EMPA DATING OF MONAZITE FROM HIGH GRADE METAMORPHIC ROCKS
ALONG THE HIGHLAND- VIJAYAN BOUNDARY ZONE, SRI LANKA.

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Abstract

Sri Lanka, a small-scale aggregate of contrasting crustal domains, has been the focus of lower crustal research for the past two decades. The timing of high-grade granulite metamorphism in the central Highland Complex (HC) of Sri Lanka is well-constrained at 570-550 Ma (Kroner et al., 1994; Sajeev et al., 2010). Amphibolite facies metamorphism of the adjacent Vijayan Complex (VC) to the east is less well constrained but apparently somewhat younger (Holzl et al., 1994). Additionally, the timing and nature of juxtaposition (via thrusting) of the HC above the VC is uncertain. The contact between the HC and VC, characterized by strong deformation, exotic tectonic slivers, migmatites, local serpentinite bodies, magnetite deposits, and gold mineralization is a major suture separating the Paleoproterozoic HC from the Grenville-age VC.

21 oriented samples were collected within and near (<6 km) the HC-VC boundary zone. West of the boundary (granulite terrain), coarse garnet-sillimanite-graphite gneiss with 5 mm euhedral inclusion-rich garnets are locally sheared with garnet elongate in the foliation plane. Within the boundary zone, garnet-(amphibole)-biotite gneisses exhibit a strong mesoscopic fabric consisting of ribbon quartz and compositional layering. Microscopically, static annealing is prevalent. East of the HC-VC deformation zone, coarse plagioclase-biotite orthogneisses exhibit compositional banding, augen, and incipient migmatization.
EMPA *in-situ* spot-dating of monazite grains record timing of peak and retrograde metamorphism of HC rocks. Thirty spot ages from eight monazite grains from the HC reveals a dominance of Pan African ages (533-613 Ma), and minor Paleoproterozoic and Mesoproterozoic ages (1069-1872 Ma). The qualitative monazite textural descriptions suggest that the age data are a function of chemical domains formed during and/or re-absorption of monazite. The average age for higher Y concentrations (>4000 ppm) is 558 Ma and 572 Ma age for lower Y concentrations (<4000 ppm). These ages consistent with a regionally widespread peak metamorphic age of 570 Ma for HC followed by retrograde metamorphism during exhumation at about 555-545 Ma (Sajeev et al., 2010).

Forty spot ages from seven monazite grains from the Boundary Zone preserved a dominance of Pan African spot ages between 595 and 635 Ma. Also, Paleoproterozoic spot ages (1858-1868 Ma) and Mesoproterozoic spot ages (1255-1350 Ma) are preserved in Boundary Zone rocks. Pre Pan African Neoproterozoic ages (700-1000 Ma) recorded from the Boundary Zone are absent in HC rocks analyzed here.

The Boundary Zone age data suggest shearing of HC rocks at moderate P-T conditions at 595-635 Ma and may therefore date the initial juxtaposition of the HC and VC terranes. The crustal thickening during and after the juxtaposition may have ultimately led to the peak metamorphism of Highland Complex at 570 Ma. Peak metamorphism was followed closely by rapid exhumation of the HC rocks beginning at 558 Ma in the east and 551 Ma in the western HC terrane.
Introduction

Sri Lanka, a nation island located in the northern Indian Ocean, consists of Proterozoic crust which has undergone a polyphase deformational history extending through Pan-African time. Kroner et al. (1991) summarized the tectono-metamorphic evolution of the Sri Lankan basement in terms of a Pan-African continental collision between West Gondwana (Africa, South America) and East Gondwana (largely India, Antarctica). Pan-African high grade metamorphism in eastern and southern Africa, India, Madagascar, Sri Lanka, Arabia and Antarctica occurred from ca. 800 Ma to 470 Ma indicating a long-lived period of assembly of Gondwana. Sri Lanka is included within the Mozambique Belt in eastern Africa which marks the Pan African suture where West Gondwana and East Gondwana collided. Therefore, Sri Lanka forms a small yet very important terrane that can shed light on the formation of Gondwana at the end of the Proterozoic.

The bulk of Sri Lanka (>90%) consists of Proterozoic high to medium grade rocks subdivided into high grade granulite and medium grade amphibolite to granulite facies rocks (Kroner et al., 1991). The topographically higher central part of Sri Lanka consists of ultrahigh temperature granulites whereas the low land consists of medium grade metamorphic rocks. A thrust boundary zone separates these different lithological units. The lithological, petrographical and geochemical equivalents of Sri Lankan terranes have been identified in east Antarctica (Yoshida et al., 1990).
Geology of Sri Lanka

The Sri Lankan high-grade Precambrian basement has been divided into three main lithotectonic units: the central Highland Complex (HC), eastern Vijayan Complex (VC), and western Wanni Complex (WC); (Cooray, 1994) (Fig. 1.1). Highland Complex rocks have undergone high grade granulite metamorphism whereas Vijayan and Wanni Complexes have undergone medium grade amphibolite to granulite facies metamorphism.

Fig. 1.1 Map of Sri Lanka showing boundaries of the crustal units delineated on the basis of Nd model ages (modified after Mathavan et al., 1998).
The Highland Complex is comprised of approximately equal proportions of para and ortho gneisses (Kroner et al., 1991). Quartzites, garnet-sillimanite-biotite gneisses (metapelites) and marbles are some of the major metasedimentary lithological units in Highland Complex and charnockite gneisses and granitic gneisses make up the major metagneous lithological units. The Highland Complex is flanked to the west and northwest by the Wanni Complex, which is dominated by amphibolite to granulite facies gneisses of mainly granitic composition with only minor supracrustal intercalations of granulite grade units. To the east and southeast, Highland Complex assemblages are in tectonic contact with amphibolite grade orthogneisses of the Vijayan Complex (Kroner et al., 1991). Essentially, the Vijayan Complex consists of microcline-bearing granitic gneisses, hornblende-biotite gneisses, migmatites and minor quartzite and calc-silicate rocks (Cooray, 1994). Metagneous rocks in the Vijayan Complex vary in composition from leucogranites to tonalite. A pronounced tectonic boundary separates the HC and VC (Fig 1.1; Fig. 1.2) with strong evidence for thrusting events whereas there is no definite structural boundary defined between HC and WC. In southernmost Sri Lanka, tectonic inliers of Highland Complex rocks are infolded within the Vijayan Complex. For instance, the Kataragama Klippe is characterized by granulite-facies rocks within the Vijayan Complex (Cooray, 1994). Nd model ages of the HC are greater than 2.2 Ga and older than Nd model ages of the

**Fig.1.2** Cross section from SW towards NE of Sri Lanka across the thrust boundary (A-A’ in Figure 1.1). Highland Complex thrust over Vijayan Complex resulting in numerous folds and deformation (Kleinschrodt, 1994).

**Location of Sri Lanka within Gondwana**

It is important to correlate the three Proterozoic lithotectonic terranes of Sri Lanka, and their boundaries, with surrounding Gondwana fragments preserved today as parts of other landmasses. There is a strong geological affinity among rocks making up
Sri Lanka, South India, and east Antarctica as implied in Gondwana reconstructions (Fig. 1.3) although the implicit equivalences of terrane juxtaposition have not all been demonstrated.

Fig.1.3 Gondwana assembly reconstruction showing location of Pan African events (after Grunow et al., 1996). Pan African Belt: B, Brasiliano; DF, Dom Feliciano; D, Damra; G, Gariep Belt; K, Kaoko Belt; L, Luffilian Belt; LH, Lutzo Holm Bay; MD, Madagascar; Y, Yamato Mountains; R, Ross Orogeny; S, Saldanial Belt; SH, Shackleton Range; SL, Sri Lanka; SR, Sor Rondane Mountains; Z, Zambezi Belt; QML, Queen Maud Land.
In Sri Lanka, the VC was either a separate arc complex or micro continent, perhaps connected with the similarly composed Yamato-Belgica Complex (YBC) in east Antarctica (Yoshida et al., 1990). In particular, more recent studies of basement geology in Sri Lanka and Antarctica appear to indicate that the HC and the Lutzow-Holm Complex (LHC) in east Antarctica are contiguous in the reconstruction of Gondwana (Shiraishi et al., 1994) (Fig. 1.4), but this has not yet been supported geochronologically.

![Fig. 1.4 Correlation of metamorphic complexes between Antarctica and Sri Lanka. LH, Lutzow Holm Complex, YB, Yamato Belgica Complex; N, Napier Complex; R, Rayner Complex; A, Africa; M, Madagascar; K, Kerala Khondolite Belt; V, Vijayan Complex; H, Highland Complex; W, Wanni Complex (Shiraishi et al., 1994).](image-url)
Age dating results suggest that high-grade metamorphism in the LHC took place at ca. 550-520 Ma. Ion microprobe U-Pb dating of zircon from LHC and YBC in east Antarctica has shown that high-grade regional metamorphism and associated folding occurred between 521 ± 9 and 553 ± 6 Ma (Shiraishi et al., 1994). Related zircon data further suggest that the maximum depositional age of the LHC is analogous to that of the HC in Sri Lanka (~2900-1500 Ma). Recent isotopic data suggests that the age of high grade metamorphism in southern Madagascar is c.550 Ma (Kroner et al., 1996).

