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Emplacement and Evolution History of Pegmatites and Hydrothermal Deposits, Matale District, Sri Lanka

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Abstract

Excellent outcrops in Matale Sri Lanka provide unique insight into the emplacement and evolution history of hydrothermal and pegmatitic rocks in the central highlands of Sri Lanka. Field, structural, petrological, thermo-barometric studies in the metamorphic basement rocks in the central highlands and related hydrothermal deposits are presented in this study. Detailed petrographic and mineralogical data reveal peak metamorphic conditions for the crustal unit in the study area as 854 ± 44˚C at 10.83 ± 0.86 kbar. Hydrothermal veins consisting of quartz and mica are closely related to cross-cutting pegmatites, which significantly post-date the peak metamorphic conditions of the crustal unit. Field relations indicate that the veins originated as ductile-brittle fractures have subsequently sealed by pegmatites and hydrothermal crystallization. Geological, textural and mineralogical data suggest that most enriched hydrothermal veins have evolved from a fractionated granitic melt progressively enriched in H_2O, F, etc. Quartz, K-feldspar, mica, tourmaline, fluorite and topaz bear evidence of multistage crystallization that alternated with episodes of resorption. It was suggested that the level of emplacement of pegmatites of the Matale District was middle crust, near the crustal scale brittle-ductile transition zone at a temperature of about 600˚C. For this crustal level and temperature range, it is considered very unlikely that intruding pegmatitic melts followed pre-existing cracks. As such the emplacement temperatures of the pegmatites could be well below the peak metamorphic estimates in the mafic granulites. The metamorphic P-T strategy and position of formation of hydrothermal deposits and pegmatites is summarized in the modified P-T-t-D diagrams.

Keywords: Hydrothermal Veins, Pegmatites, Emplacement History, Brittle Deformation, Sri Lanka

1. Introduction

Pegmatite veins are supposed to form from hydraulic fractures driven by the excess pressure of intruding hydrous melts (Brisbin [1]). For tensile cracks to form by hydraulic fracturing, the fluid pressure must exceed the magnitude of the least principle stress by the tensile strength of the rock (Shaw [2]) or, in fracture mechanics terminology, exceed the fracture roughness of the rock. Upon cooling and crystallization, the portion of volatiles in the pegmatitic melt that is not incorporated into minerals is liberated as a fluid phase (Burnham [3]). Transport of this fluid phase away from the crystallizing magma is governed by the porosity and permeability of the host rock of the pegmatite vein.

Minerals of hydrothermal rocks have crystallized from hot water or have been altered by such water passing through them. Hydrothermal deposits in extension-driven subsidence basins from any geological period are found worldwide (Kyser [4] references therein). Hydrothermal systems are commonly related to the emplacement at shallow levels of fractionated, hydrous magmas. In this environment, crystallization of medium- to coarse-grained granite, which is forcefully invaded by later, fine-grained material, is common. Common precipitation mechanisms are mixing of fluids (Baatartsogt *et al.* [5]), or changes in fO_2 or pH (Gleeson and Yardley [6]), whereas temperature and pressure decrease is thought to be less important in most cases (Large *et al.* [7]). There is no satisfactory answer to the question of the actual source of the fluids and the reason for their ascent. Fluid circulation or fluid migration in convection cells is often invoked to explain the ascent of fluids to the site of mineralization, but requires a driving force (Oliver *et al*. [8]).

Matale district in Sri Lanka contains the highest number of pegmatites and hydrothermal deposits exposed in the metamorphic basement, which is considered as an important Gondwana fragment. Up to now, only a few studies have been done on the mineralization and evaluation of pegmatite and hydrothermal deposits in Sri Lanka (Pitawala *et al*. [9]) because of lack of methods available to ascertain the PT history of pegmatite and hydrothermal deposits although the metamorphic history of the metamorphic basement is fairly known (Harley [10], Newton and Perkins [11], Schumacher *et al*. [12], Voll *et al*. [13], Raase, [14], Fernando [15], Sajeev and Osanai [16,17], Osanai *et al*. [18]). This is attributed to the lack of methods available to ascertain the PT history of pegmatites and hydrothermal deposits, the fluid generation and migration. Open questions still remain on the timing of the mineralization, the emplacement history and generation of fluids to form pegmatite and hydrothermal deposits in the Matale district and its relationship to the metamorphic basement.

In this paper the authors: 1) describe the basic geometric properties of pegmatite and hydrothermal veins of Matale District; 2) propose the P-T history of surrounding metamorphic rocks with garnet-orthopyroxene thermobarometry using the latest experimental data and; 3) propose the timing and mineralization of the pegmatites and hydrothermal rocks.

2. Outline of Geology of Sri Lanka

Sri Lanka was a part of East Gondwana, together with fragments of Antarctica, Australia, India, Madagascar, Mozambique and Tanzania (e.g. Powell *et al*. [19]; Kröner [20]; Yoshida *et al*. [21]; Jacobs *et al*. [22]). Sri Lanka acted as a bridge through which Antarctica and East Africa can be correlated. Thus Sri Lanka reveals remarkable geological, geochronological and geotectonic similarities to those of neighbouring Gondwana fragments. The Proterozoic basement of Sri Lanka exposes substantial parts of the lower continental crust. Four different units were distinguished on the basis of isotopic, geochronological, geochemical and petrological constraints viz, the Vijayan Complex (VC) in the east, the Highland Complex (HC) in the central Wanni Complex (WC) in the west and the Kadugannawa Complex (KC) (Kröner *et al*. [23]; Cooray, [24], Milisenda *et al*. [25]) (Fig.1). The VC consists mainly of amphibolite-facies granitoid rocks, metadiorites, metagabbros and migmatites (e.g. Cooray [24]; Kröner *et al*. [23]; Kehelpannala [26]), The HC is composed of intercalated meta-sedimentary and meta-igneous rocks of pelitic, mafic such as quartzo-feldspathic granulites, charnockites, marble and quartzite. Most of HC rocks have attained granulite-facies conditions whereas some contain ultra-high temperature assemblages (Sajeev and Osanai [16,17] Osanai *et al*. [18]). Rocks in the Wanni Complex are granitoid gneisses, granitic migmatites, scattered metasediments and charnockites, metamorphosed under upper amphibolite to granulite facies conditions. Rocks of the KC are seen in the cores of six doubly plunging synforms, which were named as '*Arenas*' by Vitanage [27]). The dominant rocks of the KC are hornblende and biotite-hornblende gneisses with interlayered granitoid gneisses in the core, pink feldspar granitic gneisses at the inner rim and metasediments at the outer rim of the arenas (Perera [28]). Rocks of KC are metamorphosed under upper amphibolite to granulite facies conditions. Some granulites are exposed in the southern part of VC near Buttala and Kataragama. Post-peak metamorphic magmatic and hydrothermal activities are responsible for the formation of pegmatite, dolerite, carbonatite and granite bodies found in Sri Lanka (Pitawala *et al*. [9,29]).

