.27% compared to the core with ThO_2 18.60%, La_2O_3 16.31% and Ce_2O_3 28.25%.

The La/Ce ratios are rim, 0.51 and core, 0.58 both close to the actual average. A monazite grain in a sample from a gem pit at Opanayake had a very unusual composition. ThO_2 4.44%, La_2O_3 25.25%, Ce_2O_3 31.65%, high in total rare-earth elements and low in Th with a La/Ce ratio of 0.8 and well above the crustal average (Fig. 3). A stream sediment sample, also from a gem pit at Opanayake, contains monazite grains with remarkably different compositions (Table 1). Notable here is the very low Th content and the absence of La

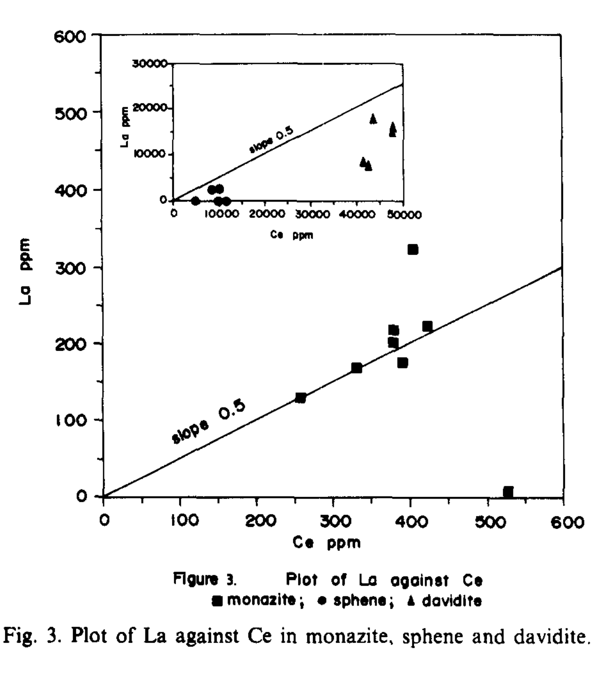

Fig. 3. Plot of La against Ce in monazite, sphene and davidite.

Table 1. Variation in the chemical composition of two monazite grains from a stream sediment sample from a gem pit in Opanayake

	GRAIN 1	GRAIN 2
P_2O_5	46.25	36.49
ThO_2	1.85	12.59
CaO	5.31	1.91
La_2O_3	0	15.46
Ce_2O_3	46.73	28.76
U_2O_3	0	4.92

in grain 1 whereas grain 2 is more or less "average" monazite with La/Ce = 0.54. These differences suggest different bedrock sources.

When differences in rare-element contents of monazites were first noted, this mineral appeared to hold promise as a diagnostic mineral indicating the possible presence of gems. However, the analysis of rare-earth elements in sphene (and davidite) from samples from the low-potential Ridigama area also had anomalously low La/Ce ratios.

Scapolite

Scapolite in rock samples from Opanayake and Ridigama occur in Ca-rich rocks and calc silicates, and have Ca^{2+}/Na^{+} ratios greater than 1.8. Ca^{2+}/Na^{+} ratios in scapolite from Opanayake range from 4.1 to 8.2 whereas at Ridigama it ranged from 1.8 to 3.1.

It is not known if the higher Ca^{2+}/Na^{+} ratios in the gem-bearing Opanayake area are significant other than indicating a very Ca-rich source, probably marbles and skarns.

The CaO content in scapolite varies from 14 to 20% and a good correlation between Ca and Na can be identified. It is to be accepted that the scapolite mineral lies between meionite and marialite and most of the scapolite which were found are toward meionite. This could be observed very well in Opanayake area. Unusual high concentrations of SrO_2, 0.11%, in scapolite was reported in Ridigama.

In the Opanayake area, the most potential bedrock sources are marbles and skarns, pegmatites, garnetiferous and graphitic gneisses, some of which, notably marbles and garnet–graphite associations were almost certainly derived from carbonate-bearing sediments and charnockitic gneisses.