The amalgamation of the three terranes making up Sri Lanka today occurred during the assembly of the Gondwana supercontinent (Mathavan et al., 1998). It has been proposed that the rocks making up the WC and HC originally belonged to Africa/Madagascar and equivalent to high-grade gneisses of Mozambique, Tanzania, and southeastern Madagascar.

**Deformational histories and structures**

Polyphase ductile deformation has been recognized in all three lithotectonic terranes of Sri Lanka (Berger and Jayasinghe, 1976; Voll and Kleinschrodt, 1991) (Fig. 1.5 a). However, the deformational history of the better exposed Highland Complex is well constrained in comparison to that of VC or WC. Four deformation events have been identified (D1-D4) in the HC by Yoshida et al. (1990), Kleinschrodt et al. (1991), Kriegsman (1991), and Kleinschrodt (1994). In the Highland Complex, D1 resulted in a prominent flattening foliation (S1) and stretching lineation L1 (Voll and Kleinschrodt,
1991). Small rootless folds (F1) in metasediments and isoclinal folds in many basic dykes were produced during D1. D2 produced both small-scale and large-scale isoclinal folds (F2) with hinge lines parallel to L1 (Voll and Kleinschrodt, 1991). D2 also produced a local stretching lineation L2 which is subparallel to L1 and a flattening foliation (S2) which is parallel to S0 and S1 and boudinage. Granulite grade metamorphism occurred during both D1 and D2 (Yoshida et al., 1990b; Voll and Kleinschrodt, 1991).

In the Vijayan Complex, the events corresponding to D2 and D3 have been recorded (Kriegsman, 1991b). These deformations folded the Vijayan Complex (VC) rocks into N-S trending isoclinal folds and upright folds successively. Both HC and VC have been refolded during the D3 deformation indicating their juxtaposition (Fig. 1.5 a and b).
Fig. 1.5a Sampling locations in and around the HC-VC major thrust boundary zone, Sri Lanka (After Geological Survey and Mines Bureau, Sri Lanka, 1997, 2001).

Legend:
- **Highly folded intercalated para-ortho gneisses (HC)**
- **Gently folded ortho gneisses (VC)**
Fig. 1.5b Sampling locations in and around the HC-VC major thrust boundary zone, Sri Lanka (After Geological Survey and Mines Bureau, Sri Lanka, 1997, 2001).
Fig. 1.5c Sampling locations in HC, major shear zones within the thrust boundary zone, Sri Lanka. Blue: Marble, Yellow: Quartzite, Orange: Quartzofeldspathic gneiss, Pink: Granitic gneiss, Green: Hornblende-biotite gneiss, Red: Garnet-biotite gneiss, Purple: Charnockitic gneiss, Pink with dots: Migmatites. See inset map of Figure 1.5 a (After Geological Survey and Mines Bureau, Sri Lanka, 1997, 2001).
The thrust boundary between HC and VC is a tectonic contact with strong shearing and high strain (Kleinschrodt, 1994). Granulite grade HC rocks were thrust over the amphibolite grade VC along a deep crustal, gently west dipping thrust surface (Fig 1.2). The thrust contact has been folded into open to gentle folds which are superimposed on preexisting structures in the HC and VC (Kleinschrodt, 1992). The orientation of fold hinges is parallel to the strong stretching lineation in the border zone and oriented in a N-S direction (Kleinschrodt, 1994). The E-W stretching lineation in the VC (Kriegsman, 1995; Kleinschrodt, 1994, 1996; Kehelpannala, 2003) and the L2 lineation in HC have been reoriented near the HC-VC thrust contact. The different orientations of stretching lineation show that the two complexes (Highland Complex and Vijayan Complex) have different deformational histories. The folding of the thrust boundary postdates peak metamorphism (Kehelpannala, 2003). The folds might have formed during a younger D4 stage of deformation. The granulite inliers within the VC are interpreted as relict klippe (Silva et al., 1980) of HC rocks which underwent partial melting and migmatization (Mathavan et al., 1998). Continued collision subsequently folded the thrust zone forming open, plunging, upright folds still under amphibolite grade conditions (Kleinschrodt, 1994, 1996). Small scale ductile shear zones observed in the VC could be related to HC-VC major thrusting event.
Metamorphic pressure-temperature evolution

The thermo-tectonic pressure-temperature evolution of Sri Lankan Precambrian rocks is well-documented. It has been shown that peak metamorphic temperatures range from 700 to 900 °C in the eastern parts of the Highland Complex, while pressures ranged from over 9 kbar in the eastern and southeastern parts to 5 kbar in the western part. These data underscore the existence of regional gradients in temperature and pressure (Faulhaber and Raith, 1991; Schumacher and Faulhaber, 1994; and Raase and Schenk, 1994), which can be correlated also with regional differences in structural level. The regional granulite-facies metamorphism of the WC occurred at 3.5-7.5 kbar and 600-900 °C (Schenk et al., 1991; Schumacher et al., 1990; Schumacher and Faulhaber, 1994; and Raase and Schenk, 1994). There is no evidence for prograde granulite metamorphism in the WC rocks or the rocks in the northwest portion of the HC (Hiroi et al., 1992). This suggests that the two units, HC and WC were amalgamated during the very last stage of the prograde metamorphism of the HC, perhaps during decompression and heating (Hiroi et al., 1992). However, the P-T conditions for this amphibolite-facies metamorphism in the VC are not yet constrained (Kehelpannala, 1997).

P-T evolution of the HC has been reconstructed using mineral reaction textures in garnet-bearing metabasite and metapelites (Schenk et al., 1991). The high-pressure assemblage in metabasic rocks, garnet + clinopyroxene + quartz, is restricted to the southeastern and eastern part of the HC. In contrast, the western and northwestern parts
of the HC reflect lower metamorphic pressures where the metabasic rocks containing ortho pyroxene + plagioclase + garnet or garnet + clinopyroxene + plagioclase (both without quartz) are present. Petrologic studies of pelitic granulites reveal that much of the HC evolved along a clockwise P-T path at medium to high pressure and high temperature conditions (Hiroi et al., 1994; Raase and Schenk, 1994). Initial thermobarometry data indicate peak P-T conditions of ~12 kbar and c.1100 °C. After peak metamorphism, four different stages can be explained as follows. The assemblage garnet- sapphireine –quartz likely represents initial isobaric cooling; the presence of symplectite suggests isothermal decompression at ultrahigh temperatures; biotite represents further isobaric cooling and orthopyroxene rims on biotite may represent a second isothermal decompression (Sajeev and Osanai, 2004).

The highest grade of metamorphism is recorded from ultrahigh-temperature granulites near Kandy, in the central Highland Complex. Here temperatures reached ~1050 °C at a pressure of c. 0.9 GPa (Sajeev et al., 2010). A multistage P-T history is indicated by the appearance of Mg and Al rich granulites following ultrahigh temperature metamorphic conditions. The HC contains mafic granulites, Mg and Al pelitic granulites and aluminous quartzofeldspathic granulites. These granulites contain a near peak assemblage of sapphireine-garnet-orthopyroxene-sillimanite-quartz-feldspar.

VC rocks are typically felsic, amphibolite facies orthogneisses containing hornblende ± biotite. In the southeast, at the border between the HC and the VC, a sudden change in P-T conditions is evident, which may reflect either differential crustal
uplift of the HC and VC or overthrusting of the southeastern HC assemblages atop the VC (Schenk et al., 1991).

A proposed correlation of metamorphic complexes among Gondwana fragments is suggested based on regional distribution of minerals (Kato et al., 2010). The ultrahigh temperature granulites in HC and high grade metamorphic terrain in Lutzow Holm Complex in east Antarctica were derived from Gondwana supercontinent. It is considered that the HC in Sri Lanka collided with the Lutzow Holm Complex during the Gondwana time period. Peak granulite metamorphism likely took place in both complexes during Pan African metamorphism.

**HC-VC thrust boundary**

The Highland Complex- Vijayan complex thrust boundary is the major lithotectonic boundary which represents the Gondwana suture in Sri Lanka (Kroner et al., 1991) (Fig 1.3; Fig. 1.4). The boundary separates granulite grade HC rocks from the amphibolite grade VC rocks (Fig 1.5 a). This thrust zone was first suggested as the boundary between HC and VC based on the existence of a large gravity anomaly over the area (Hatherton et al., 1975).