Numerous thermobarometers and different mineral paragenesess have been used to estimate the peak P-T conditions of crystalline rocks of Sri Lanka. Lowest temperatures of 670 - 730˚C were estimated to represent peak metamorphic conditions using garnet-clinopyroxene and garnet-orthopyroxene thermometry (Sandiford *et al*. [30]). Maximum temperature of 900˚C for the HC was obtained using two-pyroxene thermometry (Schenk *et al*. [31]). Temperatures ranging from 760 - 820˚C were also obtained for mafic granulites using garnet-orthopyroxene and garnet-clinopyroxene pairs (Schumacher *et al*. [12]). Schumacher and Faulhaber [32] estimated the P-T condition of the Eastern, North-Eastern and South-Eastern parts of the HC at 760 - 830˚C (garnet-orthopyroxene of Harley [10] and 9 - 10 kbar (garnet-clinopyroxene-plagioclase-quartz barometer of Newton and Perkins [11]). Peak temperatures of metamorphism at 850 - 900˚C were derived using two-feldspar thermometry (Voll *et al*. [13], Raase [14]). Maximum temperatures of 875 ± 20˚C (orthopyroxene-clinopyroxene thermometer) at the peak pressure of 9.0 ± 0.1 kbar (garnet-clinopyroxene-plagioclase-quartz) for the silicic granulite, peak temperatures of 840 ± 70˚C (orthopyroxene-clinopyroxene thermometer) at 9 kbar for ultramafic rocks and 820 ± 40˚C for coexisting spinel sapphirine the reaction zone were calculated within the HC (Fernando [33]). Thermodynamic modeling in the CaO-Na_2O-K_2O-FeO-MgO-Al_2O_3-SiO_2 system for mafic granulites in Sri Lanka indicates peak metamorphic conditions of 12.5 kbar at 925˚C (Sajeev *et al*. [18]).

The sapphirine-bearing pelitic granulites of the HC have been evidenced for ultrahigh-temperature (UHT) metamorphic conditions at around 900 to 1150˚C (Faulhaber and Raith [34], Hiroi *et al*. [35], Raase and Schenk [36], Kriegsman and Schumacher [37], Sajeev and Osanai [16,17], Osanai *et al*. [38]). However, many of the previous studies on mafic granulites gave relatively low temperatures even though the sample locations were in the high–temperature-pressure zone (Faulhaber and Raith [34]). This is probably due to the resetting of co-existing minerals on slow rate of cooling (Chakraborty and Ganguly [39]).

3. The Study Area

The study area (Matale District) is located in the central part of the Highland Complex, which has been considered as the oldest metamorphic unit in Sri Lankan crust (**Figure 1**). Pegmatites and hydrothermal deposits are best exposed in Matale district, which ideally suit for the study of the emplacement and evolution history of the metamorphic basement of Sri Lanka.

3.1. Geological and Structural Setting

Matale District is underlain by Precambrian crystalline rocks of the HC (**Figure 2**). Major rock types in the area are meta-sediments such as marble, garnet sillimanite biotite gneiss, quartzite and calc gneiss. Orthogneisses of granitoid composition and charnockitic gneisses represent the meta-igneous affinity. Meta-sedimentary and meta-igneous rocks are intercalated with each other in the entire area. North south striking rock units are dominant in the northern part of Matale whereas rocks from southern part strikes towards the NNW direction.

Basement rocks trending NNE-SSW and N-S directions occur as an intensely stretched. Isoclinally folded series of antiforms and synforms (**Figure 3**) which may have formed during the D_3 deformation (Berger and Jayasinghe [40]) and large-scale folds (in the western part) formed due to refolding of earlier folds (Kehelpannala [26]) are the other ductile structures of the area.

Brittle structures characteristic of the study area are

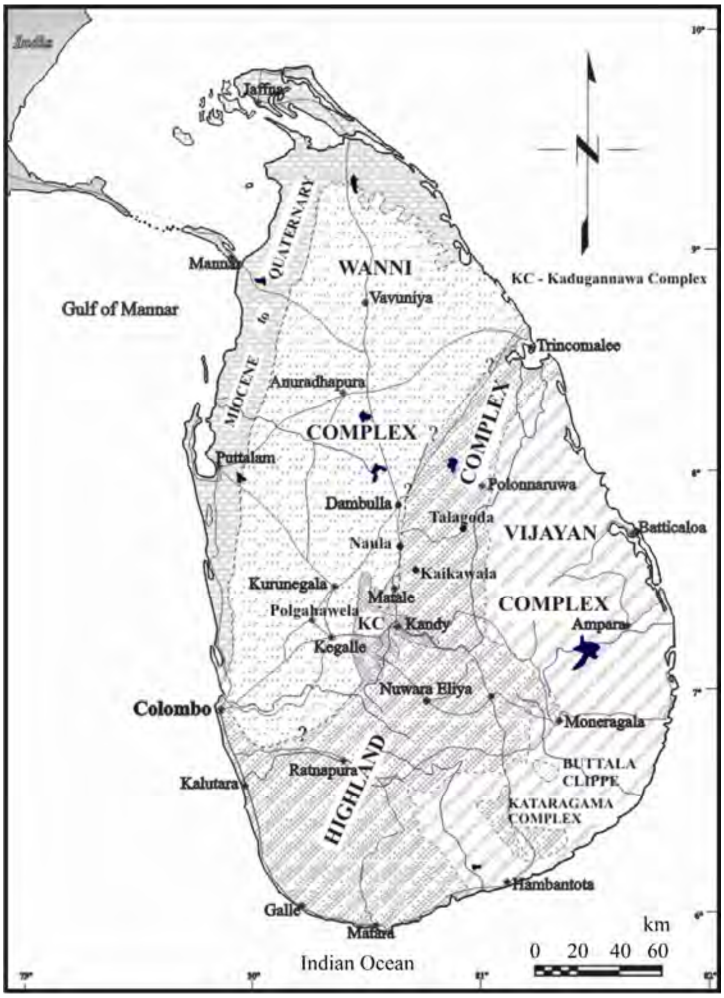


Figure 1. Simplified geological map of Sri Lanka (after Kröner *et al*. [23];Cooray [24]).

