

PRELIMINARY DATA ON PLATINUM GROUP ELEMENT AND GOLD IN THE HIGHLAND COMPLEX, SRI LANKA: A SEARCH FOR HIDDEN SULPHIDE SATURATION

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ABSTRACT

Sulphide saturation in mafic-calcic magmatic melts has important implications on chalcophile element mineralization. Therefore, this study was undertaken as a preliminary investigation of the geochemistry of platinum group elements (PGE) and Au of MgO- and CaO-rich gneisses from the Highland Complex (HC), Sri Lanka in order to constrain magmatic processes related to sulphide saturation. Here we report data of PGE (Re, Pd, Pt, Rh, Ru, Ir) and Au together with major and rare earth elements (REE) in magnesio-calcic granulites collected over a wide spatial distribution, along a NE-SW transect of the central HC. The studied samples belong geochemically, to two groups: (a) low magnesio-calcic (LMC) with low MgO (<13 wt %) and CaO (<12 wt %) and (b) high magnesio-calcic (HMC) with high MgO (>13 wt %) and CaO (>12 wt %). The HMC granulites have low overall REE abundances compared to the LMC granulites. The concentration of PGE and Au show a systematic positive correlation with increasing MgO contents. Between the HMC and LMC samples there is a clear distinction of Pt/Pd vs. MgO, in which the HMC group shows a negative correlation while the LMC samples display a positive correlation. The variation of the Pt/Pd shown by the HMC samples indicates that the ratio of Pt/Pd gradually increases with decreasing MgO content. Similar behavior can be observed in the Au vs. MgO plot for the LMC group. Further, in the Pd vs. MgO plot the HMC samples show a robust positive correlation with MgO content. These geochemical trends indicate that the PGE of the HMC samples are mainly controlled by a progressive segregation of an immiscible sulfide melt cluing a potential chalcophile mineralization. There is no evidence for sulphide saturation in the LMC group.

Keywords: Sri Lanka, Granulites, Platinum group elements, Gold

INTRODUCTION

Many of the world's chalcophile element deposits are genetically linked to sulphide saturated magmas. Especially, some MgO- and CaO-rich (magnesio-calcic) rock suites have been indicators of chalcophile mineralizations (Setiabudi et al., 2007). Therefore, geochemistry of rocks associated with sulfide melts has very important applications in the exploration of chalcophile elements bearing mineral deposits (e.g. Campbell and Barnes, 1984). If reducing conditions prevailed in and around a magma conduit or chamber, the magma can become sulfide saturated and an immiscible sulfide

liquid is usually generated. In such environments, strongly chalcophile elements such as platinum group elements (PGE), Au, Cu etc. will be rapidly stripped-off from the magma and preferentially partitioned into the immiscible sulphide melt formed. Therefore, by analyzing the PGE and Au abundances and ratios in rocks, the onset of sulfide saturation in the parent magma of a given rock suite can be identified. This has important implications on the geochemistry of an evolving petrological system.

Compared to other chalcophile elements, the PGE (Re, Pd, Pt, Rh, Ru, Ir), Au and Cu have

much higher partition coefficients in sulfide-bearing geochemical systems (Francis, 1990; Peach et al., 1994; Bezmen et al., 1994; Crocket et al., 1997; Fonseca et al., 2009) and therefore are more sensitive indicators of sulfide saturation. Hence, studying chalcophile element geochemistry in specific rock units indicates whether a PGE, Au and Cu enriched sulfide saturated melt may have escaped from the rock in the past, and has crystallized in a hidden mineralized zone associated with the rock unit.

Sri Lanka being a part of the Gondwana Supercontinent, unexplored mineralized belts could exist within the basement rocks, as is the case in other Gondwana fragments like Australia, Mozambique, Brazil, etc. (e.g. Dissanayake and Chandrajith, 1999). Therefore, geochemical investigation of PGE, Au and Cu in the Highland Complex rocks may provide new insights of possible hidden mineralized zones within the Sri Lankan basement.

In the present study, we analyzed several magnesio-calcic granulites from the Highland Complex of Sri Lanka, for their whole rock major, rare earth, PGE and Au geochemistry in search of hidden chalcophile mineral deposits.

OUTLINE GEOLOGY OF THE HIGHLAND COMPLEX

The Sri Lankan Precambrian basement has been subdivided into four major terrains (Cooray, 1994): the Wannu Complex (WC) to the West together with the Kadugannawa Complex (KC), the Highland Complex (HC) in the center, and the Vijayan Complex (VC) to the East (Figure 1). The WC, KC and VC domains are considered as Grenville-aged terranes of arc-related settings at the outer margin of the Rodinia supercontinent (Kehelpannala, 2003, 2004; Kröner et al., 2003; Willbold et al., 2004; Kröner et al., 2013). The WC is considered to represent a higher crustal level than that of the HC although there is no clear structural break

between the rocks of the two complexes. The boundary between the VC and the HC is well defined as a thrust/shear contact (Hatherton et al., 1975; Vitanage, 1985; Voll and Kleinschrodt, 1991; Kriegsman, 1994). Three tectonic klippen of similar petrological and structural features to the HC are exposed in the south eastern part of Sri Lanka as inliers, namely Kataragama Klippe, Buttala Klippe and Kuda Oya Klippe.

The HC domain is interpreted as a part of a supracrustal basin developed in a suture zone with the Lützow-Holm Complex in East Antarctica during the final phase of Gondwana assembly (Shiraishi et al., 1994). The HC is dominantly composed of granulitic meta-quartzites, marbles, calc-silicates and metapelitic gneisses, in association with charnockites (Cooray, 1962, 1984; 1994; Perera, 1984; Prame, 1991; Mathavan et al., 1999; Dharmapriya et al., 2014). Bands of wollastonite-scapolite and diopside-bearing calc-granulites and cordierite-bearing gneisses occur in the south and southwestern parts of the HC (Cooray, 1962, 1984, Hapuarachchi, 1968; Perera, 1984; Prame, 1991; Mathavan et al., 1999; Mathavan and Fernando, 2001).

ANALYTICAL TECHNIQUES

Polished thin sections of sampled rocks were prepared for petrographic study under polarizing microscope at the Department of Geology, University of Peradeniya. Representative samples devoid of surface alteration or weathering were used for major, trace and PGE analyses. The size of the samples was initially reduced in a jaw crusher, and then fine-powdered in an agate mortar. Major oxides were analyzed by X-ray fluorescence (XRF) and rare earth elements, PGE and Au by inductively coupled mass spectrometry (ICP/MS) at Intertek Genalysis Laboratories, Australia. For XRF, lithium tetraborate fusion technique was applied.