A number of geologic features suggest that the boundary is an important tectonic contact. An abundance of serpentinite bodies near the southeastern part of the country likely represent ultramafic tectonic slivers caught up along the thrust boundary (Munasinghe and Dissanayake, 1982) (Fig. 1.6). Gold mineralization, magnetite
deposits, corundum deposits, and calcite deposits all indicate major mineralization along the thrust boundary. Hot water springs (35–65°C) are preferentially located along the boundary and provide a source of geothermal energy (www.srilankatrekking.com, 15th January, 2010). The longest river in Sri Lanka, the Mahawelli flows along a major fault towards the northeastern part of Sri Lanka from the central highlands which ends at Trincomalee Canyon.

Fig.1.6 A. Photograph looking east of serpentinite body along the HC-VC thrust boundary, southeastern part of Sri Lanka. B. Photograph of hot water springs recreation area, southeastern part of Sri Lanka (photo credit: Dr. Nalaka Ranaasinghe).

Kleinschrodt (1994) explained that the thrust boundary is characterized by very strong deformation and evidence for partial melting and migmatization under the granulite facies conditions just prior to the thrusting. Retrogression under amphibolite grade during thrusting is supported by hornblende and biotite replacement of syn-kinematic garnets (Kleinschrodt, 1994). The age for the juxtaposition between HC-VC has not been resolved.
Continuation of Sri Lankan Highland-Vijayan boundary in other localities

The HC-VC thrust boundary has been interpreted to continue into other localities in the world (Fig 1.3). A collisional tectonic relationship similar to that between the VC and HC boundary has been proposed for the LHC and YBC complexes based on the mode of occurrence and chemistries of basic and ultrabasic rocks in the LHC (Hiroi et al., 1991) (Fig. 1.4). It is explained that both HC in Sri Lanka and LHC in east Antarctica formed as a result of accretion-collision tectonics between east and west Gondwana (Shiraishi et al., 1994). Further, occurrences of graphite and other commercial mineral deposits in the HC of Sri Lanka correlate with those of the Kerala Khondolite Belt, India, and southeastern Madagascar. Thus, Sri Lanka appears to have represented a bridging landmass between East African and Antarctica crustal fragments during Gondwana time (Dissanayake and Chandrajith, 1998).

Previous Geochronology of Sri Lanka

The deep crustal bedrock of Sri Lanka has been the focus of abundant geochronologic research over the past two decades. The results reveal widespread Pan African high grade metamorphism of Proterozoic terranes of varying ages (Table 1). Precursor sediments of the Highland Complex were deposited at ca. 2 Ga or earlier (Kroner et al., 1987, 1991; Holzl et al., 1991, 1994). An ion-microprobe (SHRIMP) U-Pb study on zircons by Kroner et al. (1987) initially documented late Archean to
Paleoproterozoic ages (3.2-2.4 Ga) for detrital grains from the HC, and Millisenda et al. (1988) also reported Nd model ages of 3.0-2.2 Ga. De Maesschalck et al. (1990) inferred an Rb-Sr whole-rock isochron age of 1930 ± 130 Ma for granulites from the Kataragama Klippe, which lithologically resemble rocks from the HC. In contrast, both the VC and WC are apparently younger than the HC according to U-Pb zircon and Nd crustal-residence ages (Table 1).

Table 1: Summary of Proterozoic- Cambrian crust formation and metamorphic events in Sri Lanka (modified after Shiraishi et al., 1994 & Kroner et al., 2003)

<table>
<thead>
<tr>
<th>Event</th>
<th>Wanni Complex (WC)</th>
<th>Highland Complex (HC)</th>
<th>Vijayan Complex (VC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial crustal formation</td>
<td>1-2 Ga</td>
<td>2-3 Ga</td>
<td>1.0-1.8 Ga</td>
</tr>
<tr>
<td>Depositional or emplacement</td>
<td>750-1080 Ma Plutonism</td>
<td>650-1942 Ma magmatic emplacement</td>
<td>~1100 -1000 Ma Plutonism</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>~530-610 Ma Charnockitisation &amp; amphibolite to granulite facies</td>
<td>~550-610 Ma Granulite facies Metamorphism, Folding, Charnockitisation</td>
<td>~456-591 Ma Amphibolite</td>
</tr>
</tbody>
</table>

A relatively late, small-scale process of in-situ charnockitization was studied in detail by Burton and O’Nions (1990b) on samples from quarries near Kurunagala (WC). They obtained small-scale Rb-Sr and Sm-Nd whole-rock ages of ca. 535 Ma for samples from an amphibolite-granulite transition-zone, as well as Sm-Nd, Pb-Pb, and Rb-Sr mineral ages ranging from 524 to 486 Ma which they interpreted as cooling ages. Baur et
al. (1991) reported U-Pb zircon crystallization ages of ca. 1940, 770, and 660 Ma for rocks from both the HC and WC. All of their samples showed indications of severe Pb loss at \(~560-550\) Ma, and these workers estimated the timing of high-grade metamorphism as ca. 660-550 Ma. Granulite-facies metamorphism was initially documented at \(~650\) Ma in the HC and at \(~550\) Ma in the WC (Kroner and Williams, 1994; Holzl et al., 1991, 1994; Kroner et al., 1994). Therefore, it is suggested that these two terranes underwent granulite-facies metamorphism prior to their amalgamation. In contrast, amphibolite-grade metamorphism in the VC occurred at 465-558 Ma (Kroner and Williams, 1993).

In combination, the high-grade regional metamorphism of the HC, VC, and WC took place between 455 and 610 Ma (Cooray, 1994). Based on lithology, geochemistry, structure, and metamorphic history, the HC, WC, and VC represent three discrete Proterozoic crustal units that were amalgamated by convergent tectonism and metamorphism during latest Neoproterozoic time.

It is exciting to see newly documented zircon and monazite ages by Sajeev et al. (2010) from quartz-saturated granulites in central highlands, Sri Lanka using the high-resolution ion microprobe technique. They reveal detrital zircon cores with dates of ca. 2.5-0.83 Ga. Contrasting Th/U record indicates two different ages of zircon growth at \(569 \pm 5\) and \(551 \pm 7\) Ma and monazite growth at \(547 \pm 7\) Ma. The zircon age of 570 Ma is interpreted to indicate partial melting prior to peak metamorphism and the ca. 550 Ma zircon and monazite ages to indicate post-peak isothermal decompression (Sajeev et al., 2010).
In summary, the available geochronology of Sri Lanka reveals that several hundred million years elapsed between the formation of Precambrian rocks of the VC, WC, and HC and their Pan-African high-grade metamorphism at 500-600 Ma. Protracted collision subsequently folded the Highland Complex-Vijayan Complex thrust zone forming open, upright folds under amphibolite facies conditions (Kleinschroft, 1994, 1996). Late in situ formation of charnockites, and metasomatism and retrogression of some orthogneisses along the contact could have been happened during the thrusting event. Late pegmatites are likely post collisional since they are not deformed.
Petrographic Characterization

The Highland Complex -Vijayan Complex boundary extends NNE for 600 km across Sri Lanka (Fig 1.1). Over thrusting of a warm VC crust which contains mainly hydrous mineral assemblages might have resulted in abundant silica poor, pegmatitic, syenites with both biotite and hornblende in a broad contact zone between HV-VC thrust boundary. The contact is a wide deformation zone representing a thrust contact between the HC and VC.

Samples were collected from localities near (< 6 km) the boundary zone and from within the mapped zone itself (Fig 1.5 a, b and c; see Appendix). Lithologies with good potential for monazite were targeted. Metamorphosed pelitic rocks containing garnets are very good candidates. Although the metapelites are common in HC there are also some occurrences at the major litho-tectonic boundaries in Sri Lanka (Raase and Schenk, 1994). The complexities of finding the appropriate outcrops and poor accessibility to the locations limited the number of samples. The remoteness of the study area, intense vegetation, high degree of weathering, and lack of detailed geologic maps made sampling a challenge. In the summers of 2009 and 2010 I collected 21 samples in southern and central Sri Lanka. Two professors from the University of Peradeniya, friends, and a couple of workers from the Geological Survey and Mines Bureau (GSMB) assisted me during my sampling phase. The GSMB provided a drilling machine since sampling at some localities was impossible with only hammers and chisels (Figure 1.7). Some of the
localities are inaccessible because of active mining; charnockitic gneisses are mined today extensively for building industry. In central Sri Lanka, sampling was very limited because of the prevailing war situation in the country which ended late 2010. I took photographs of every locality and strike-dip measurements for oriented samples (Fig 1.7).
Five oriented samples from VC, five oriented samples from the HC-VC thrust boundary and eleven oriented samples from HC were collected. The collected samples include sheared garnet-biotite gneiss, charnockitic gneiss, hornblende-biotite gneiss, and quartzofeldspathic gneiss. Migmatite and charnockitic rocks in the zone likely formed during thrusting and juxtaposition of the terranes. Topographic and geological maps of the study area were examined closely prior to field work in order to guide the sampling locations. These locations are plotted on the 1: 100,000 geologic map of Sri Lanka (Fig. 1.5 a, b and c). To observe and identify the fabric, oriented samples were cut perpendicular to foliation and parallel to lineation whenever present. Rock chips for selected samples were prepared using the rock cutting machine in the Department of Geology, Kent State University. The probe sections and thin sections were prepared depending on the visible deformational, textural features and the field relations. Petrographic and textural characterizations were done in order to select the most appropriate samples for age analysis. Initial SEM image analysis was done in house for some of the samples which likely contain monazite/ zircon.