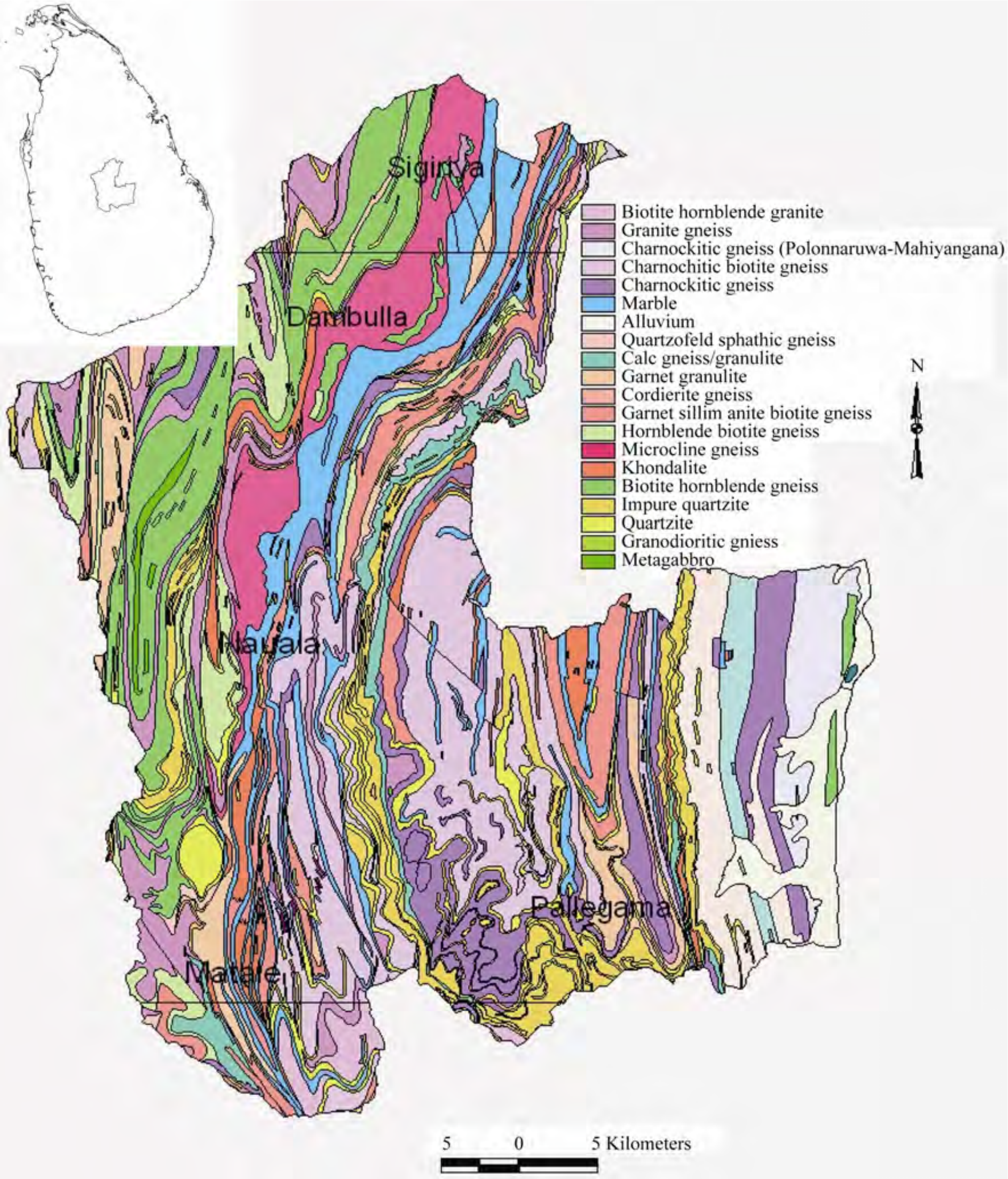


Figure 2. Detailed geological map of the Matale District.

lineaments, joints and fractures, as inferred by aerial photo interpretation and field observations. Two sets of fracture/fault zones are widespread in the area. Northern part is characterized by a NW-SE trending pattern whereas nearly E-W trending brittle fractures are predominant in the southern part around Naula, Nalanda and Kaudupelella (**Figure 3**). Fracture intensity is remarkably high in the middle part around Owala, Kavudupelella towards Nalanda where the pegmatites and hydrothermal deposits are abundant (**Figure 3**). The orientation of the veins is irregular and short vein segments with variable thickness appear. In places the veins for irregular array with net like appearance. These field relations suggest nearly contemporaneous events within a single geological episode.

3.2. Occurrence of Pegmatites and Hydrothermal Deposits

The rock types in the investigated area are characterized

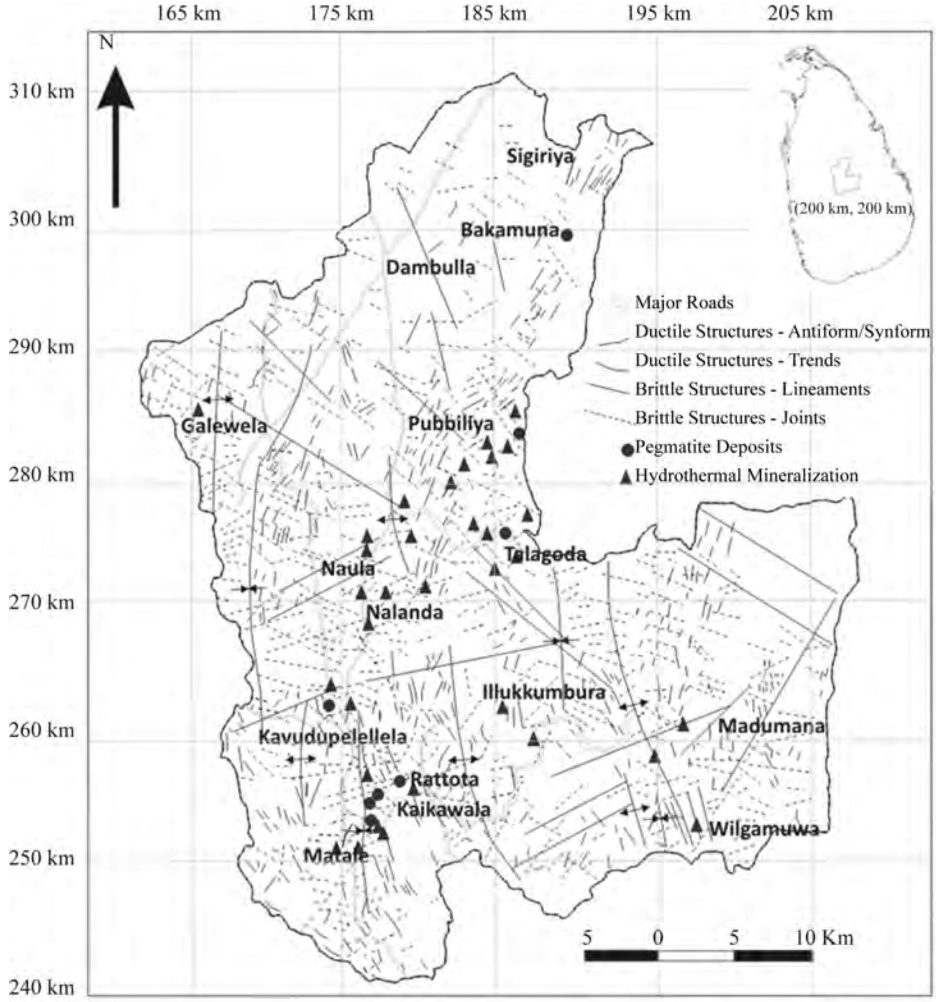


Figure 3. Major structural features of the study area. Note that most of pegmatites and hydrothermal deposits are closely associated with the deformation of basement.

by high-grade metamorphic rocks. They are frequently cut by discordant conspicuous light bands, as shown in **Figures 4** and **5**. The middle of the light bands are invariably constituted by a pegmatitic or aplite vein with a thickness ranging from a few mm to several metres.

Pegmatites in the Matale district can be categorized into two groups. The first group occurs as narrow (1 metre wide) concordant or discordant bodies as dykes, lenses, pods and veins in high-grade metamorphic rocks (**Figure 4**). The composition of these varies widely from felsic to mafic composition and contacts with the country rock are irregular and often gradational. These structural features are interpreted as products of partial melting of high grade rocks.