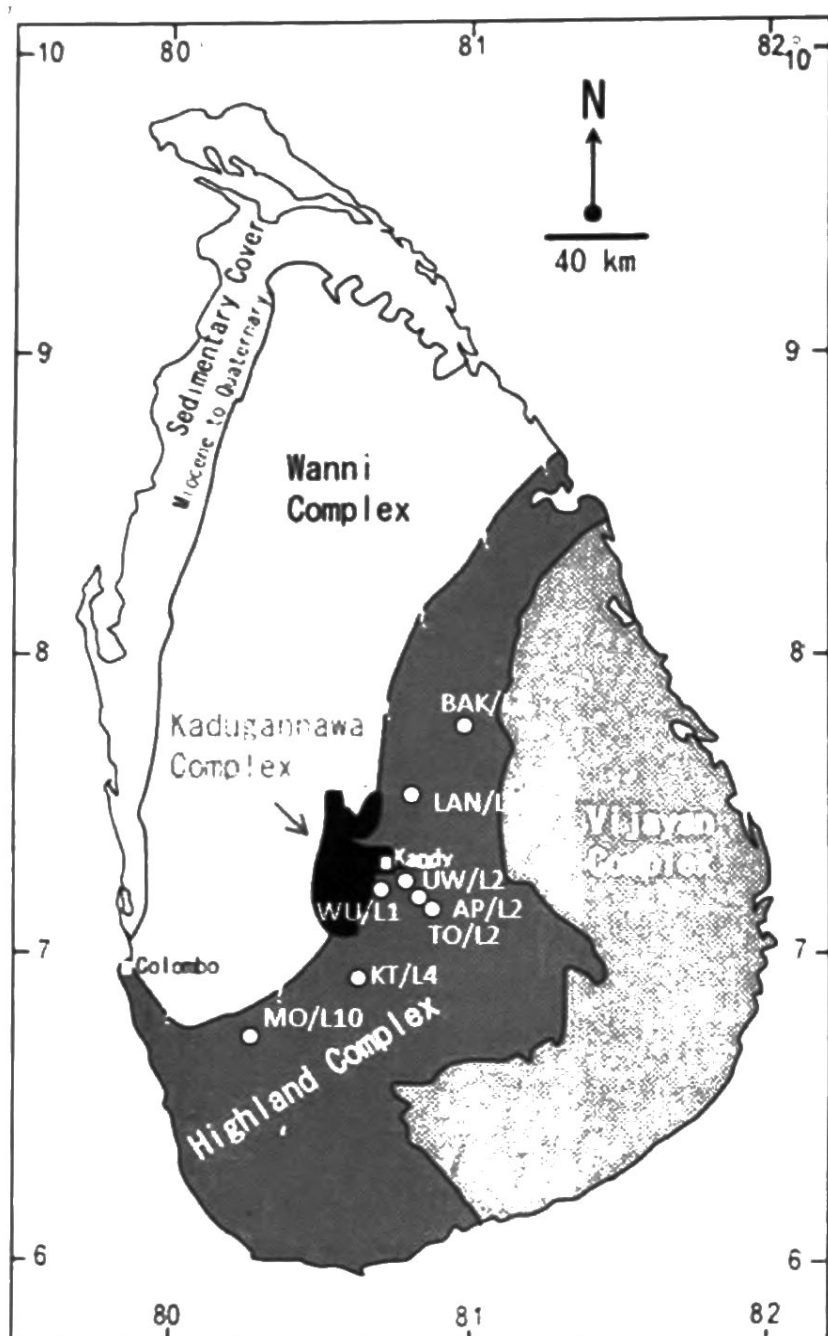


Fig. 1 Lithotectonic subdivision of Sri Lanka (after Cooray, 1994), showing the sampling locations along a NE-SW transect in the central Highland Complex.

Ni-sulphide fire assay technique was employed for analysis of PGE and Au in the samples. The pulped samples were weighed at 25 g and mixed with a flux and fired in a furnace. When fired, the flux sample mixed forms a nickel sulphide matte and an immiscible slag which separate owing to density differences. The precious metals are collected in the nickel sulphide matte (button). The button is separated from the slag, weighed and pulverized. A portion of the pulverized button is catch weighed and dissolved in boiling HCl. The addition of various reagents to the boiling HCl solution and careful observation of the dissolution process ensure that the platinum group elements and gold are quantitatively recovered by filtration as insoluble residues. These residues are dissolved in aqua regia. The solution is diluted and read on an ICP mass spectrometer for a detection limit of 1 to 2 ppb (0.001 to 0.002 ppm) with corrections for various interferences of

polyatomic species. Internal standards are used to correct for drift and plasma fluctuations. The results are corrected for the various catch weights and the button weight by the LIMS system. More details on PGE and Au analytical procedures could be found in Setiabudi et al., 2007.

ANALYZED SAMPLES, FIELD RELATIONS AND PETROGRAPHY

Sampling localities of magnesian-calcic rocks were chosen considering a wide spatial distribution, along a NE-SW transect within the central Highland Complex (Figure 1). Samples of two pyroxene granulites and calcic granulites from Ampitiya (AP/L2), Hantana (UW/L2), Bakamuna (BAK/L2), Bulatsinghala (MO/L10), Kotmale (KT/L4), Peradeniya (WU/L1), Talatuoya (TO/L2) and Matale (LAN/L2) were collected.

GARNETIFEROUS TWO-PYROXENE GRANULITES

Sample No - AP/L2

This sample was collected from a marble quarry at Ampitiya where the rock occurs as blocks (about 3 m wide and 1 m thick) within the host marble. The sampling area consists mainly of marble, khondalite, charnockitic gneiss, quartzite and hornblende-biotite gneiss.

The sampled rock contains garnet, clinopyroxene, orthopyroxene, hornblende, plagioclase and K-feldspars as major constituents with quartz and iron ore (mainly ilmenite) as minor constituents while zircon and apatite occur as accessories. Garnet occurs in different sizes from ~3 mm to > 1.5 cm in diameter. Dark greenish coarse grained clinopyroxene (0.5 – 1 cm) is frequently observed around the garnets. Occasionally quartz grains are also visible.

Porphyroblastic garnets also contain clinopyroxene, plagioclase, quartz, ilmenite and zircon as inclusion phases. Sometimes, a rim of plagioclase can be observed around inclusions of clinopyroxene toward the outer mantle to rim of

the garnets. Rarely, medium to coarse grained clinopyroxene can be observed towards the rim area of the garnet. Core area of some garnet contains coexisting clinopyroxene, plagioclase and isolated quartz inclusions. Porphyroblastic garnets have broken down forming orthopyroxene-plagioclase symplectites (Figure 2a). Orthopyroxene was found only as a retrograde product associated with garnet and clinopyroxene. Orthopyroxene and clinopyroxene together as rims around quartz can also be observed (Fig. 2b).