**Lithological Characterization**

The HC-VC thrust boundary is defined by an approximately 10-15 km wide zone in between two different metamorphic grade terranes. The twenty-one oriented samples were collected from outcrops within or proximal to the major HC-VC thrust boundary
Samples are categorized as follows; from the shear zones along the thrust boundary, within the Highland (west of the boundary) and within the Vijayan (east of the boundary) (Table 2). Coordinates of sample locations and general rock types are presented in the Appendix. General descriptions and more detailed petrographic characterization of representative samples from the three regions is presented here.

Table 2: Sampling summary for twenty one field oriented samples. Location numbers (in parenthesis) are referenced to the geological map (Figures 1.5 a, b and c).

<table>
<thead>
<tr>
<th>Samples from HC</th>
<th>Samples from VC</th>
<th>Samples from HC-VC Boundary Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL2/09 Gt-bt-qtz-flds gneiss (L2)</td>
<td>SL1/09 Hb charnockite gneiss (L1)</td>
<td>SL3/09 Gt-bt-qtz-flds gneiss (L3)</td>
</tr>
<tr>
<td>SLR1/09 Charnockite gneiss (1)</td>
<td>SLR6/09 Gt-charnockite gneiss (6)</td>
<td>SLR3/09 Gt charnockite gneiss (2)</td>
</tr>
<tr>
<td>SLR2/09 Charnockite gneiss (1)</td>
<td>SLR7/09 Gt-bt-qtz-flds gneiss (7)</td>
<td>SLR8/09 Hyp-hb-bt-qtz-flds gneiss (8)</td>
</tr>
<tr>
<td>SLR5/09 Gt-sil-graphite-qtz-flds gneiss (5)</td>
<td>M2/10 Bt-qtz-flds gneiss (10)</td>
<td></td>
</tr>
<tr>
<td>L1/10 Gt-bt-qtz-flds gneiss</td>
<td>M4/10 Bt-qtz-flds gneiss (12)</td>
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<tr>
<td>L2/10 Gt-bt-qtz-flds gneiss</td>
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<tr>
<td>L3/10 Qtz-flds-bt pegmatite</td>
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<td>L4/10 Qtz-flds-bt pegmatite</td>
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<tr>
<td>L6/10 Gt-bt-qtz-flds gneiss</td>
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<tr>
<td>L7/10 Hyp-bt-qtz-flds gneiss</td>
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Highland Complex Rocks

The Highland Complex consists of high grade rocks such as charnockitic gneisses, garnet biotite gneisses, garnet biotite sillimanite gneiss, quartzofeldspathic gneiss, and quartzite. These outcrops were slightly weathered compared to others. Strongly sheared fabric is one of the most common features in HC rocks. The percentage of garnet observed in HC rocks is also higher compared to others; large garnets with lots of mineral inclusions are common. Hypersthene is one of the index minerals in HC rocks since charnockitic gneiss is a very common rock type. Grain size varies from medium to coarse in HC rocks.

Vijayan Complex Rocks

The Vijayan Complex consists of medium to high grade rocks such as biotite gneisses, quartzofeldspathic gneisses, migmatites and garnet biotite gneisses. Garnet is typically small and inclusion free compared to the garnets in HC rocks. Outcrops are extensively weathered. Compositional banding is moderately strong and shear indicators are rare. Biotite content is very high compared to other rocks. Grain size varies from medium to coarse.
**Boundary Zone Rocks**

The Boundary Zone consists of highly sheared rocks, migmatites and pegmatites. Biotite and garnet are the most common minerals and a well developed fabric is typical. Specifically, quartz shows a strong stretching lineation giving a very high length to width ratio. Grain size varies from fine to coarse. Pegmatites and migmatites are common intrusions close to the boundary. Pegmatites have very coarse grains of hornblende, quartz, and biotite. Migmatites enriched in biotite, quartz, feldspar are abundant and generally mapped as ‘augen gneiss’.

**Petrography and fabrics**

**Highland Complex Rocks**

*Sample SL2/09 (Gt-bt-qtz-fls gneiss):*

Locality SL2/09 is a sheared coarse-grained augen gneiss with large pods of feldspar augen elongate within the plane of a well developed foliation. Shear structures with asymmetric rotated tails are well preserved at this locality (Fig.2.1A) and sense of shear is consistently counter-clockwise in direction. The outcrop is distinctly bimodal in grain size with early very coarse, nearly pegmatitic gneiss overprinted by ductile deformation zones with medium grain size. Stretched quartz ribbons with aspect ratio of 6:1 represent the high degree of strain in the shear zones.

Sample SL2/09 is a garnet porphyroblastic gneiss collected from sheared rock at this locality. Subhedral, 1-3 mm garnet porphyroblasts make up 5-10% of the rock.
Subhedral elongated quartz (20-25%), subhedral feldspars (20-30%) and flaky, long prismatic biotite grains (20-30%) are the other major constituents.

Fig. 2.1  *Petrography and the field relations of SL2/09*  A. A well developed foliation with lots of shear indicators of feldspar within the out crop. B. Pressure shadow relationship of garnet and biotite shows the flattening of minerals along major foliation. C. Biotite flakes flow on granoblastic texture of quartz and feldspar.
In thin section, 0.3-0.5 mm, fractured subhedral garnets are poikilitic with inclusions of biotite, muscovite, staurolite and plagioclase. Deformed garnet grains are surrounded by pressure shadows filled with quartz, feldspar, and biotite (Fig. 1.1 B). Subhedral, 0.04-0.07 mm microcline, subhedral, 0.06-0.07 mm plagioclases with perthitic- antiperthitic textures, short prismatic, scattered, biotite (aligned with major foliation), and subhedral, 0.06-0.08 mm orthoclase make the bulk of the rock.

*Sample SLR1/09 (Charnockitic gneiss):*

Locality SLR 1/09 is a medium grained charnockitic gneiss. With a well developed foliation is marked by the mineral alignment and felsic mineral content is higher than the mafic mineral content. Subhedral, 0.01-1 mm plagioclase (30-40%), anhedral, 0.01-0.05 mm quartz (10-20%), subhedral, 0.05-0.1 mm hypersthene (10-20%), and subhedral, 0.05-0.1 mm orthoclase (15-20%) are the major mineral constituents. Garnet, magnetite, apatite, zircon, monazite, and muscovite are the accessory mineral constituents. Granoblastic texture is well developed with quartz-feldspar mineral associations.
Fig. 2.2 Petrography and the field relations of SLR2/09 A. Fine grained massive body of charnockite gneiss with a wide distribution of mafic and felsic minerals. B. Microscopic view of SLR2/09 with nicely developed fabric of minerals under plane polarized light. C. Mafic and felsic mineral segregation under cross polarized light.

Sample SLR2/09 (Charnockitic gneiss):

Locality SLR 2/09 is a medium grained hornblende-biotite bearing charnockitic gneiss (Fig 2.2). A strongly developed foliation is marked by the alignment of segregated
mafic and felsic minerals. The hand sample consists of 10% biotite, 20% hypersthenne, 10% hornblende, 50% feldspar and 10% quartz. In thin section, accessory minerals include magnetite, apatite, calcite, and zircon. Short prismatic euhedral biotite crystals are aligned within the foliation. High relief, rounded, 0.1-0.2 mm zircons are present inside biotite haloes. Anhedral quartz (0.5-0.8 mm) is present with fine recrystallized quartz forming the matrix. Subhedral, fractured hypersthenne grains (0.50-0.70 mm) are associated with magnetite and biotite. Anhedral to subhedral, 0.5-1.00 mm orthoclase and plagioclase grains are present. Subhedral, hornblende grains (0.5-0.6 mm) are associated with euhedral magnetite grains (0.05-0.1 mm). Overall, the rock contains granoblastic texture with triple junctions among straight grain boundaries.

Sample SLR4/09 (Meta-Dunite):

Locality SLR 4/09 is a coarse grained green metadunnite. Subhedral, 0.1-1 mm olivine (80-90%) is the major constituent of the rock. Subhedral, 0.1-0.5 mm biotite (10-15%), and spinel are the accessory minerals. A well developed annealed texture is clearly observed.

Sample SLR5/09 (Gt-sillimanite-graphite-qtz-flds gneiss):

Locality SLR5/09 is a garnet-biotite-sillimanite-graphite-quartz-feldspar gneiss (Fig. 2.3). Subhedral, pinkish red, 1-5 mm garnet porphyroblasts occur in a matrix of sillimanite, feldspar, mica and quartz and make up the bulk of the outcrop. However, cm-thick shear zones with flattened garnet porphyroblasts and an anastomosing fabric are
also present. The fabric around the garnet is highly deformed (Fig. 2.3 A upper half) and flattened/elongated garnets have length to width ratios as high as 4:1.