The second category includes large pegmatitic plutions which are made up of mega crystals of feldspars, quartz and mica (**Figure 5**). Fluorite and topaz are also found in some pegmatites. Mica-, hornblende or tourmaline-rich selvedges are rarely present at the contacts of the pegmatites with HC lithologies. The area contains over 50 individual pegmatite bodies, some of which have been investigated (Pitawala *et al.* [9]). Lateral contacts with country rocks are generally sharp and steep to vertical and some of the larger pegmatites contain deformed country rock.

Field observations imply that these larger pegmatites have been emplaced after the ductile deformation. Based on macroscopic field parameters the pegmatite bodies have been grouped into strongly zoned pegmatites in contrast to the first group of pegmatites. The size of the pegmatites is highly variable upto several hundred square metres in outcrops. They occur as circular, lenticular or rarely oval bodies up to several tens of meters in width and extending up to several hundred meters in strike length. Their modes of occurrence and petrography clearly suggest that they have a magmatic origin.

Hydrothermal processes may have associated with the mineralization of mica and vein quartz deposits. Vein-

Figure 4. Pegmatite associated with metamorphic basement as concordant body near Dambulla.

Figure 5. Formation of feldspar occurring as a hydrothermal deposit with quartz, fluorite and topaz at Kaikawala, Sri Lanka.

type mineral deposits are regionally clustered in a zone of large areas of highly fractured rocks around migmatite diapirs. The individual occurrences of them are located at pockets or small areas of highly fractured rocks with prominent development of cross fracture (Silva [41], Dinalankara [42]). Mica deposits are mainly found as fillings of brittle fractures within the high-grade rocks in the vicinity of pegmatite bodies (**Figure 3**). Fairly large veins of quartz extending to several hundred meters are found in many parts of the Matale District including Rattota, Kavudupelella and Kaikawala (**Figure 3**). Sharp contact zones with the host rocks and their size (surface area of each body covers greater than 200 m^2) clearly indicate their hydrothermal origin (Pitawala *et al.* [9]). Further, field setting of hydrothermal and pegmatite bodies clearly suggest that both formations are syngenetic and associated with brittle structures.

A topaz (Al_2 $(SiO_4)(OH,F)_2$ and fluorite (CaF_2) mineralization zone is located at the Kaikawela and Polwatta Colony at the north of Matale town (Kumarapeli [43]). Topaz and fluorite have probably been formed along with abundant quartz, feldspar and mica mineralization, all of which are believed to form from as a granitic pegmatite (Pitawala *et al.* [9]). Most of the granitic pegmatites in the Matale District, obstruct the general structure of the study area suggesting these pegmatites are structure-controlled and post-date the regional granulite-facies metamorphism.

4. Metamorphic Basement Rocks

Two localities that expose the mafic granulites, and which are widespread within the metamorphic basement of HC were identified as representative samples for this study. All the samples from this locality are appeared as unaltered and suit well for thermobarometric studies. Sampling of metamorphic rocks was done in the entire Matale district. Representative locations of the samples used in this study are shown in the **Figure 6**. Approximately 20 thin sections from metamorphic rocks were investigated by polarizing microscopy and electron microprobe.

4.1. Field Relationships

Mafic granulite exposures found at the *Dambulu Oya* junction (location 1) consist predominantly of fine to medium-grained matrix containing garnet prophyroblasts. The host marble is a white coloured, coarse to medium-grained rock composed of calcite and dolomite. A gradational contact is observed between the host marble and mafic granulite which has a composition of garnet, clinopyroxene (Cpx) and orthopyroxene (Opx)-bearing gneisses. Modal abundance of Cpx is rather high and garnets (Grt) are coarse-grained.

Mafic granulite found at the 34th km post along the

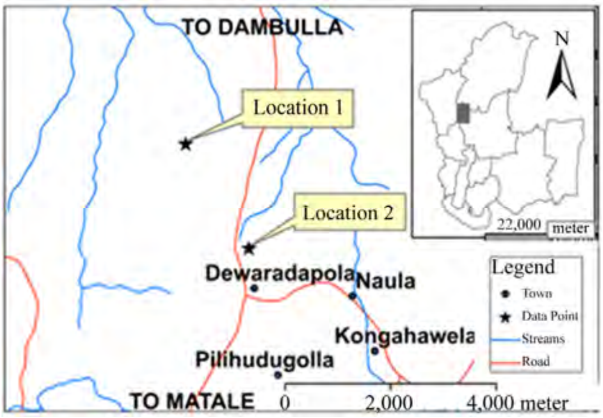


Figure 6. Locations of sampling sites of metamorphic rocks.

Matale-Dambulla road (location 2) occurs as a boudinage body with an average thickness of 1 - 10 m along the strike direction within the marble and gneissic host (**Figure 7(a)** and (**b**)). Garnet-biotite gneisses in a boudinage contain high proportions of biotite usually around garnets (**Figure 7(a)** and **(b)**). Pink coloured garnet biotite gneiss comprising less biotite and k-feldpar as major components surrounds the basic boudinage body. The basic unit appears as an older unit, which found dominantly in the area.

4.2. Mineral Assemblages

Mafic granulites are **d**ark coloured, coarse-grained, homogeneous mafic granulites that consist mainly of Grt (~30%), Opx (~40%), Cpx (~10%), plagioclase (Pl) (~8%) with subordinate ilmenite (Ilm) (~1%) and biotite (Bt) (~3%) (**Table 1**). The mafic granulite is characterized by the Opx + Pl + Grt + Ilm ± Bt (**Figure 8(a)**) and Cpx + Opx + Pl + Grt + Ilm (**Figure 8(b)**). Garnet porphyroblasts are in equilibrium with orthopyroxene and clinopyroxene in the matrix. Ilmenite is more commonly found along the grain boundaries of garnet and pyroxene. Biotite relics are embedded in garnet and are not in equilibrium with other mineral assemblages (**Figure 8(c)**). Plagioclase distributed along the grain boundaries of garnet and Cpx appears to have formed after garnet and Cpx (**Figure 8(b)**).

K-Feldspar rich surrounding gneisses are mainly composed of two feldspars (>90%), garnet (~5% and biotite (~5%) as major constituents (Table 1). Newly formed biotite is in good equilibrium with other mineral phases (**Figure 8(d)**). Most of the K-feldspars appear as undeformed augen shaped lenses at places (**Figures 7(a)** and **(b)**). K-feldspar in perthite appears to be transformed into microcline and sericitisation of plagioclase into mica is a common feature in these rocks.

Marbles in the area are medium to coarse grained rocks that consist of 95 percent of carbonate minerals and forsterite olivine (3 - 4 percent) as a common minor constituent. Occasionally, coarse-grained tremolite, associated with ilmenite and spinel, is embedded in the coarse-grained carbonate host (**Table 1**). Mafic granulites are embedded in a marble host. Mineral assemblages show that there is no mass transfer between the core of the mafic granulites and marble host.