Cooray (1961) observed scapolite of approximate composition Ma_{37} Me_{63} from the Rangala area identical with scapolite from inclusions within a syenite at its junction with limestone from the Haldumulla area.

In the Hattota Amuna area, the favourable rocks include marbles and skarns and garnetiferous or charnockitic gneisses. The presence of Ca-rich rocks in association with rocks such as charnockites or granites could indicate the presence of gems. The contact metamorphic effects of these rock types often result in the formation of corundum (Silva and Siriwardena 1988).

Spinel group

Spinels from the gem gravels at Hattota Amuna that were analyzed were mainly spinel *sensu stricto* with Mg^{2+}/Fe^{2+} ranging from 7.8 to 25. One grain of pleonaste (ceylonite) with Mg^{2+}/Fe^{2+} near 1 was found in the same stream sediment sample that contained spinel. Both pleonaste and hercynite, the Fe- spinel, were found in stream sediments from Opanayake. Spinels are good indicators of gem sources and indeed most varieties of spinels are classified as gems.

Garnets

Most of the garnets that were analyzed by microprobe were pyrope-almandine (Mg-Fe) with less than 10 mole % CaO. In the sediments from Hattota Amuna, the molar proportions are generally pyrope 60 to 30, almandine 32 to 60 and grossularite 8 to 10. Other sedimentary garnets from Hattota Amuna are slightly more calcic with pyrope 40, almandine 40 and grossularite 20.

These garnets differ somewhat from those in a mafic gneiss at Hattota Amuna which are Fe-rich and Mg-deficient (pyrope 15, almandine 65, grossularite 20).

Garnets in a hornblende–biotite gneiss from Opanayake are similar to those in the mafic gneiss at Hattota Amuna in having pyrope 27, almandine 57 and grossularite 16. At Bogawantalawa, garnets from charnockitic gneiss and acid charnockite had proportions of pyrope 9, almandine 70, and grossularite 21, again similar to those in the mafic gneiss at Hattota Amuna. Two types of garnets were found in rocks from Nilambe. Those in a hornblende–pyroxene granulite had pyrope 39, almandine 43, grossularite 18 and are similar to the more calcic garnet in sediment at Hattota Amuna. Other garnets from a garnet–biotite gneiss at Nilambe have pyrope 34, almandine 62 and grossulrite 5 and are similar to some low-Ca, high-Fe, moderate-Mg garnets in the Hattota Amuna sediments. A garnet–cordierite gneiss from Ridigama contains a low-Ca garnet with pyrope 54, almandine 41, grossularite 5, similar to some of the low-Ca garnets in sediments at Hattota Amuna.

Most of the garnets in Sri Lanka have relatively high concentrations of TiO_2 and varies from 0.05% to 0.08%. Chromium cannot be found in most of the garnets. An unusual concentration of Cr_2O_3, 0.07% was, however, found in garnets from Nilambe.

The wide variations in garnet compositions and the fact that garnets of similar composition occur in areas of high, moderate and low-potential casts doubt on their usefulness and precise indicator minerals.

However, since skarns are known to be possible source rocks for gem minerals, garnet from skarns which may be more calcic than those investigated to date: e.g. grossularite; may serve as an indicator for skarns.

Pyroxenes

Many of the bedrock samples are characterized by both the Mg–Fe orthopyroxene, hypersthene, and the Ca–Mg clinopyroxene, salite (in some cases grading to diopside): both of these pyroxenes are found in skarns and other metamorphosed carbonate rocks. The variously named gneisses and granulites from Nilambe, Ridigama, Hattota Amuna and Opanayake, containing both hypersthene and salite could have been derived from limy sediments. The carbonate-bearing rocks with very high Ca–Mg content and still containing residual carbonate are readily identifiable as skarns or marbles. Such rocks commonly also contain anorthite and/or scapolite and, as already noted, are common in the Opanayake and Hattota Amuna areas.