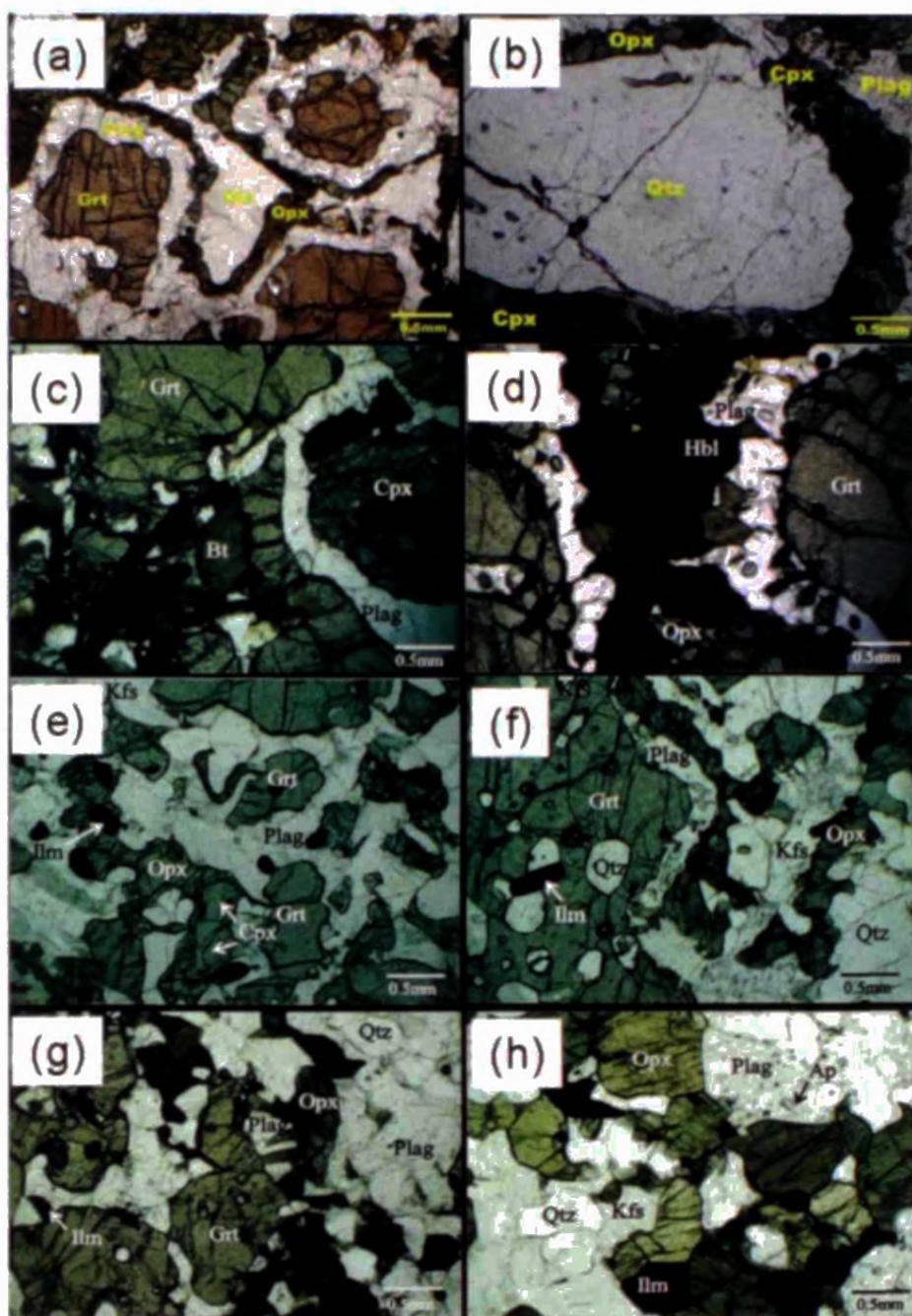


Fig. 2 (a) Opx+Plag moat around Grt in the presence of Cpx and Qtz, (b) Opx and Cpx rim around Qtz (c) Plag rim around garnet in the presence of Cpx, (d) HblPlag symplectite around Grt (e) Opx+Plag symplectite under the presence of Cpx (f) Opx+Plag symplectite in the presence of Qtz (g) Opx+Plag symplectite around Grt at garnet present domain (h) Matrix minerals at the garnet absent domain.

(a), (b): Sample AP/L2; (c), (d): Sample UW/L2; (e), (f): BAK/L2; (g), (h): MO/L10. (Opx: orthopyroxene; Plg: plagioclase; Grt: garnet; Cpx: clinopyroxene; Qtz: quartz)

Sample No: UW/L2

Garnet, clinopyroxene, orthopyroxene, amphibole and biotite containing mafic granulite was collected from an area at Uduwela (Hantana), South of Kandy. The sampling area consists with charnockite, quartzites and garnet bearing biotite gneiss and garnet-sillimanite-biotite-graphite gneiss (khondalite). The sampling location is characterized by charnockitic boulders of various sizes (< 50 cm to > 6 m in diameter).

In this sample large garnets (<0.2 - > 1.5cm) can be observed in a relatively fine grained matrix. Garnet mainly contains clinopyroxene and plagioclase as major inclusion phases while ilmenite as a minor inclusion. Later overprints of biotite formed during retrogression of the rock can also be observed. In the matrix, garnet, clinopyroxene, orthopyroxene, plagioclase and K-feldspars are found as major constituents while hornblende, biotite, ilmenite as minor constituents. Most of the garnet are decompressed producing orthopyroxene and plagioclase coronas in the presence of clinopyroxene (Fig.2c). Local occurrence of hornblende and plagioclase symplectite can be observed around garnet with clinopyroxene and orthopyroxene (Fig. 2d).

Sample No - BAK/L2

Garnet, clinopyroxene, orthopyroxene and hornblende bearing granulite was collected at Bakamuna. The sampling area contains mainly marble, quartzite, garnet bearing quartzofeldspathic granulites and charnockite. This rock occurs as thin layers (about 30- 45 cm) within garnet bearing quartzo-feldspathic granulite. Coronatic textures can clearly be identified around garnet even in hand specimens.

This mafic granulite contains medium to fine grained garnets (<0.1 to 0.5cm), anhedral clinopyroxene (<0.25 - 0.5 cm), anhedral orthopyroxene, plagioclase and quartz as major constituents. Hornblende occurs as a minor mineral while zircon and apatite occur as accessory minerals. Garnets contain anhedral to

subhedral plagioclase, subhedral orthoclase and quartz, and ilmenites as inclusion phases. Garnets have broken down, forming orthopyroxene-plagioclase symplectites. Orthopyroxene is present only as a retrograde phase, commonly forming a corona with plagioclase along grain boundaries between garnet and clinopyroxene or garnet and quartz (Figure 2e, f).

Sample No: Mo /L10

Garnet, clinopyroxene and orthopyroxene bearing mafic granulite were collected from a road outcrop close to Molkawa at Bulathsinghala. The sampling area mainly consists with charnockitic gneiss, quartzite, quartzo-feldspathic gneiss, granitic gneiss and cordierite bearing garnet, sillimanite, biotite-graphite gneisses (khondalite). The studied sample contains garnet rich and garnet absent domains. In garnet present domains clusters of fine to medium garnet (<0.75 cm) can be observed. In garnet absent domains medium to coarse pyroxene grains are found.

Within garnet present domains, anhedral medium to fine grained garnets (<0.2 – 0.6 mm), plagioclase (<0.1 - 0.5mm) and coarse grained quartz (0.25 - >1cm), anhedral medium grained K-feldspars occur as major mineral phases and fine grained orthoclase and ilmenite are found as minor mineral phases.

Garnet absent domains are comprised of medium to fine grained anhedral orthopyroxens (<0.1 – 0.5 cm), anhedral fine grained quartz, anhedral plagioclase and orthoclase as major constituents while ilmenite as a minor constituent (Figure 2g, h).

GARNET ABSENT TWO-PYROXENE GRANULITES

Sample No: KT/ L4

Clinopyroxene, orthopyroxene and hornblende bearing granulite was collected from a quarry close to Kotmale reservoir. The rock is massive sapphirine and spinel bearing garnet-orthopyroxene granulite and cordierite bearing

garnet-sillimanite-graphite gneiss are found as a thin layer within this rock.