4.3. Mineral Chemistry

Carbon-coated polished thin sections from granulites were used for electron microprobe analyses. A CAMECA SX 50 electron microprobe (EMP) equipped with 4

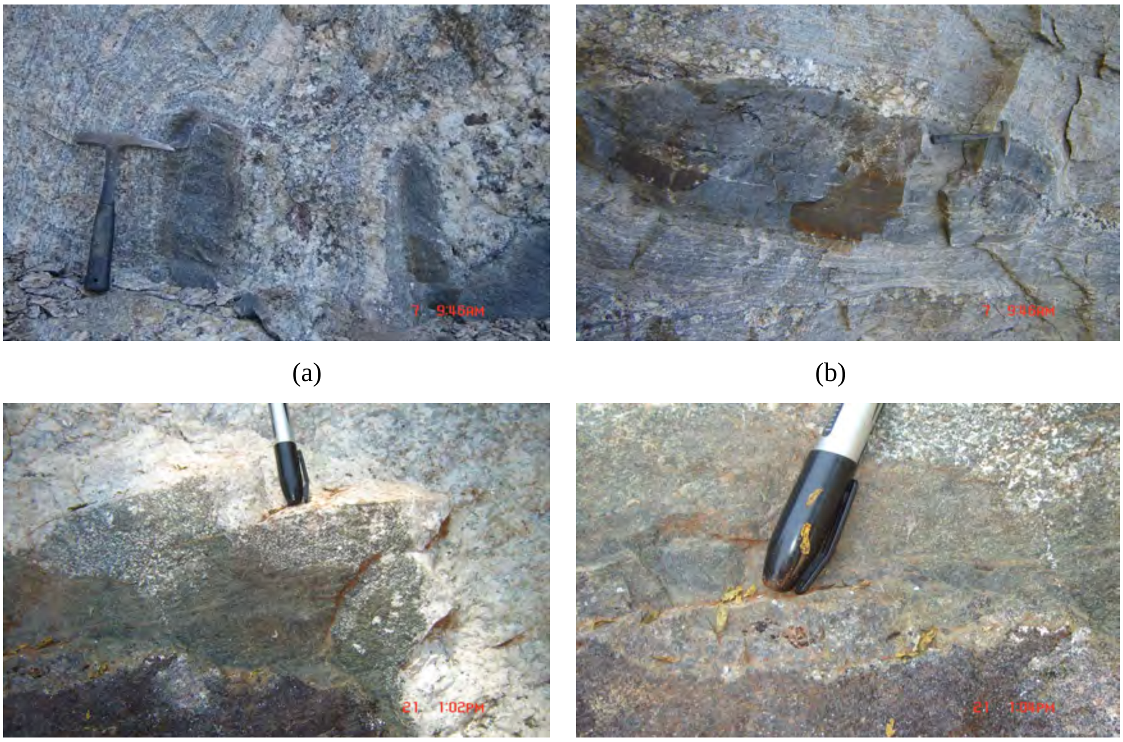
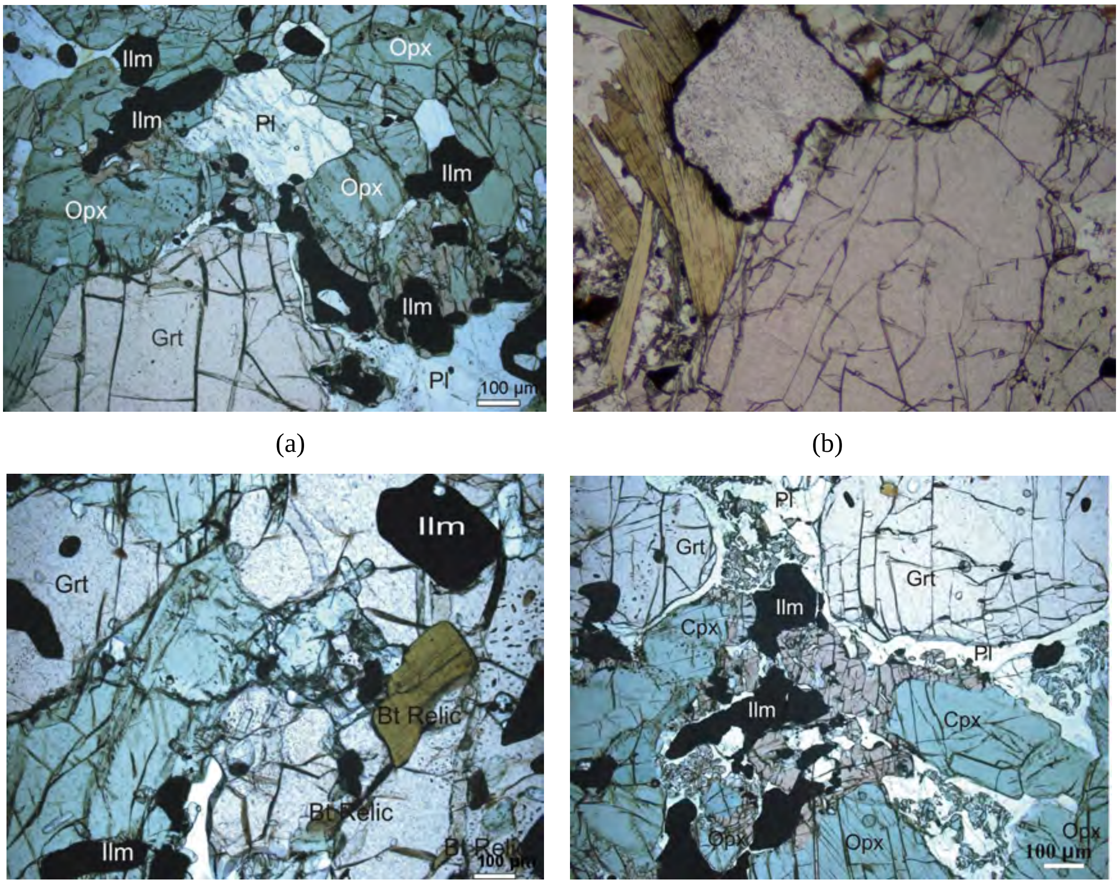

(a) (b)
(c) (d)

Figure 7. (a) (b) Boudinage with mafic granulite in a K-feldspar rich gneissic host. Note that development of augen gneisses at places and coarse grained K-feldspar grains; (c) (d) Boudinage of mafic granulites in a marble host.



(a) (b)

(c) (d)

Figure 8. Photomicrographs of studied rocks from the mafic granulites at Naula in Matale District. (a) Opx + Pl + Grt + Ilm ± Bt (CPL); (b) Cpx + Opx + Pl + Grt + Ilm (CPL); (c): Biotite Relics in mafic granulites (CPL); (d) Grt + Bt + Pl + Kflp (PPL) in surrounding k-feldspar rich gneisses.

Table 1. Mineral assemblages from Mafic Granulites, K-Feldspar-rich gneisses and marble.

Sample	Grt	Ilm	Pl	Opx	Cpx	Bt	Spl	Ol	Cal/Dol	Tre	Kf
Mafic Granulites	x	x	x	x	x	x					
Marble							x	x	x	x	
K-feldspar rich Gneisses	x		x			x					x

spectrometers (LiF-, PET-, TAP and PCO as detector crystals) at the Ruhr-Universität Bochum, Germany was used for the determination of quantitative mineral compositions. An additional EDX detector allowed the full X-ray spectrum to be observed and the identification of all elements with Z > 6 present in concentrations above the limit of detection. Accelerating voltage was set to 15 kV with a beam current of 10 - 15 nA. Peak counting time was fixed to 20 s for quantitative analysis. Sodium bearing phases (e.g. plagioclase, micas) were measured with a defocused beam of 5 µm diameter to minimise signal drifts. Data reduction was performed using the automated PAP correction procedure supplied by CAMECA. Element distribution mapping was carried out using a CAMECA-CAMEBAX microprobe with three wavelength-dispersive spectrometers. A Fortran programme namely RCLC developed by Pattison *et al.* [44] was used to refine the peak temperature and pressure.