Fig. 2.3 Petrography and the field relations of SLR5/09  
A. Garnet porphyroblasts in the matrix of sillimanite, mica, quartz and feldspar.  
B. Garnet and sillimanite shows pressure shadow relationship. 
C. Thin section view showing typical minerals in SLR5/09 under CPL.
Garnet makes up 20-25% of the rock. In thin section, subhedral, 1-8 mm diameter, high relief garnets are surrounded by subhedral, 0.1-0.5 mm secondary garnet grains. Sillimanite and biotite pressure shadows are observed around the garnet porphyroblasts (Fig. 2.3 B). Elongate sillimanite (0.5-2 mm long, 0.05-0.08 mm wide) grains aligned in the plane of major foliation are abundant (30-40%). Sillimanite occurs as inclusions in garnet (Fig. 2.3 C) and as crystals surrounding garnet (Fig. 2.3 B). Anhedral, 0.6-1.0 mm quartz (10-15%), subhedral, 0.03-1.0 mm plagioclase grains (5-10%), and anhedral, 0.1-0.2 mm k-feldspar (5%) make up the rest of the rock. Anhedral (0.06-0.1 mm) magnetite, subhedral (0.02-0.03 mm) muscovite flakes, and high relief well rounded zircon and/or monazite grains (0.02-0.05 mm) are present as accessory minerals.

Sample L1/10 (Gt-bt-qrtz-flds gneiss):

Locality L1/10 is a folded garnet-biotite quartzofeldspathic gneiss. This is a medium grained rock with segregated mafic (higher %) and felsic (lower %) banding and spectacular similar folds. Euhedral, 0.05-1 mm size garnets (5-10%), anhedral, 0.5-2 mm quartz (40-45%), subhedral, 0.1-1mm plagioclase (25-30%), and subhedral, short prismatic, 1-3 mm, biotite grains (15-20%) make up the bulk of the rock.

In thin section, a fine to medium-grained recrystallized texture is evident with dominantly subhedral crystals of garnet, plagioclase, quartz, prismatic biotite, 0.1-0.2 mm magnetite, and 0.01-0.03 mm zircon or monazite grains as accessory minerals (1-5%). Quartz and feldspar grains form annealed, polygonal texture. Garnet grains and biotite
flakes are distributed anisotropically (Fig. 2.4 B) within a granoblastic texture (Fig. 2.4 C).

Fig. 2.4 Petrography and the field relations of L1/10 A. Parallel folds in garnet biotite gneiss (L1/10). B. Thin section view shows the garnets in the fabric. C. Granoblastic texture associated with quartz and feldspar.

Sample L2/10 (Gt-bt-qtz-flds gneiss):

Locality L2/10 is a garnet-biotite gneiss (Fig 2.5). This is highly deformed bimodal gneiss with a strong foliation and segregated layers of mafic and felsic minerals.
Euhedral, 1-3 mm garnets (5-10%) are widely distributed throughout the outcrop. Subhedral, 0.1-1 mm biotite flakes (15-20%), anhedral, 1-5 mm quartz (30-35%), and subhedral, 1-3 mm plagioclase (25-30%) make up the bulk of the outcrop.

Fig. 2.5 *Petrography and the field relations of L2/10* A. Zone of deformation with different types of folding with different mafic and felsic compositions. B. Thin sectional view shows garnet and biotite aligns to form major foliation. C. Microscopic view shows very small monazite or zircon grains associate with quartz.

In thin section, subhedral, high relief inclusion free garnets, short prismatic biotite, subhedral plagioclase anhedral to subhedral, granoblastic quartz grains, and
subhedral, 0.1-0.2 mm orthoclase are the major constituents of L2/10 whereas subhedral, 0.04-0.1 mm magnetite grains and subhedral, 0.02-0.05 mm zircon or monazite grains are the minor constituents (Fig. 2.5).

Sample L3/10 and L4/10 (Pegmatites):

Localities L3/10 and L4/10 are mildly deformed quartz-feldspar pegmatites. Feldspar augens (10-30%) are observed in thin section. Recrystallized plagioclase and orthoclase grains align with biotite (subhedral, 0.1-0.5 mm, 10-15%). Antiperthite-perthite texture in feldspar is common.

Vijayan Complex Rocks

Sample SL1/09 (Hornblende bearing charnockite gneiss):

Locality SL1/09 is a highly deformed hornblende bearing charnockitic gneiss (Fig. 2.6). Strongly developed foliation is dominant and minerals are stretched with quartz and feldspar ribbons aligned in the major foliation. Plagioclase (35-40%), hypersthene (10-15%), hornblende (5-10%), quartz (5-10%), and phlogopite (5-10%) make up the bulk of the outcrop.

In thin section, subhedral, 0.2-1.0 mm plagioclase, anhedral, 0.5-1.0 mm quartz, subhedral, 0.1-0.15 mm hornblende, subhedral, 0.05-0.1 mm hypersthene, short prismatic 0.01-0.05 mm phlogopite flakes are the major constituents. Subhedral, 0.03-0.05 mm garnets (<1 %), 0.03-0.04 mm magnetite and calcite are major accessory minerals and mineral inclusions in the garnets are very minor. Sericite alterations are observed in
feldspars. Abundantly, quartz and feldspar make up the granoblastic texture as a result of high temperature annealing. Bending, faulting and fracturing of polysynthetic twinning in plagioclase observed.

Fig.2.6 Petrography and the field relations of SL1/09  A. A well developed foliation with 1-10 mm garnets and elongated quartz-feldspar bandings. B. Thin section view of the sample with considerable amounts of garnets and hornblende. C. Microscopic view of typical charnockite gneiss in high grade Highland Complex with high amounts of hydrous minerals like hornblende showing annealed texture.
Sample SLR6/09 (Gt bearing charnockitic gneiss):

Locality SLR6/09 is a moderately deformed garnet bearing charnockitic gneiss. Foliation is well developed with segregation of felsic and mafic minerals. Subhedral, 0.1-0.5 mm plagioclase (30-35%), subhedral, 0.5-2 mm, hypersthene (20-25%), short prismatic, 0.01-0.2 mm biotite (10-15%), subhedral, 0.1-0.5 mm garnet (5-10%) and anhedral, 0.1-2 mm quartz (5-10%) make up the bulk of the rock. Granoblastic texture is the common texture with polygonal quartz-feldspar associations.

Sample SLR7/09 (Biotite gneiss):

Locality SLR7/09 is a biotite gneiss. The major foliation develop with the segregation of mafic and felsic minerals. Subhedral, 0.1-0.5 mm plagioclase (20-30%), anhedral, 0.01-1 mm quartz (10-15%), subhedral, 0.01-0.5 mm biotite (20-25%), and subhedral, 0.01-0.5 mm orthoclase (20-25%) make up the bulk of the rock. Garnet, phlogopite, and muscovite are accessory minerals. Annealed texture is abundant.

Sample M1/10 (Microcline-qtz-bt gneiss):

Locality M1/10 is a strongly foliated granitic gneiss with continuous bandings of feldspar and quartz. Pink, K-feldspar layers are dominant with subhedral, 0.1-2 mm grains (40-45%). Subhedral, 0.5-1 mm of quartz (25-35%) and subhedral to anhedral, short prismatic 0.01-2 mm biotite flakes (10-15%) make up the bulk of the outcrop. Major foliation is developed by the segregation of felsic and mafic minerals.
Fig. 2.7 Petrography and the field relations of M1/03 A. Hand sample of M1/10 with k-feldspar rich layers. B. Thin sectional view of M1/10 with biotite and K-feldspar bandings throughout the rock. C. Microscopic view of M1/10 with k-feldspar, biotite and zircon accessory.

In thin section, elongated quartz grains (0.2-0.4 mm in length and 0.01-0.02 mm wide) and short prismatic biotite (0.02-0.04 mm) grains align with the major foliation of the rock (Fig 2.7 B). Sericite alteration is visible in some of the feldspar grains. Subhedral, 0.01-0.02 mm muscovite grains (5%), subhedral, 0.03-0.04 mm plagioclase
(10 %), euhedral, 0.01-0.1 mm magnetite grains show up as the minor constituents. Annealed texture is developed by major minerals; quartz and k-feldspar (Fig. 2.7).

Sample M2/10 (Hb bearing biotite gneiss):

Locality M2/10 is a hornblende bearing biotite gneiss. This is a orthogneiss with high percentage of felsic minerals. Major foliation developed with the mafic and felsic mineral segregation. Subhedral, 0.1-0.5 mm orthoclase (30-40%), anhedral, 0.1-1 mm quartz (15-20%), subhedral, 0.01-0.02 mm biotite (10-15%), and subhedral, 0.1-0.5 mm hornblende (15-20%) make the bulk of the rock. Biotite flakes align with the recrystallized quartz and feldspar.