The studied rock is mostly homogeneous and medium to fine grained containing clinopyroxene, orthopyroxene, plagioclase and K-feldspars as major constituents while, iron ore (mainly ilmenite) hornblende, biotite and quartz as minor constituents. Medium to fine (<0.2 - ~0.5 cm) clinopyroxene can be identified always together with orthopyroxene (Figure 3a, b).

Sample No: WU/L2

The studied cases granulite sample contains subhedral to anhedral clinopyroxene, biotite and spinel (<0.1 – 0.75 cm) as major constituents while plagioclase is present as minor constituent. Zoisite is encountered as an accessory phase. Spinel mainly contains ilmenite as inclusions (Figure 3c). Occasionally clinopyroxene, plagioclase and zoisite inclusions can be observed in spinel. In some domains of the rock clinopyroxene is observed. Zoisite can be found only in biotite present domains and appears as an overprinted product on biotite and clinopyroxene during retrogression (Figure 3d).

Sample No - TO/L2

This sample contains clinopyroxene, calcite, scapolite, hornblende (pargasite), spinel, and biotite as major phases and occurs as a well-foliated layer within a massive marble at a road-cut close to Thalatuoya. The studied rock appears to be fine-grained and dark greenish in colour. Some of the coarse grained green-spinel (0.5 – 1 cm) and biotite can be identified with naked eye. Biotite shows layer-parallel preferred orientation marking a foliation in tiny layers. Spinel can be observed as subhedral to anhedral grains (<0.25 - > 1 cm) coexisting with clinopyroxene and plagioclase. Rare calcite is observed among clinopyroxene and could be of secondary in origin as a product of alteration of Ca rich clinopyroxens. In some domains, the rock contains only (>90%) clinopyroxene. Scapolite is mainly observed as coexisting with spinel and plagioclase. Euhedral pargasite grains (0.5 – 1 cm) show compositional zonation (Figure 3 e,f).

Sample No: Lan/L1

This fluorite (CaF₂) bearing calcic granulite was collected from a marble quarry close to Lenadora, North of Matale. The rock is found as blocks (from 30 cm to >1m in diameter) within impure marble. This mafic granulite does not show any foliation and occurs as massive and dense blocks. At the contact between marble and the mafic rock, large phlogopite aggregates (up to 10 cm in diameter) can be observed.

The mafic granulite contains subhedral to anhedral clinopyroxene (<0.1 – 0.5 cm), anhedral spinel, (< 0.1mm – 1cm), fluorite (0.1 –

> 0.5cm) and phlogopite as major constituents and plagioclase as a minor constituent. Fluorite is mainly associated at the margins of clinopyroxene where clinopyroxene shows irregular/dissolved grain boundaries (Figure 3g, h). Sometimes, clinopyroxene can also be found associated with fluorite and plagioclase. Locally, plagioclase and calcite are also found close to clinopyroxene and spinel. phlogopite in the matrix mainly occur at the margins of clinopyroxenes.

RESULTS OF WHOLE ROCK GEO-CHEMISTRY

Analytical results of major elements, rare earth elements and PGE are given in Table 1 and 2.

MAJOR ELEMENT CHEMISTRY

The studied magnesian-calcic granulite samples can be divided based on their major element composition, into two suites: a) low magnesian-calcic (LMC) and high magnesian-calcic (HMC). The samples of The LMC suite are characterized by low MgO (<13 wt %) and CaO (<12 wt %) while HMC suite shows high MgO (>13 wt %) and CaO (>12 wt %). Additionally, the LMC samples show distinctly high Al₂O₃ (>13.5 wt %) and TiO₂ (>1.6 wt %) contents (Table 1). Hence, the samples of AP/L2, UW/L2, BAK/L2 and MO/L10 belong to the LMC suite while the samples of KT/L4, WU/L1, TO/L2 and LAN/L2 belong to the HMC suite. In general, the entire set of samples displays a linear correlation in the MgO-CaO diagram (Figure 4a), clearly showing their magmatic evolution from low Mg end to high Mg end. However, the slope of the correlation lines of the two suites is different, which sufficiently describe that the two sets of samples have distinctly different genesis. The SiO₂ content of the samples display a bimodal distribution in a SiO₂ versus FeO/MgO diagram (Figure 4b) showing a clear positive correlation, with HMC samples displaying a steep slope. In this diagram the HMC granulites fall geochemically in the calc-alkaline field while the LMC samples fall in the tholeiitic field of