The only analyzed pyroxene from charnockitic gneiss were samples from Bogawantalawa. These were ferro-augites and ferro-hypersthenes in contrast to the Ca–Mg rich, Fe-deficient salite and the "average" Mg–Fe hypersthene.

Apart from their possible use in distinguishing igneous charnockites from metamorphic sediment-derived granulites and other calcic silicate rocks, pyroxene compositions do not appear to be of any direct use as indicator minerals. Salite, however, is a reflection of an original lime-rich environment which after extensive granulite facies metamorphism appears to constitute a potential bedrock source for gems such as sapphire, ruby and spinel. The value of salite as an indicator mineral lies in the fact that it could indicate locations where there had been contact metamorphism involving lime-rich rocks and which yield gem minerals.

Observations on heavy minerals in stream sediments

The gem-bearing sediments, locally termed 'illama', are composed of heavy and light minerals including gemstones. Some samples were taken from the gem pit and washed until the clay was removed. The remaining portion, termed 'nambuwa' in Sinhala, was investigated for mineral distribution. However, during the process of washing, light gem minerals such as amethyst and beryl are often washed away with other light minerals, namely calcite, fluorite and feldspar.

It was observed that the area around Hattota Amuna and Pubbiliya has a lower concentration of heavy minerals than in the area around Ratnapura. The greater abundance of heavy mineral-bearing pegmatites in the southern part of the island could be one reason for the presence of high amounts of heavy minerals in the Opanayake area. The high rate of erosion and the long distance of transportation also resulted in the high concentrations of heavy minerals in the sediments. Strong erosion of source rocks cause more minerals to be washed down and longer transportation helps in better sorting out of the heavy minerals, depending on their density.

In the Hattota Amuna and Pubbiliya areas, pegmatites are more felsic and the accumulation of heavy minerals therefore is comparatively less. Careful mineral analyses provide the necessary information on the mineralogy of the gem field, particularly in cases where there is a good correlation between the stream sediment mineralogy and that in the gem deposit. The presence of La, Th and Ce-bearing minerals such as monazite, for example, provides further evidence on the possible origin and genetic relationships with other minerals. Other rare minerals such as fergusonite, gadolinite, samarskite and niobian rutile could sometimes be used as indicators of minerals of gem deposits. They originate mostly from pegmatites. Many of these minerals which escape detection in the field can be subjected to detailed investigations in the laboratory.

Non-gem quality spinels, corundum and zircon even though they may be of low concentration, are also of importance as indicator minerals.

CONCLUSIONS

Of the minerals considered above, Mg-rich ilmenite, geikielite, Mg-rich spinel, Ca-rich scapolite, the Ca-Mg pyroxene, (salite), possible Ca-rich garnet (grossularite) and minerals containing REEs such as sphene, davidite and monazite should be considered as good candidates for indicator minerals. From among these the Ca- and Mg-rich minerals, in particular, reflect a favorable original carbonate environment now metamorphosed to the granulite facies. The potential roles of sphene, davidite and monazite, however, are, as yet, unclear. This information suggests that this is a method worth pursuing in an attempt to identify useful index (pathfinder) minerals suggesting the presence of gems.

In connection with the probable high-potential of limy source rocks referred to above, de Maesschalck and Oen (1989) report pure CO_2 fluid inclusions in corundum from four localities in Sri Lanka, including Ratnapura district. They conclude that the high density of the primary inclusions, 1.05 g/cm^3, is compatible with formation of corundum under granulite facies metamorphism at $>630°C$ and 5.5 kbar pressure (Munasinghe and Dissanayake 1981; Rupasinghe and Dissanayake 1985).

The CO_2 inclusions, being primary and formed during granulite facies metamorphism, may reflect the limestone-rich environment postulated as favorable for the occurrence of sapphire, ruby and spinel. However, the origin of this CO_2 is still not well understood.

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