Sample M4/10 (Bt bearing quartzofeldspathic gneiss):

Locality M4/10 is a biotite bearing quartzofeldspathic gneiss. Foliation is marked by felsic and mafic mineral segregation. Subhedral, 0.1-1 mm plagioclase (20-30%), subhedral, 0.5-1 mm orthoclase (20-25%), anhedral, 0.1-2 mm quartz (30-35%), subhedral, 0.01-0.3 mm biotite (15-20%) and euhedral, 0.1-0.2 mm magnetite make up the bulk of the rock. Coarse grained, annealed texture could be observed. Recrystallization of orthoclase, quartz, and plagioclase is abundant.
**Boundary Zone Rocks**

*Sample SL3/09 (Gt–bt–qtz–flds gneiss):*

Locality SL3/09 is highly deformed garnet biotite gneiss (Fig. 2.8). Garnet porphyroblasts (1-10 mm) are sheared and deformed (5%). Shear structures with asymmetrically rotated tails show a counter-clock wise sense of motion frequently. Ribbon quartz (30-40%) shows average length: width ratio as 7:1 and short prismatic, 1-3 mm biotite flakes (20-30%), elongated feldspars (40-50%) make up the bulk of the outcrop.

In thin section, stretched, anhedral to subhedral, 1-5 mm quartz, subhedral, 1.5-2.0 mm plagioclase, subhedral, 0.04-0.05 mm microcline, subhedral, 0.05-1 mm garnet and subhedral, 0.06-0.1 mm biotite are the major constituents of the rock. Biotite flakes show a flow fabric aligned with the major foliation (Fig. 2.8 B). Euhedral, 0.01-0.02 mm zircon and/or monazite is present as accessory mineral constituents. Ribbon quartz grains are present along the longitudinal side of the thin section. The length: width ratio for the quartz is 14:1 in some grains.
Fig. 2.8 Petrography and the field relations of SL3/09  
A. Garnet porphyroblasts align in major deformational fabric associate with biotite and magnetite.  
B. Thin section view of SL3/09 shows orientation of biotite and flattening of quartz feldspar grains.  
C. High relief, elongated monazite or zircon grain associate with felsic minerals.

Sample SLR3/09 (Garnet bearing charnockite gneiss):

Locality SLR3/09 is a highly deformed garnet bearing charnockitic gneiss. Mafic and felsic minerals are strongly segregated and that results a very strong foliation.
plane. Subhedral, 1-2 mm garnet (10-15%) subhedral, 1-2 mm hornblende (15-20%) are very common within mafic layers whereas anhedral 0.1-0.5 mm quartz (10-15%) and subhedral 0.01-1 mm feldspar (30-35%) are common within felsic layers.

Fig 2.9 Petrography and the field relations of SLR3/09 A. Garnet bearing hornblende biotite geniss with mineral bandings shows mafic-felsic bandings. B. Thin section view shows the association of garnet with hornblende, mica and magnetite, garnet grains are scattered and dissolved. C. Zircon or monazite associate with hornblende, quartz and feldspar.
In thin section, subhedral, fractured, 0.04-0.06 mm of garnets (15-20%) surrounded by hornblende, are inclusion free. Subhedral, 0.04-0.06 mm microcline with cross hatch twinning (30-35 %), subhedral, 0.02-0.05 mm plagioclase with polysynthetic twining (5-10%), anhedral, 0.02-0.5 mm (10-15%), subhedral, 0.06-0.08 mm hornblende (15-20%) are make up the bulk of the outcrop. Elongated, 0.02-0.04 mm grains of magnetite (5-6%) are associated with hornblende and garnet. Elongated, high relief, 0.01-0.05 mm zircon and/or monazite grains (5%) are visible near to hornblende or feldspar. Zircons and/or monazite, magnetite, and apatite are the minor constituents in SLR3/09. Perthite and anti-perthite texture in feldspars is well preserved. Zircon or monazite grains are conformable with micro textural fabric developed due to major foliation while some of them have core-rim relationship (Fig. 2.9). Equigranular texture could be observed where mineral grains annealed and show a common equilibrium phase. The re-crystallization of minerals might have happened during the deformation.

**Sample SLR8/09 (Hb-Bt bearing charnockitic gneiss):**

Locality SLR8/09 is hornblende-biotite bearing charnockitic gneiss. Major foliations are marked by the segregation of minerals. Subhedral, 0.1-0.5 mm plagioclase (35-40%), 0.1-0.2 mm biotite (10-15%), 0.1-1 mm hypersthene (10-15%), 0.01-0.1 mm orthoclase and 0.1-0.5 mm hornblende (5-10%) make up the bulk of the outcrop. Zircon and/or monazite, magnetite, muscovite are the minor constituents of the rock. In thin section, biotite flakes align with the major foliation.
Sample M3/10 (Gt-bt-qtz-fls gneiss):

Locality M3/10 is a garnet biotite gneiss with 1-2 mm garnet porphyroblasts in the matrix of biotite, quartz, and feldspar (Fig. 2.10). Subhedral, 0.01-0.5 mm quartz (25-30%), subhedral, 0.1-0.5 mm plagioclase (35-40%), subhedral, and 0.01-0.1 mm biotite flakes (10-15%) make the bulk of the outcrop. Strongly developed foliation could be observed.

In thin section, subhedral, fractured, high relief 0.08-1 mm garnet, subhedral, 0.05-0.06 mm plagioclase, short prismatic, subhedral, 0.02-0.05 mm biotite, anhedral to subhedral, and 0.1-0.2 mm quartz are the major mineralogical components. Quartz grains elongated and associated mainly with garnet, quartz, feldspar and mica. Biotite flakes and garnets align in the major foliation (Fig. 2.10 B). Needle like 0.01-0.02 mm muscovite (1-5%), and euhedral, 0.04-0.05 mm zircon or monazite (1-2%) are the minor components. Inequigranular texture could be observed.
Fig. 2.10 *Petrography and the field relations of M3/10* shows garnet, biotite, quartz, feldspar. A. Hand samples show garnet distribution and sample is moderately weathered. B. Garnet porphyroblasts in the matrix of biotite flakes, quartz and feldspar. C. Subhedral, sub-rounded garnet porphyroblasts with no mineral inclusions inside.
Garnet Morphology

Garnet is a key metamorphic mineral that often yields important textural information that can link metamorphism with deformation. The felsic rocks collected from Highland Complex, just west of the boundary have larger diameter garnet porphyroblasts compared to Vijayan Complex, eastern part of the thrust boundary. The shape of some garnet porphyroblasts indicates the deformational history with respect to the matrix (Fig.2.11). Some of the garnet grains show elliptical shape aligned with the deformational fabric. Early porphyroblasts prior to deformation show strong deflection of matrix foliation around the porphyroblasts which indicates the preexistence of garnet porphyroblasts prior to the deformation. Mineral inclusions (Eg: quartz, staurolite, muscovite etc) within the garnet porphyroblasts are abundant in HC rocks but largely absent in the VC. Sample SLR5/09, from HC contains 2-10 mm diameter garnet porphyroblasts with inclusions and smaller (1-5 mm) garnet grains which cluster around the coarse garnet porphyroblasts. This is identified as a secondary garnet growth (Fig. 2.11). These garnet grains may have formed during a deformational event where recrystallization occurred. Sample SLR 6/09, from VC contains fine grains of garnets with the diameter of 0.5-1 mm.

Two different generations of garnets are recognized texturally. Pre-tectonic garnets are evident by pressure shadows and shearing of garnets. Garnets have recrystallized during the tectonism and secondary garnets (post-tectonic) formed close to major garnet porphyroblasts (Fig. 2.11).
Fig. 2.11 Microscopic view to show the variation of garnet morphology from western HC-VC boundary towards eastern HC-VC boundary A & B. Sub-rounded garnet grains (red color dotted line) around the garnet porphyroblast (orange color dotted line) show secondary growth of garnets from HC (SLR5/09). C. Garnet porphyroblast (5 mm) from HC associated with sillimanite needles in pressure shadow (SLR5/09). D. Small garnet porphyroblast (1.5 mm) from boundary zone (SL3/09) associate with biotite.
Scanning Electron Microprobe (SEM) Imaging

SEM imaging was done in house at Kent State University on five samples, three of which were found to contain monazite and zircon. Monazite and zircon grains appear bright (white or light gray) compared to the matrix minerals (black or dark gray). Chemical concentration plots were then used to distinguish monazite from zircon. With monazite grains yielding high Ce, P, O peaks and zircon grains yielding zirconium peaks. Two major populations of monazite grains were identified in terms of the size of the grains (Fig 2.12). The two sizes of the grains range from 10-50 µm and 100-300 µm. Monazite grains are aligned with the major deformational fabric.
Fig. 2.12 Scanning electron microprobe (SEM) view with two different sizes of populations of monazite grains in high grade rocks in Sri Lanka (SL3/09); Two sizes range from 10-50 µm to 100-300 µm. Monazite grains are aligned with the major deformational fabric. The shapes of the monazites indicate the deformation.
EMPA Monazite Geochronology

Monazite is a datable, REE phosphate mineral commonly used as a geochronometer to determine deformation and metamorphic histories. Typically, monazite is a common accessory mineral in igneous and metamorphic rocks and is more abundant in felsic rocks (especially metamorphosed pelitic rocks) than in mafic or ultramafic rocks. Chemical mapping of monazite complements petrofabric analysis, as mapping allows for qualitative examination of potential metamorphic domains of multiple ages. Distinct chemical domains within monazite may reflect multiple periods of growth during polyphase deformation and metamorphism. This technique is particularly valuable for analyzing the tectonic history of higher temperature metamorphic events as monazite remains a closed system during high grade resetting and secondary monazite growth. High resolution measurements are needed for analysis of elemental concentrations within each growth domain. To achieve such high resolution, analysis is often conducted using an electron microprobe (Williams et al., 1999; Williams & Jercinovic, 2002). High resolution X-ray maps of Th, U, Pb and Y in monazite indicate the continuous spatial distribution of these elements in a single monazite grain (Goncalves et al., 2005).