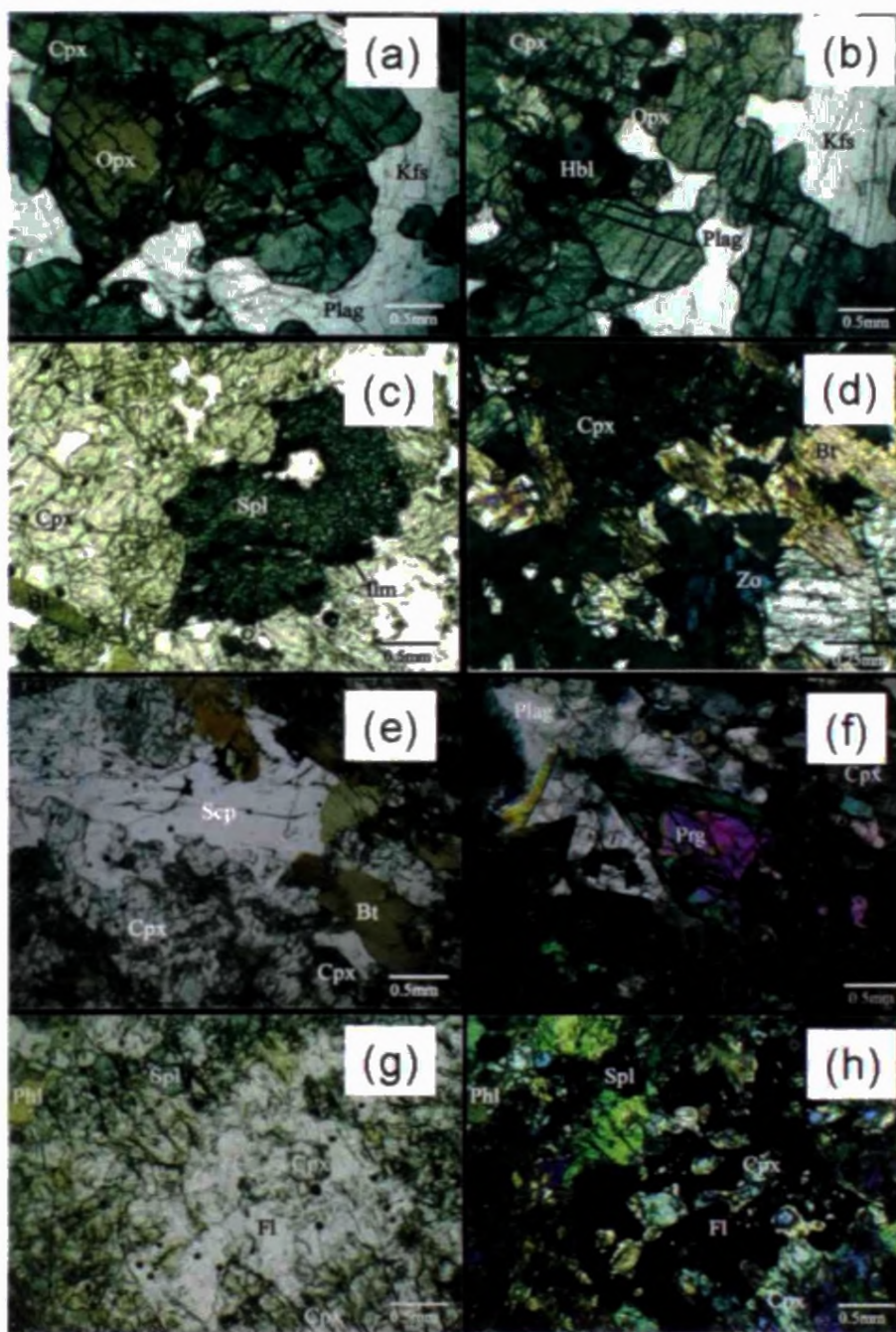


Fig. 3 (a) Co-existence of Opx and Cpx in the matrix (b) Overprinted Hbl after Cpx and Opx (c) Coarse Spl grains with Ilm inclusion in the matrix (d) CPL view of Zo next to Cpx and Bt (e) CPL view of euhedral, Scp grain in the matrix (f) Zonation of the Prg grains (g) PPL view of formation of Fl in the matrix (fine Spl and medium grained Cpx are also present), (h) CPL view of formation of Fl in the matrix. (a), (b): Sample KT/L4; (c), (d): Sample WU/L1; (e), (f): TO/L2; (g), (h): LAN/L 2. (Opx: orthopyroxene; Cpx: clinopyroxene; Hbl: hornblende; Spl: spinel; Ilm: ilmenite; Zo: zoisite; Bt: biotite; Scp: scapolite; Prg: pargasite; Fl: fluorite).

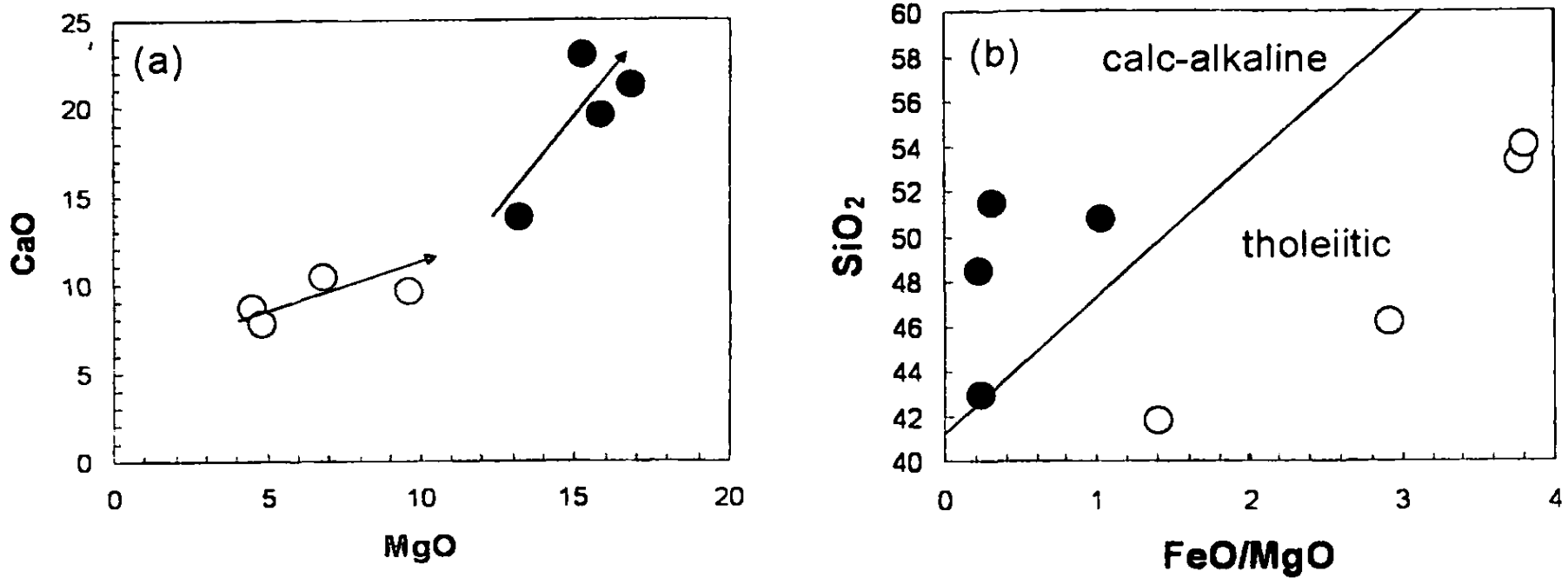


Fig. 4 Geochemical variation of the analysed samples. Open circles: low magnesian-calcic (LMC) rocks; closed circles: high magnesian-calcic (HMC) rocks. (a) Positive-linear correlations shown by the LMC and HMC with different gradients in the CaO vs. MgO diagram (b) Bimodal distribution of the LMC and HMC samples showing calc-alkaline nature of the LMC group and tholeiitic nature of the HMC (classification after Miyashiro, 1974).

magmatic rocks (classification after Miyashiro, 1974).

RARE EARTH ELEMENT (REE) CHEMISTRY

In general, all the samples have light rare earth element (LREE) enriched geochemical patterns

clearly reflected by high-overall REE abundances of their trace element diagrams.

The samples of UW/L2, AP/L2 and BAK/L2 of the LMC group demonstrate near-equal HREE abundances. The Gd/Yb ratio of the Sample UW/L2 is greater than that of the other two