Representative electron microprobe analyses of all mineral assemblages are given in **Table 2**.

Garnet analysed is a solid solution of almandine-grossular-pyrope ($Alm_{53.9\ -\ 54.8}$-$Grs_{17.4\ -\ 18.8}$-$Pyr_{24.6\ -\ 26.8}$)

Table 2. Representative Electron Microprobe Analyses of Garnet, Opx, Biotite and Plagioclase in Mafic Granulites.

Mineral	Garnet	Garnet	Garnet	Garnet	Garnet	Garnet	Opx	Opx	Opx	Opx
Sample	**47**	**48**	**51**	**52**	**55**	**56**	**46**	**50**	**53**	**54**
Position	**rim**	**core**	**rim**	**core**	**rim**	**core**	**core**	**rim**	**core**	**rim**
Al_2O_3	21.1	21.2	21	21.2	20.8	20.4	1.73	1.9	2.07	2.24
SiO_2	37.9	38.2	37.9	38.2	37.7	37.5	50.7	50.5	50.3	50.2
CaO	6.74	6.5	6.79	6.41	6.28	6.43	0.65	0.58	0.62	0.61
FeO	28.1	27	28.1	27.3	28.4	28.1	27	26.3	27.9	27
MgO	5.16	6.04	5.34	6.1	5.43	5.73	19	19.2	18.2	18.3
MnO	0.59	0.52	0.55	0.56	0.62	0.55	0.2	0.17	0.17	0.2
Total	99.6	99.5	99.6	99.7	99.2	98.7	99.3	98.7	99.3	98.5
	O = 12	O = 12	O = 12	O = 12	O = 12	O = 12	O = 6	O = 6	O = 6	O = 6
Al	1.96	1.96	1.95	1.96	1.95	1.92	0.08	0.09	0.09	0.1
Si	2.99	3	2.99	3	2.99	2.99	1.95	1.95	1.94	1.94
Ca	0.57	0.55	0.57	0.54	0.53	0.55	0.03	0.02	0.03	0.03
Fe	1.86	1.77	1.86	1.79	1.89	1.87	0.87	0.85	0.9	0.88
Mg	0.61	0.71	0.63	0.71	0.64	0.68	1.09	1.1	1.05	1.05
Mn	0.04	0.03	0.04	0.04	0.04	0.04	0.01	0.01	0.01	0.01
Sum-Cat	8.03	8.02	8.04	8.03	8.04	8.05	4.01	4.01	4.01	4.01

Sample	**Bt L7H 4-1**	**Bt L7H 4-2**	**Bt L7H-4-3**	**Bt L7H-4-4**	**Plag L7D-1-1**	**Plag L7D-1-2**	**Plag L7D-1-3**	**Plag L7D-1-4**
Al_2O_3	14.2	14.4	14.3	14.1	26.7	27.7	24.7	24.9
SiO_2	39.6	39.5	39.7	39.7	58.2	56.8	61	61
CaO	0	0	0.01	0	8.76	10.1	6.68	6.35
FeO	4.67	4.68	4.85	4.88	0.13	0.17	0.19	0.2
TiO_2	3.94	4.27	4.11	3.95				
MgO	22.7	22.9	23.3	23	0.01	0	0	0.01
MnO	0	0.01	0.01	0.01				
BaO	0.64	0.8	0.73	0.73	0	0	0.03	0
Na_2O	0.22	0.26	0.23	0.18	6.68	5.77	7.47	7.63
K_2O	9.73	9.64	9.83	9.61	0.48	0.38	0.7	0.72
F	1.87	1.9	1.91	1.93	_	_	_	_
Cl	0.34	0.36	0.35	0.33	_	_	_	_
Total	97.9	98.7	99.3	98.4	101	101	101	101
	O = 22	O = 22	O = 22	O = 22	O = 32	O = 32	O = 32	O = 32
Al	2.22	2.24	2.22	2.2	5.59	5.83	5.15	5.18
Si	5.27	5.22	5.22	5.26	10.4	10.1	10.8	10.8
Fe	0.52	0.52	0.53	0.54	0.02	0.03	0.03	0.03
Ti	0.39	0.42	0.41	0.39				
Mg	4.5	4.51	4.56	4.54	0	0	0	0
Mn	0	0	0	0				
Ca	0	0	0	0	1.67	1.92	1.27	1.21
Ba	0.03	0.04	0.04	0.04	0	0	0	0
Na	0.06	0.07	0.06	0.05	2.31	2	2.57	2.62
K	1.65	1.63	1.65	1.62	0.11	0.09	0.16	0.16
Sum-Cat	14.6	14.6	14.7	14.6	20	20	20	20
Ab					56.5	49.8	64.3	65.7
An					40.9	48	31.8	30.2
Or					2.7	2.2	4	4.1

mixture. Garnet associated with the othopyroxene is enriched in Mg and Ca.

Othopyroxene has a formula of [$Mg_{1.03}$ $Fe_{0.87}$ $Al_{0.07}$ $Ca_{0.03}$] $Si_{1.9}$ $Al_{0.01}$ O_6. It is noted that garnet coexisting with orthopyroxene has altered its core composition due to possible diffusion of trace elements during the cooling stage (Fernando *et al*.[15]).

Biotite enriched in Fe. X_{Mg} = [Mg/(Mg+ Fe)] of garnet is 0.23 in cores and 0.22 in rims when in contact with biotite. X_{Mg} of garnet is 0.26 - 0.28 in cores and 0.24 - 0.25 in rims when in contact with orthopyroxene. Garnet core and rim compositions suggest its chemical zonation after the equilibrium at the peak metamorphism. Relict biotite in garnet are enriched in Mg with X_{Mg} = 0.89.

Feldspars belong to albite (Ab) – anorthite (An) series and have a composition raining from Ab $_{65.70\text{ - }49.8}$ and An $_{30.2\text{ - }48.0}$.

5. Pressure Temperature Estimates of Metamorphic Basement Rocks

The mineral assemblages of Opx + Pl + Grt + Ilm ± Bt in the mafic granulites at Naula can be represented by the CaO-FeO-MgO-Al_2O_3-TiO_2-SiO_2 system. Coexisting garnet and Opx pairs were used for temperature estimation. In order to estimate maximum equilibrium temperatures, core-core compositions of Grt and Opx were used at 9, 10, 11 and 12 kbars conditions using the solution model of Ganguly *et al.*, 1996. Rim-rim compositions were also used to determine the resetting temperatures in the garnet-orthopyroxene pairs. Temperature estimates from garnet-orthopyroxene thermometry are summarized in **Table 3**. It was observed that the maximum equilibrated temperatures of 830 - 842˚C at 9 kbar were obtained from the core compositions of co-existing Grt and Opx whereas temperatures of 750 - 766˚C at 9 kbar were obtained from the rim-rim compositions. Co-existing Opx-rim and garnet-core were recorded as 814 - 820˚C, which is much higher than the temperature estimates of the co-existing Opx core- and the garnet-rim of 752 - 796˚C. It suggests that compositions of the orthopyroxene have re-equilibrated to a lesser degree altered than the garnet compositions during the cooling stages of the rocks.