The most important assumption regarding the in-situ monazite chemical dating is that all analyzed Pb is produced through the decay process of Th and U. With its low diffusivity monazite typically behaves as a closed system during growth and/or
recrystallization. For other U bearing minerals (zircon, titanite) common Pb can potentially generate geologically meaningless ages since common Pb consists of ‘initial Pb’ and Pb generated with open system behavior (Kelsey et al., 2003). However, for monazite this is generally not a problem and can be readily checked with the use of other radiometric systematics.

**Methodology**

Electron microprobe analytical (EMPA) work was done on the Cameca SX 100 at New Mexico Institute of Mining and Technology. Probe sections were carbon coated (simultaneously with the standard) to create a conductive surface for the electron beam. Both the major and trace elemental analyses were run with a 200 nA beam current. Large scale elemental maps were made of Ce, Y, and Fe to determine if samples contained monazite. After locating sizable monazites, Backscatter electron (BSE) images were taken of the monazites and Th, Y, and U maps were created of each of the selected grains. These elemental maps (Figs. 3.2; 3.3) were utilized in selecting areas to conduct major elemental analyses, as differing degrees of brightness on the Th maps suggests high versus low elemental concentrations and potential growth domains. The monazites analyzed were typically 50 µm – 100 µm in diameter, large enough for choosing multiple probe points; two to nine points per grain were measured for Th, Y, Pb, and U concentrations (among other elements). Probe points were chosen using the Th maps to measure different chemical domains, and BSE images were used to avoid grain edges, fractures, and holes to minimize trace elemental mass transfer. Background scans were
run to eliminate background concentrations and ensure the measurement of only trace concentrations. To determine the appropriate background levels for Th, Y, Pb, and U the data were processed in BK GII (Background II), a program developed by Mike Jercinovic (University of MA Amherst) that performs a regression analysis to determine background concentrations.

![BSE images and Th concentration maps](image)

**Fig. 3.** BSE images (left) and Th concentration maps (right) of high grade metamorphic monazites from samples; SL3/09 and M3/10 with corresponding ages.
Fig. 3.2 BSE image (left) and Th concentration maps (right) of monazite grains from high grade metamorphic rocks, Sri Lanka with corresponding spot ages; sample SLR5/09.

Many trace element analysis points were selected near points measured for major element data and used to calculate the background concentrations. Picking trace points close to the majors ensures trace concentrations were collected for Th, U, Pb, and Y using the appropriate calibrations for the different chemical domains. These trace concentrations were entered into the age dating equation. Before ages were accepted in
the final dataset the trace element analysis points, seen in the final BSE images, were compared to the trace concentrations to eliminate any disputable data.

**Results**

Seven samples were selected for EMPA work. Rapid, low resolution scanning for Y revealed three of the seven samples have significant populations of monazite grains. Grain size varies from 20-200 µm in diameter. Sample SL3/09 contains two distinct size populations, a coarser population with diameters of 200-400 microns and finer population with 30-50 micron diameter (Fig. 2.12).

The flattened/ elongated shape of the monazite grains is an important feature which provides information about relationship between monazite growth and deformation. Most of the monazite grains are aligned with the major fabric. Sixteen monazite grains were characterized and analyzed in this study. Backscatter electron images and Th concentration maps are presented in Figs. 3.1 and 3.2. Table 3.1 describes the shape, aspect ratio, size, and Th complexity for each grain analyzed. All analytical data recorded in table 3.2 and 3.3.
Table 3.1 Characterization of monazite grains and Th complexity at the spot of interest from high grade metamorphic terrane, Sri Lanka. BZ=Boundary Zone HC=Highland Complex

<table>
<thead>
<tr>
<th>Sample/ Grain</th>
<th>Shape of the grain</th>
<th>Aspect ratio (Length/width)</th>
<th>Grain Size (longest length in µm)</th>
<th>Th Complexity</th>
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</thead>
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<tr>
<td>SL3/G1 (BZ)</td>
<td>Sub-angular</td>
<td>1.5</td>
<td>450</td>
<td>Complex</td>
</tr>
<tr>
<td>SL3/G2 (BZ)</td>
<td>Sub-rounded</td>
<td>2.5</td>
<td>110</td>
<td>Simple</td>
</tr>
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<td>240</td>
<td>Core-rim</td>
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<td>55</td>
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</tr>
<tr>
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<td>Complex</td>
</tr>
<tr>
<td>SLR5/G3 (HC)</td>
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<td>125</td>
<td>Simple</td>
</tr>
<tr>
<td>SLR5/G4 (HC)</td>
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<td>100</td>
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</tr>
<tr>
<td>SLR5/G5 (HC)</td>
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Table 3.2 EMPA Total monazite age data from shear zones in HC-VC thrust boundary zone, *Sri Lanka*. **Younger ages**  | **Middle Ages**  | **Older Ages**
<table>
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<th></th>
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<tbody>
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<td><strong>Th (ppm)</strong></td>
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<td>3770</td>
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Table 3.3 EMPA Total monazite age data from shear zones in high grade HC tarrane, Sri Lanka.

<table>
<thead>
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<th>Younger ages</th>
<th>Middle Ages</th>
<th>Older Ages</th>
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<tbody>
<tr>
<td>Spot of Interest</td>
<td>Y (ppm)</td>
<td>Th (ppm)</td>
</tr>
<tr>
<td>SRL5 G1 S1</td>
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</tr>
<tr>
<td>SRL5 G9 S4</td>
<td>1790</td>
<td>32470</td>
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</table>
Sample SL3/09- (Gt –Bt-Qtz-Flds gneiss):

Six monazite grains were analyzed from sample SL3/09 (Table 3.1). Grain 1 is sub-angular and slightly elongate with the long axis aligned in the plane of the foliation. Th concentration texture is complex with fine interfingering of low and high concentrations. The grain records two age populations of 587-590 Ma (two spot ages) and 1850-1870 Ma three spot ages (Table 3.1).

Grain 2 is sub-rounded and elongate with an aspect ratio of 2.5. Th concentration texture is simple with higher Th concentration recorded at the grain edges. Trace elemental concentrations were not analyzed successfully due to problems with the microprobe.

Grain 3 is sub-rounded and mildly elongate with an aspect ratio is ~ 1.6. The grain has a tapered edge which may have formed during deformation. The long axis of the grain is slightly misaligned with respect to the major foliation. A core and rim relationship could be identified very clearly with Th concentration higher at the edge of the grain. Two groups of ages are recorded as 667-682 Ma in two spots at the core and 586-594 Ma in two spots at the rim.

Grain 4 is sub-angular and elongate with an aspect ratio of 2. The grain has relatively uniform Th composition. The grain is strongly misaligned being perpendicular to the major foliation. A single spot age of 598 Ma was recorded from this grain.

Grain 5 is sub-angular and circular. The variation in Th content is complex with Th concentrations with three domains in the grain interior and
a fourth cross cutting domain at the edge, forming a sharp rim along three edges. Two different ages are recorded; an interior age of 793 Ma and rim ages of 580 and 607 Ma.

Grain 6 is sub-rounded and the axis of the grain elongated slightly along the foliation plane. The aspect ratio is 1.6. Th concentration varies from low to high across the grain. Core and rim relationship could be identified with younger ages nearer the edge and older ages in the middle. Two populations of ages are recorded; a 1255-1350 Ma from two spots and 627-730 Ma from three spots.

Sample M3/10-(Gt-bt-qtz-fls gneiss):

Only two monazite grains are recorded for M3/10 (Table 3.1). Grain 1 is rounded and contains a number of inclusions. The aspect ratio of the grain is 1.6. Th concentrations vary slightly and are higher compared to other grains. One rim analysis gave an anomalously younger age of 541 Ma; all other ages are in the range of 595-671 Ma. 15 spot ages were obtained from this grain.

Grain 2 is angular and elongated with aspect ration of 4. Fluid texture is nicely observed here with cavities, bays and sharp edges. Th concentrations are middle to higher values.