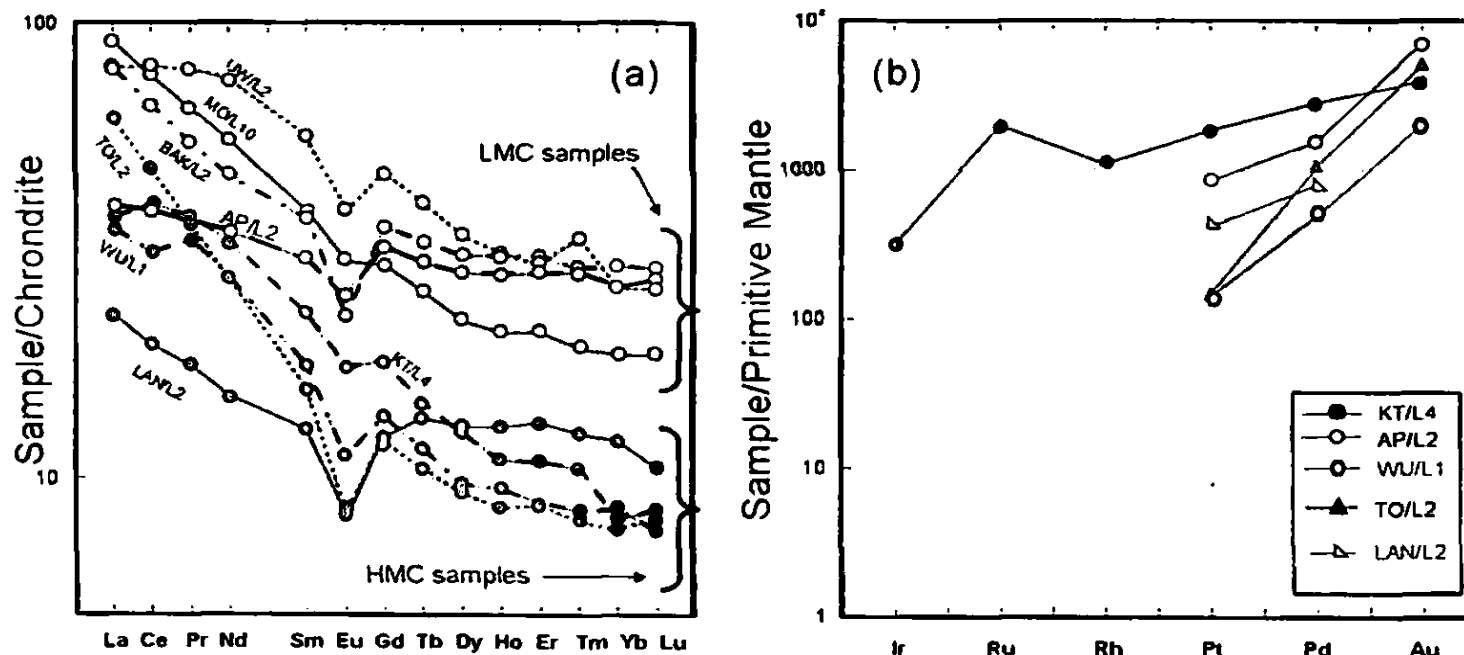


Fig. 5 (a) Rare earth element (Chondrite normalized after McDonough and Sun, 1995) and (b) platinum group element and gold (Primitive Mantle normalized after Barnes et al., 1999) variation of the analyzed samples.

with variable amounts of negative Eu anomalies. Interestingly, HMC granulites have low overall rare earth elemental abundances (Table 2). The LMC and HMC group-division based on major elements is also displayed especially by the distribution of the middle to heavy rare earth elements (MREE - HREE) showing a marked gap between the two groups (see Figure 5a). The presence of garnet in all the LMC samples is

samples. These three samples have a pronounced Eu negative anomaly. Sample MO/L10 of the same group is characteristically depleted in middle to HREE with a slight Eu negative anomaly, although its LREE abundance is the second most within the group. The lowest LREE abundance of the LMC group is marked by the sample AP/L2, which displays a more-or-less flat middle to HREE pattern.

Interestingly, in the HMC group, the sample LAN/L2 has the lowest LREE content and the highest HREE content while the sample TO/L2 has the highest LREE and the lowest HREE contents. Samples WU/L1 and TO/L2 shows more-or-less similar REE abundances except for the elements La, Ce and Eu. The sample TO/L2 has LREE almost close to the level of that of the LMC samples.

PLATINUM GROUP ELEMENTS AND AU GEOCHEMISTRY

In samples of the LMC group, all the PGE data of the BAK/L2 and Rh, Ru and Ir of the samples AP/L2, UW/L2, MO/L10 are below the detection limit of the ICP-MS. In the HMC group, the sample KT/L4 has all the PGE data (Pd, Pt, Rh, Ru, Ir) available while Rh, Ru and Ir of the samples WU/L1, TO/L2 and LAN/L2 are below the detection limit. The sample MO/L10 of the LMC group and the samples of WU/L1 and LAN/L2 of the HMC group have Au contents below the detection limit (Table 2). The sample from Ampitiya (AP/L2) contains the highest Au content of 7 ppb (Table 2). The highest Pd and Pt contents are reported from the sample from Kotmale (KT) (11 and 13 ppb, respectively). The concentration of PGE and Au shows a systematic positive correlation with increasing MgO contents (Figure 6a), complying with the bimodal distribution. In the Primitive Mantle normalized PGE and Au elemental variation diagram shown in the Figure 5b, the entire samples show a steep depletion trend from Pd to Ir, except for the sample KT/L4 of the HMC group, which has a relatively gentle pattern with a positive Ru anomaly. Gold shows enriched compositions.

DISCUSSION

Sulphide saturation in magmatic melts has significant implications on chalcophile mineralizations. Therefore, this study was undertaken as a preliminary step in investigation of the PGE and Au geochemistry of magnesio-calcic rocks from the Highland Complex in order to determine the extent to which the distribution of chalcophile elements provide

constraints on magmatic processes related to sulphide saturation. Our major element, REE, PGE and Au data clearly indicate that the two groups of samples (LMC and HMC) formed in distinctly different genetical environments, as displayed by the bimodal distribution of data (e.g. Figures 4b, 5a and 6a). Petrographically, the LMC samples are characterized by occurrence of essentially garnet, ortho- and clino-pyroxenes and hornblende as major phases (Figure 2). Probably, garnet controls the REE budget of the LMC samples due to increased compatibility of many REE in garnet structure during the formation, as indicated by their high level of abundance (Figure 5a). In contrast, the HMC samples are characterized by the presence of clino-pyroxenes and calcic minerals abundantly (Figure 3). The ranges of REE concentrations and pattern-types observed in the HMC samples appear to be controlled by the combined effect of early formed silicate minerals such as Cpx and late-stage accumulation of calcic minerals. The REE pattern of the HMC samples where depletion from the MREE to HREE suggests a continued growth of these primary mineral phases from the evolving magma. On the other hand, the enrichment of LREE in both LMC and HMC suites could be explained by late metasomatic enrichment processes (e.g. Mathez, 1995). The shapes of the REE patterns expressed by $[La/Yb]_N$ also have a strong relationship to the total incompatible element contents. The LMC samples, $(La/Yb)_N$ Vs. MgO shows a negative slope while that of the HMC samples is steep (e.g. Figure 6b). In the plots of $(La/Yb)_N$ Vs. Nd and Lu, the correlation is negative and positive, respectively for both LMC and HMC samples (Figure 6c, d). This can be ascribed to incompatible and compatible characteristics of Nd and Lu (to the melt phase), respectively. However, these slopes are fairly steep for both LM and HMC suites.

Table 1. Major element compositions of the samples measured by XRF

Rock suite*	Sample #	SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	Fe ₂ O ₃ ^{tot}	MnO	MgO	CaO	Na ₂ O	K ₂ O	BaO	P ₂ O ₅	SO ₃	LOI ^{b)}	Total
HMC	KT/L4	50.67	0.8	6.41	0.21	13.38	0.21	13.31	13.73	1.39	0.29	x	0.124	0.13	-0.13	100.56
HMC	WU/L1	51.64	0.11	4.26	x	4.58	0.07	15.22	23.04	0.7	0.03	x	0.019	0.02	0.41	100.16
HMC	TO/L2	48.48	0.32	5.13	x	3.77	0.05	16.84	21.29	0.47	0.87	0.12	0.068	0.09	2.76	100.25
HMC	LAN/L2	42.82	0.93	13.69	0.03	3.61	0.03	15.63	19.55	0.42	1.21	0.02	0.679	0.11	1.39	100.13
LMC	AP/L2	41.75	1.8	16.77	0.04	13.35	0.1	9.64	9.57	1.92	0.81	x	0.188	8	4	100.17
LMC	UW/L2	46.23	2.49	13.57	0.02	19.39	0.27	6.69	10.36	1.79	0.26	0.01	0.294	0.16	-0.82	100.77
LMC	BAK/L2	53.93	1.67	13.32	x	17.28	0.27	4.55	8.67	1.02	0.17	x	0.195	0.58	-0.58	100.65
LMC	MO/L10	53.61	2.05	13.46	x	18	0.22	4.76	7.9	0.48	0.03	x	0.285	0.03	-0.87	100.12
Detection Limit		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.002	0.01	0.01	