Table 3. Peak Metamorphic Temperatures Estimated using Co-existing Garnet and Orthopyroxene Compositions after the Method of Ganguly *et al*. [47].

Opx	Grt	Estimated Temperatures (˚C)			
		9 kbar	**10 kbar**	**11 kbar**	**12 kbar**
Core (46)	Core (48)	842.0	847.7	853.4	859.0
Core(53)	Core(56)	830.1	835.7	841.3	847.0
Core(46)	Rim (47)	752.0	757.2	762.4	767.6
Core (53)	Rim (55)	796.6	802.1	807.5	813.0
Rim (50)	Core (52)	820.7	826.3	831.8	837.4
Rim (54)	Core (56)	814.3	819.8	825.3	830.9
Rim (50)	Rim (51)	750.5	755.7	760.9	766.1
Rim (54)	Rim (55)	781.7	787.1	792.5	797.9

This idea is further supported by the observation of identical temperatures of core opx (46)-rim garnet (47) and rim opx(50)-rim garnet(51) as shown in the Table 3. It is not rather surprising that the diffusion coefficients of orthopyroxene are much less than those of garnet by several magnitudes (Chakraborty and Ganguly[39]).

The results of thermobarometry of current study compare well with the P–T estimates of other areas of the Highland Complex. Schumacher and Faulhaber[32] estimated the P–T conditions of the Eastern, North-eastern and South-eastern part of the Highland Complex at 760 - 830˚C and 9 - 10 kbar. Sandiford *et al*. [30] used Gt–Cpx and Gt–Opx thermometry to illustrate the minimum temperature of metamorphism to be 670 - 730˚C. They noted that the actual peak metamorphism could easily be much higher than these conditions. Kriegsman [45] obtained peak equilibrium temperatures for sapphirine-bearing granulites at 830˚C and 9 kbar using petrogenetic grids. Schenk *et al*.[31] derived a maximum temperature of 900˚C from two-pyroxene thermometry. Voll *et al*.[13] estimated the peak temperatures of metamorphism between 850 - 900˚C using revised two-feldspar thermometry. However, the general observation of the current study is that a significant number of thermobarometry based temperature estimates of granulites determined over past 30 years are too low and are therefore misleading. Many of these estimates are inconsistent with the stability of the mineral assemblages of the rock.

6. Refining the Peak PT Conditions

Table 4 shows the pressure and temperature estimates using co-existing garnet and orthopyroxene compositions incorporating Fe-Mg exchange and Fe-Al exchange of the Grt-Opx. Solution model of Berman [46] with the TWQ software for mineral assemblages mentioned above were used. Pressure-temperature estimates obtained from this method too shows identical values with the previous calculation made using Ganguly *et al*. [47]. However, initial temperature estimates made from the Fe-Mg exchange of the garnet and orthopyroxene (Ganguly and Tazzoli [48]) are significantly different from the temperature estimate corresponding to Fe-Al composition of orthopyroxene. It is not surprising that Al diffusion of

Table 4. Peak Metamorphic Temperatures Estimated using Co-existing Garnet and Orthopyroxene Compositions Uncorrected for Fe-Mg Exchange and Fe-Al Exchange after the Method of Berman [46].

Mineral Pair	Uncorrected Fe-Al		Uncorrected Fe-Mg	
	Temp (˚C)	Pressure (Kbar)	Temp (˚C)	Pressure (Kbar)
Grt core (48) - Opx core (46)	827	11.3	827	11.3
Grt core (56) - Opx core(53)	851	10.7	807	9.8
Grt rim (47) - Opx core(46)	805	11.3	724	9.8
Grt rim(55) - Opx core(53)	863	11.0	786	9.7
Grt core(52) - Opx rim(50)	803	9.7	786	9.5
Grt core(56) - Opx rim(54)	863	11.0	786	9.7
Grt rim(51) - Opx-rim(50)	791	9.9	712	8.6
Grt rim(55) - Opx rim(54)	845	10.4	748	8.8

Table 5. Peak Metamorphic Temperatures Estimated using Co-existing Garnet and Orthopyroxene with due Consideration of Fe-Mg Exchange with the other Phases (Biotite) after the Method of Pattison *et al*. [44].

Mineral Pair	Corrected for Al in orthopyroxene and Fe-Mg bearing minerals	
	Temp (˚C)	Pressure (kbar)
Grt core (48) - Opx core (46)	825	11.3
Grt core (56) - Opx core(53)	870	10.7
Grt rim (47) - Opx core(46)	847	11.5
Grt rim(55) - Opx core(53)	871	10.5
Grt rim(51) - Opx-rim(50)	830	10.0
Grt rim(55) - Opx rim(54)	888	10.6

garnet and orthopyroxene is several magnitudes lower than Fe-Mg diffusion and hence temperature estimates done using the Fe-Al exchange is closer to the real peak metamorphic estimates.

Temperature estimates from Grt-Opx of this study suggests that both garnet and orthopyroxene compositions were reset during the retrograde changes. It is also possible that complete garnet compositions even in the core of the garnet have reset (Fernando *et al*.[15]). Therefore, the temperature estimates based on coexisting core-core compositions of the Grt and Opx do not reflect the peak metamorphic conditions of the area. A method is required to refine the peak temperatures by considering the Fe-Mg exchange between Grt and Opx and the Al- content of the Opx.

The method proposed by Pattison *et al*. [44] may be most useful for thermobarometric calculations because it adjust the Fe-Mg ratios of Grt and Opx according to their modal abundance by incorporating the intergranular and intragranular exchange of Fe-Mg between two phases. In rocks that contain Fe-Mg phases in addition to Grt and Opx, (in this case Bt) are also incorporating their modal abundance into the mass balance equation, and is simultaneously solved for Fe-Mg ratio of each phase, so that each of the Grt-Opx and Grt-Bt are accounted (**Table 5**).

Modal abundances of Fe-Mg phases are used as mentioned under the petrography. RCLC is a Fortran programme developed by Pattison *et al*.[44] to refine the peak temperature and pressure accounting the inter-granular and intra-granular diffusion of Fe-Mg during retrograde conditions. Aluminium component of orthopyroxene was taken into consideration during the estimates as it is obvious that diffusion coefficient of Al in orthopyroxene is less than diffusion coefficients of Fe and Mg in orthopyroxene by several magnitudes (Pattison *et al*, 2003). A model assuming ideal Tschermak exchange [$(\mathrm{Fe,Mg})^{vi}$ +Si^{iv} =Al^{vi}+Al^{iv}] give rise to scheme X_{Al}^{Opx} = (Al/2)/2 (for six-oxygen Opx formula unit)] was used because it gives reasonable and less scattered temperature estimates and less erroneous values than the calculating X_{Al}^{Opx} by the site occupancy method as X_{Al}^{Opx} = Al ^{M1} = Al^{total} – (2-Si) (Pattison *et al*.[44]).