Sample SLR5/09-(Gt-Sillimanite-Graphite-Qtz-Fls gneiss):

Eight monazite grains were analyzed from sample SLR5/09 (Table 3.1). Grain 1 is sub-angular with a very irregular shape. Fluid texture could be identified. The grain
itself has bays and bulging features. Th complexity is very high. Two different ages are recorded: a rim age of 533 Ma and two core ages of 580 Ma and 607 Ma.

Grain 3 is sub-angular and the edges of the grain are rough and sharp with the aspect ration of 2. Fluid texture could be identified. Th complexity is simple and Th concentration is very low for the most part of the grain. Three different ages are recorded: two rim ages of 546 Ma and 611 Ma and a core age of 1069 Ma. There are some fluid cavities with in the grain.

Grain 4 is angular and well developed grain boundaries could be observed. Aspect ratio is 1.5. Th concentrations recorded are low to medium for this grain. Four younger ages are recorded as 553, 557, 558, and 544 Ma. The age distribution is relatively uniform across the grain.

Grain 5 is rounded and the grain boundaries are very smooth. Aspect ratio is 2. A very sharp core and rim relationship could be observed with different Th concentrations. Th concentration is higher at the edges of the grain. Two populations of ages are recorded as 535-567 Ma and 601-613 Ma from rim and core regions respectively.

Grain 6 is sub-angular and elongate with an aspect ratio is 2.4. Th concentration is relatively uniform and only one age is recorded (589 Ma). Grain 7 is angular and pseudo-hexagonal shape could be seen. The grain axis is elongated slightly and a well-developed zoning (core and rim) relationship could be observed with lower Th concentrations in the middle of the grain. Seven ages are recorded and they basically represent two groups of 544-577 Ma at the rim and 1797-1821 Ma in the center.
Grain 8 is sub-rounded and circular. The shape of the grain boundary is altered in some places. Th complexity is higher and four younger ages are recorded (570, 555, 586, 577 Ma) across the grain. Grain 9 is sub-rounded and elongated along the axis (aspect ratio is ~2). The grain has alternating dark and light layers. Th concentrations vary highly within the grain. Two different age groups are recorded as older and middle ages. The middle ages recorded are 1368 Ma and 1390 Ma whereas older ages are 1755 Ma and 1872 Ma.

**Summary of EMPA ages**

Figure 3.3 graphically represents the relationship between the frequency and ages produced in this study. Forty spot ages from seven monazite grains from samples SL3/09 and M3/10 also preserve a dominance of Pan-African spot ages ranging from 541 Ma to 730 Ma (average age=617 Ma). One grain yielded three tightly clustered Paleoproterozoic spot ages of 1858 Ma, 1866 Ma and 1868 Ma. Another grain yielded two Mesoproterozoic core ages of 1350 Ma and 1255 Ma. Two grains preserve a cluster of ages between about 800 Ma and 1030 Ma.

Thirty spot ages from eight monazite grains from sample SLR5/09 reveal a dominance of Pan-African core and rim ages ranging from 533 Ma to 613 Ma (average age = 567 Ma). Three grains preserve old ages in their cores ranging from 1069 to 1872 Ma. Five core spots yielded Paleoproterozoic ages between 1755 and 1872 Ma (average age of 1810 Ma). Three spots yielded Mesoproterozoic ages of 1391, 1368, and 1069
Ma. Pre-Pan-African population of ages is largely absent from the Highland Complex EMPA monazite results.
Fig. 3.3 Graphical representations of the ages for high grade rocks, Sri Lanka. Top: Three different age groups found from SLR5/09. Bottom: Three different age groups found from the boundary rocks; SL3/09 and M3/10.
Chemical-Age analysis

The qualitative monazite textural descriptions above suggest that the age data are a function of chemical domains formed during growth and/or re-absorption of monazite. To better quantify this relation, chemical concentrations (Th, Y, and U) in Highland Complex rocks (SLR5/09) and the Boundary Zone rocks (SL3/09 and M3/10) were plotted with respect to spot ages in Fig 3.4 and 3.5. Additionally, Th/U ratios were calculated and plotted against Y concentrations sorted by age.

In the Highland Complex, pre-Pan African ages show a narrow elemental concentration variation (Y, Th, and U) whereas Pan African ages show a broad range of elemental concentrations. In HC, Pan-African ages have a wide range of Th/U ratios (0-30) whereas pre-Pan African ages have Th/U ratios varying in range from 3-16. U and Th concentrations for Pan African ages range from 2000-13000 ppm and 10000-90000 ppm respectively. Y concentrations from the data separate into two clusters: 1) low Y cluster which typically signifies monazite growth during prograde metamorphism when garnet is stable and 2) a high Y cluster which typically signifies monazite growth during break down of garnet. The average age for higher Y concentrations (>4000 ppm) is 558 Ma whereas the average age for lower Y concentrations (<4000 ppm) is 572 Ma.
Fig. 3.4. Plots of chemical variation with respect to spot ages of monazite, Highland Complex (SLR5/09).
Fig. 3.5. Plots of chemical variation with respect to spot ages of monazite, Boundary Zone SL3/09 and M3/10.
In the Boundary Zone, U, Th, and Y elemental concentrations are similarly distributed with Pan African ages showing the greatest variation in concentration. However, Pan African ages do not cluster systematically into high and low Y concentrations. Overall, Pan African ages representing primary metamorphism are recorded in BZ monazite between 595 and 635 Ma. BZ monazites also record pre Pan African ages ranging from 700-1000 Ma but those ages are absent in HC monazites dated in this study.

**Interpretation**

Fig. 3.6 summarizes the P-T-t path for Highland Complex rocks reported by Sajeev et al. (2010) using SHRIMP U/Pb geochronology on zircon and monazite from the central HC. They report old zircon core ages of ca. 1700 Ma and 800-1000 Ma surrounded by overgrowths dated at 569±7 Ma and 551±7 Ma. They interpreted the older overgrowth as the age of prograde metamorphism and the younger overgrowth as the time of retrograde metamorphism during near-isothermal decompression. Their textural work suggests that early garnet growth during peak metamorphism was followed by garnet consumption during decompression forming sapphireine and orthopyroxene. The timing of peak and retrograde HC metamorphisms obtained in this study (Fig. 3.6) and by Sajeev et al. (2010) are remarkably similar despite the use of different techniques (EMPA and SHRIMP) and disparate localities (~50 km distance).
Fig. 3.6: P-T-t path constructed based on U/Pb zircon and monazite ages for Highland Complex, Sri Lanka (modified after Sajeev et al., 2010).
Conclusions

New data reported here confirm a regionally widespread peak metamorphic age of 570 Ma for HC followed by retrograde metamorphism during exhumation at about 555-545 Ma. The slightly older age of retrogression from this study might indicate earlier onset of exhumation of the eastern Highland Complex.

The Vijayan Complex consists only of 1100-1000 Ma as older lithologies (Table 1). Therefore, the 700-1000 Ma ages preserved in the Boundary Zone indicate that the rocks caught up in the deformation are from the Highland Complex. Pan African ages recorded are older than those obtained from HC monazites. The 595-635 Ma ages recorded from the BZ likely formed during shearing of HC rocks at moderate P-T conditions (Fig. 3.7) and may therefore date the initial juxtaposition of the HC and VC terranes. If so, terrane collision and crustal thickening at 595-635 Ma may have ultimately led to peak metamorphism of the HC rocks at 570 Ma. Peak metamorphism was followed closely by rapid exhumation of the HC rocks beginning at 558 Ma in the east and 551 Ma in the western HC terrane (Fig 3.7). Rapid cooling of the HC via motion along the BZ occurred at conditions below that of monazite growth and therefore it is not detectable via dating of monazites. Further, study of lower temperature thermochronometers are needed to confirm this proposed interpretation.
Fig. 3.7. Schematic synopsis of proposed timing of metamorphism and deformation preserved in rocks near and within the boundary zone between the Highland Complex and Vijayan Complex, Sri Lanka.
References


Geological Survey and Mines Bureau (Sri Lanka), 1997. 1:100,000 Geology provisional map series: Sheet no. 17, Nuwara Eliya-Haputale.

Geological Survey and Mines Bureau (Sri Lanka), 2001. 1:100,000 Geology provisional map series: Sheet no. 18, Panama-Buttala.
Geological Survey and Mines Bureau (Sri Lanka), 2001. 1:100,000 Geology provisional map series: Sheet no. 20, Rakwana-Tangalla.


Appendix

Appendix 1: UTM locations (SL Grid_99 coordinate system) of samples and rock types

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample Number</th>
<th>E</th>
<th>N</th>
<th>Rock name</th>
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</thead>
<tbody>
<tr>
<td>Wellawaya south</td>
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<td>241047</td>
<td>170587</td>
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<td>Pelawatta road</td>
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<td>178121</td>
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<td>Pareiyana ella</td>
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<td>183440</td>
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