*: HMC: High magnesian-calcic granulite; LMC: Low magnesian-calcic granulite

^{a)} Total Fe as FeO

^{b)} Loss on ignition

x: below detection limit

Table 2. Rare earth and Platinum Group element and Au compositions of the samples measured by ICP-MS

Rock suite*	Sample #	Trace elements (in ppm)														Platinum Group Elements and gold (in ppb)									
		La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Pd	Pt	Rh	Ru	Ir	Au				
HMC	KT/L4	8.9	24.5	3.49	15.1	3.41	0.99	3.59	0.53	3.09	0.6	1.74	0.26	1.31	0.21	11	13	1	1	1	4				
HMC	WU/L1	8.3	19.2	3.1	12.6	2.62	0.63	2.7	0.42	2.38	0.52	1.42	0.21	1.38	0.19	2	1	x	x	x	x				
HMC	TO/L2	14.6	29.1	3.34	12.6	2.33	0.48	2.39	0.38	2.29	0.47	1.39	0.2	1.25	0.2	4	1	x	x	x	5				
HMC	LAN/L2	5.4	12	1.64	6.9	1.9	0.47	2.45	0.49	3.17	0.71	2.11	0.31	1.95	0.26	3	3	x	x	x	x				
LMC	AP/L2	9.4	23.7	3.41	15.9	4.49	1.41	6.42	1.07	6.94	1.53	4.5	0.7	4.22	0.67	6	6	x	x	x	7				
LMC	UW/L2	18.6	49.2	7.31	34.4	8.38	2.18	9.25	1.44	8.41	1.71	4.72	0.83	4.21	0.64	2	1	x	x	x	2				
LMC	BAK/L2	19.2	40.3	5.06	21.2	5.49	1.28	7.09	1.19	7.59	1.68	4.92	0.71	4.71	0.71	x	x	x	x	x	4				
LMC	MO/L10	21.6	47	6.05	25.3	5.68	1.69	5.87	0.93	5.49	1.15	3.37	0.48	3.03	0.46	x	1	x	x	x	x				
Detection Limit		0.2	0.5	0.05	0.1	0.05	0.05	0.05	0.02	0.05	0.02	0.05	0.05	0.05	0.02	1	1	1	1	1	2				

*: HMC: High magnesian-calcic granulite; LMC: Low magnesian-calcic granulite

x: below detection limit

It is possible that the REE patterns become steeper with increasing amounts of trapped interstitial liquid because of the contrasting influence of the liquid compositions and the

(Naldrett et al., 1987, 1990). On the other hand, magmas that are initially S-undersaturated can become S-saturated through either differentiation of magma or cooling, or both,

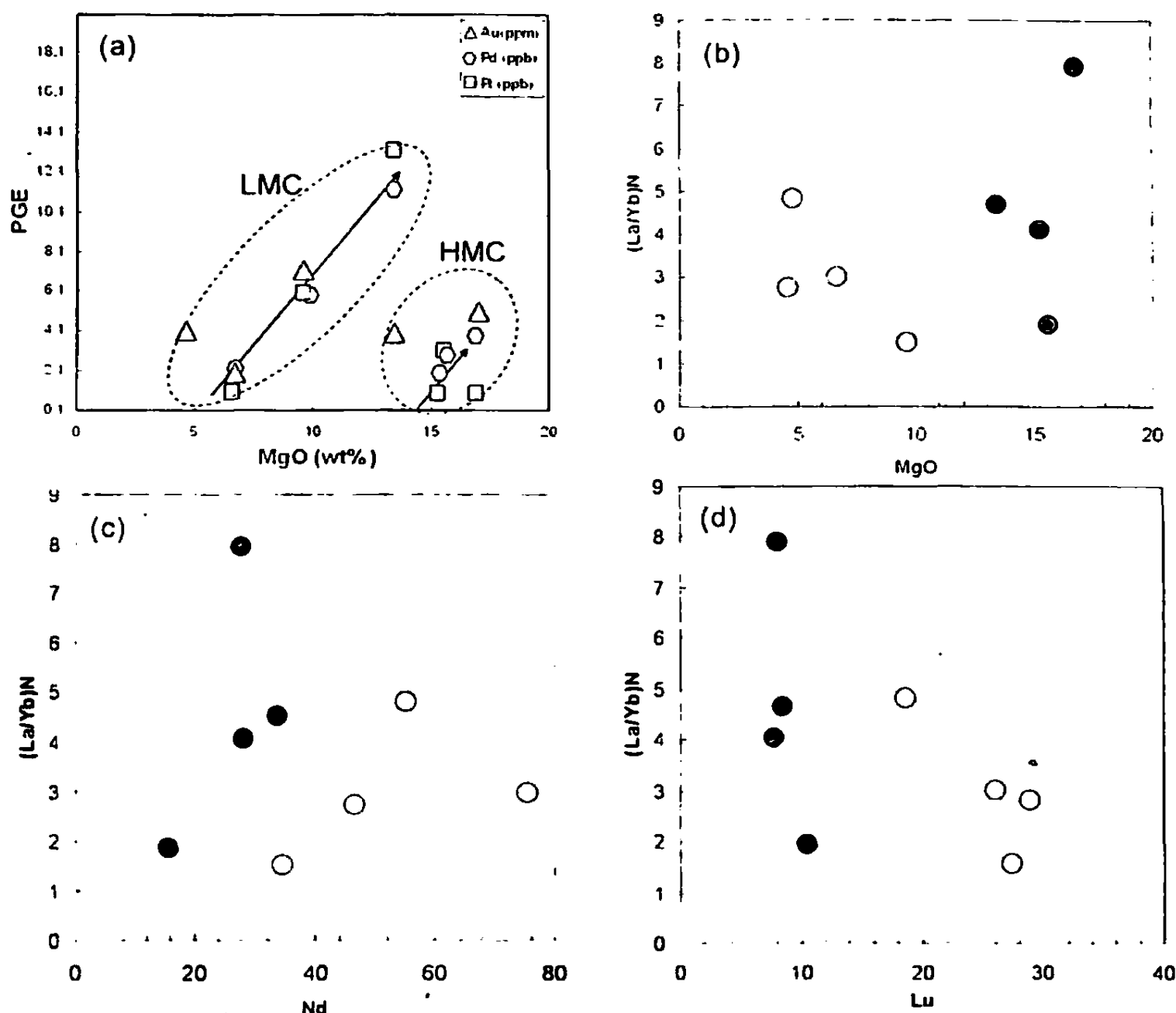


Fig. 6 (a) Bi-modal positive correlation shown by the LMC and HMC groups in PGE and Au vs. MgO plot. (La/Yb)_N vs. MgO (b), (La/Yb)_N vs. Nd (c) and (La/Yb)_N vs. Lu for the studied samples. (Symbols are same as in the Figure 4).

partition coefficients for La and Yb. In contrast, in a more evolved liquid the REE patterns tend to be rather flat. Therefore, the Samples LAN/L2 of the HMC and AP/L2 of the LMC suites may have been produced by a relatively evolved parental magma.