Pressures and temperatures refined from the above method reveal that the mafic granulites experienced granulite facies metamorphism at conditions of 854 ± 44˚C at 10.83 ± 0.86 kbar. It is noteworthy that temperature estimate from garnet-biotite pairs are much less than (~400˚C) temperature estimate from other methods. This suggests that garnet and biotite are not in equilibrium (see also **Figure 4(c)**).

7. Geometry of Veins and Level of Emplacement

Owing to incomplete reactions in the alteration zone, the level of vein emplacement can hardly be constrained by thermo-barometry based on mineral phase equilibria. Most of these veins cluster in the southern part of the Matale district and around Rattota-Kaikawala (**Figure 3**), but are spread over the whole district. The mineralizations are thought to have formed from H_2O-F-dominated cooling hydrothermal fluids (Baatartsogt *et al*. [5]). In the view of K-feldspar in perthite transformed into microcline, sericitisation of plagioclase and newly formed biotite, a broad range of temperatures between 500˚C and 600˚C appears feasible (Parson and Lee[49]). Temperatures near 600˚C must have been reached for a short time at the contact with the intruding pegmatitic melt, with a temperature of at least 650˚C, and hot fluids liberated from the magma upon solidification.

Information on the crustal level can also be achieved from geometric features that reflect brittle failure of the crust. The veins observed in Matale district are mostly straight and approximately plane parallel boundaries, and reveal a high degree of fitting between the opposite walls (**Figure 5**), suggesting that veins formed along the brittle tensile cracks. At a deep crustal level brittle failure requires a high pore fluid pressure. Therefore it is concluded that pegmatite veins formed along hydralulic fractures driven by the pressure of the hydrous melts. In places the veins occur as sets of different orientations without uniform crosscutting relations, suggesting a nearly contemporaneous timing of the different propagation events. The shape of pegmatite bodies as a function of crustal depth, regional stress field and rock anisotropy has been discussed by Brisbin [1]. A tabular shape and preferred orientations are proposed to indicate the emplacement along dilatants fractures in the brittle upper crust, while more irregular shapes may reflect emplacement beneath the brittle-ductile transition zone.

The vast majority of pegmatites in the study area, however, consist almost exclusively of quartz and feldspars and lack of exotic minerals, and hydrothermal alteration envelopes. Where there are minerals other than quartz and feldspar (e.g. topaz, tourmaline and fluorite), the commonly cited fluxing components in pegmatite magmas are H_2O, B, and F. As fluxes, they lower the melting and crystallization temperatures (e.g., London, 1997 [50]), and they enhance miscibility among otherwise less soluble constituents.

Based on these considerations, it is concluded that the level of emplacement of pegmatites of the Matale District is middle crust, near the crustal scale brittle-ductile transition zone at a temperature of about 600˚C and even lower, whenever the H_2O, B, and F rich fluxes are incorporated. For this crustal level and temperature range, it is considered very unlikely that intruding pegmatitic melts followed pre-existing cracks. This suggests that the emplacement temperatures of the pegmatites are well below the peak metamorphic estimates of 854 ± 44˚C at 10.83 ± 0.86 kbars in the mafic granulites.

8. Revisiting the P-T-t Path of Sri Lankan Crust

This study assesses temperatures of formation of mafic granulites by combining experimental constraints on the PT stability on the granulite facies mineral associations with a garnet-orthopyroxene thermometry scheme based on Al-solubility of orthopyroxene corrected for the late Fe-Mg Exchange. Mass balance method along with modal abundance of Fe-Mg bearing minerals was used to assess the Fe-Mg exchange among minerals present in the rocks. It accounted for corrections not only for late Fe-Mg exchange but also Al diffusion of orthopyroxene.

From the detailed petrographic and mineralogical data of the mafic granulites in the Matale district, we inferred peak metamorphic conditions of the crustal unit belonging to Matale district as 854 ± 44˚C at 10.83 ± 0.86 kbar. Hydrothermal veins consisting quartz and mica are closely related to cross-cutting pegmatites, which significantly post-date the peak metamorphic conditions of the crustal unit. Development of brittle structures of the pegmatites and other hydrothermal deposits appears to be concurrent with the brittle deformation of the area.

The metamorphic P-T strategy and post-metamorphic structural history inferred from this area is summarized in the modified version after P-T-t-D diagrams after Kriegsman [45] (**Figure 9**). The P-T strategy made here is based on the combination of P-T conditions estimated in this study and direct evidences obtained from structural settings of the Matale district.

9. Conclusions

The Earth's crust thins during extensional tectonics, leading to exhumation and decompression of deep- and mid-crustal rocks. Due to the strong difference in compressibility between rocks and fluid, pore fluid becomes over-pressured during this decompression. If pressure re-equilibration is achieved by draining of excess fluid, significant volumes of fluid can be produced. We thus present a new model to explain the derivation of hydrothermal fluids from the middle and upper crust of the metamorphic basement of Sri Lanka.

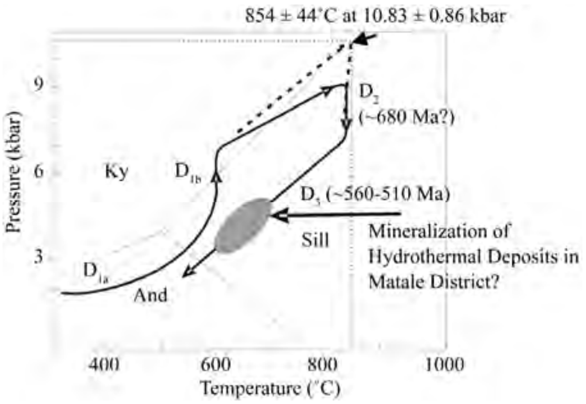


Figure 9. P-T-t-D path for the granulites of the Highland Complex in Sri Lanka (after Kreigsman, 1993). The prograde path is characterized by crustal thickening (D_1), and subsequent heating, while the retrograde path shows early isothermal decompression (D_2), followed by isobaric cooling and late cooling and thrusting (D_3). P-T-t-D diagram after Kreigsman [45] was modified after incorporated the new PT data from this study. Mineralization of Matale district may be depicted after all of major deformational events.

The unique outcrops of mafic granulites and associated pegmatites and hydrothermal mineralization of the central highlands found in the Matale District, Sri Lanka yield insight into a high temperature metamorphism followed by magma driven mineralization. A detailed field, structural and petrographical study reveals that the crustal unit of the central highlands had metamorphosed at 854 ± 44˚C at 10.83 ± 0.86 kbar under granulite facies conditions. The pegmatitic veins are interpreted to represent hydraulic fractures driven by volatile-rich melt with minimum temperature of 600˚C, emplaced in a middle crust near the brittle-ductile transition zone. Hydrothermally derived pegmatite dikes are largely undeformed and reveal a coarse-grained matrix devoid of any obvious preferred orientation and compatible with conditions in the mid crustal levels with low geologic strain rates. Hydrothermal veins associated with pegmatites are also emplaced at a shallower crustal level and within a cooler country rock as a brittle event. Mineralization of pegmatites in Matale District was attributed to occur in the late event after the D_3 deformations of Berger and Jayasinghe [40].

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