Primitive mantle-normalized PGE patterns (Barnes and Maier, 1999) are shown in the Figure 5b, in the order of increasing chalcophile character. It indicates that the abundances of the different PGE patterns are not simply related to lithology. In mafic intrusions, the PGE and Au are trace elements that are generally regarded as having being derived from sulphide melts which is likely to have formed as a dense, immiscible liquid that accumulated with silicate melts

and the sulphide formed can scavenge PGE from the magma to form immiscible melts which ultimately crystallize PGE deposits associated intimately (e.g. Keays, 1995; Maier & Barnes, 2004). In addition to sulphide saturation, fluids are also responsible for transport and remobilization of PGE (Boudreau and McCullum, 1992; Boudreau & Meurer, 1999). However, for the studied rock suites, there is little information on specific links between the spatial distribution of PGE and sulphide saturation due to the small number of samples studied here. The ratio of Pt/Pd is regarded as an indicator for identifying sulfide saturation in evolving magmas (e.g. Campbell and Barnes, 1984; Vogel and Keays, 1995; Philipp et al., 2001). This is because Pd partitions

preferentially into sulfide melt relative to Pt. Therefore, if a silicate melt becomes sulfide-saturated and an immiscible sulphide melt has formed, the Pt/Pd ratio will rapidly increase in the residual magma. Between the HMC and LMC samples there is a clear distinction of Pt/Pd vs. MgO variation (Figure 7a), in which the HMC group shows a negative correlation while the LMC samples show a positive correlation. The variation of the Pt/Pd shown by the HMC samples indicates that the ratio of Pt/Pd gradually increases with decreasing MgO content (Figure 7a). Similar behavior can be observed in the Au vs. MgO plot as well, for the LMC group (Figure 7b), unfortunately, that for the HMC group is not observable due to low contents of Au (Au data available for only two samples in the HMC group). Further, in the Pd vs. MgO plot (Figure 6a) the HMC samples show a strong positive correlation with MgO content. Usually, similar trends are observed in magmatic systems which indicate segregation of PGE-rich melts (e.g. Philipp et al., 2001). In addition, the sample with the highest Au

controlled by a progressive segregation of an immiscible sulfide melt. Further, opaque phases are only concentrated mainly in garnet or pyroxene as inclusions, and rarity of iron ores in the matrix of these samples indicates low oxidizing conditions prevailed at the genesis of parental magmas. This support the requirement of reducing conditions to occur sulphide saturation in melts. However, evidence for sulphide saturation is not obvious from the chalcophile element trends (e.g. Pt/Pd and Au vs. MgO) shown by the samples of the LMC group (Figure 7).

Thus, our preliminary results obtained from PGE and Au geochemistry of the studied rock suites imply that there is a potential chalcophile mineralized zone virtually unsampled hidden within the Highland Complex of Sri Lanka probably associated with the HMC rocks. Detailed investigations are necessary, incorporating PGE and Au geochemistry of more samples from other sections of the HC which should throw light on the chalcophile

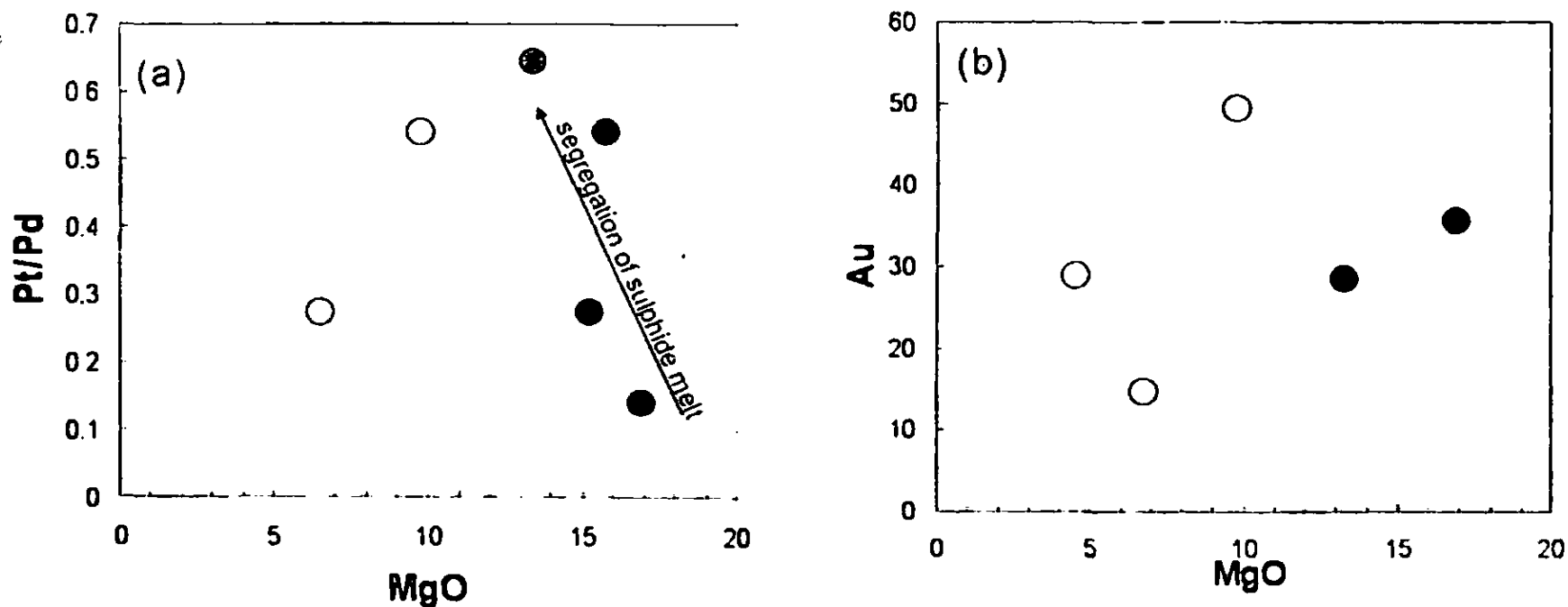


Fig. 7 Pt/Pd and Au vs. MgO variation in the studied samples (a) Pt/Pd ratio increases with decreasing MgO content indicating sulphide saturation in parental magmas of the HMC group (b) Weak positive correlation shown by Au with MgO in the LMC samples (Symbols are same as in the Figure 4).

contents does not have the highest Pd content in the HMC group. Contrary, the sample with the highest Au content in the LMC group has the highest Pd content (Table 2). This difference could be related to the higher compatibility of Pd compared to Au in immiscible sulfide melts (Francis, 1990). Hence, these geochemical characteristics imply that the variation of PGE and Au of the studied HMC samples is mainly

elemental chemistry of the Highland Complex in future studies.

CONCLUSIONS

The PGE and Au results obtained in this study suggest that there is a sign of sulfide saturation in parental magmas of the HMC rocks of the Highland Complex, Sri Lanka. Rarity of iron-

ores in the studied samples indicates low oxidizing conditions prevailed during the genesis of those parental magmas. An immiscible sulfide melt possibly may have segregated and crystallized associated with the HMC rock suite.

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