Extreme Crustal Metamorphism during a Neoproterozoic Event in Sri Lanka: A Study of Dry Mafic Granulites

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ABSTRACT

Garnet-clinopyroxene-quartz granulites of the central Highland Complex of Sri Lanka preserve textural and compositional features indicative of high-pressure, ultrahigh-temperature (HP-UHT) crustal metamorphism and multistage retrogression. Grains of the peak metamorphic assemblage, garnet-clinopyroxene-quartz, are commonly separated and embayed by late orthopyroxene-plagioclase symplectites; however, in some domains, rare grain-to-grain associations of the peak assemblages are still preserved. Thermodynamic modeling in the CaO-Na_2O-K_2O-FeO-MgO-Al_2O_3-SiO_2 system indicates peak metamorphic conditions of 12.5 kbar at 925°C. The temperature estimates using garnet and clinopyroxene core compositions are in the range 844°–982°C, in agreement with the thermodynamic modeling. In conclusion, the textural, geochemical, and thermodynamic modeling and thermobarometric data indicate a multistage decompression after HP-UHT metamorphism. U-Pb zircon (laser ablation–inductively coupled plasma mass spectrometry) ages represent the timing of the peak metamorphism at ca. 580 Ma. A Sm-Nd internal isochron from mineral phases (garnet, clinopyroxene, orthopyroxene, and felsic fraction) and from a whole rock yields an age of 534 ± 12 Ma interpreted as the time of isothermal decompression (retrogression). Our results from the central Highland Complex of Sri Lanka provide important constraints on the Neoproterozoic orogeny associated with the assembly of Gondwana.

Online enhancements: appendix tables.

Introduction

Extremely high-temperature heat input with related granulite facies metamorphism of the lower crust is considered an ultrahigh-temperature (UHT) metamorphic process ($T > 900$°C; Harley 1998*a*, 2004), and evidence of UHT metamorphism is likely preserved in Mg-Al-rich pelitic granulites (e.g., Harley et al. 1990; Brown and Raith 1996; Raith et al. 1997; Harley 1998*b*; Goncalves et al. 2004; Sajeev and Osanai 2004*a*, 2004*b*; Sajeev et al. 2004, 2006; Sajeev and Santosh 2006 and references therein) and rarely preserved in mafic and ultramafic granulites (Harley 1989). Harley (2004) cautioned that UHT data from mafic granulites are reliable only if the surrounding pelitic granulites also preserve reaction textures of UHT metamorphism, because of the possibility of misinterpreting igneous textures (e.g., exsolution lamellas) as UHT textures.

In contrast to UHT metamorphism, evidence for high-pressure granulites (O'Brien and Rötzler 2003; Pattison 2003; Brown 2006, 2007) can be easily identified in mafic granulites and in pelitic rocks. Rocks stabilized in the orthopyroxene-absent field with a garnet-clinopyroxene-quartz (Grt-Cpx-Qtz) assemblage, with or without plagioclase, can be

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considered high-pressure granulites (O'Brien and Rötzler 2003; Pattison 2003; Brown 2007). Most granulites worldwide have been retrogressed and hydrated (overprinted by hydrous minerals such as hornblende [Hbl] or biotite [Bt]) during uplift.

This study attempts to explain extreme crustal metamorphic signatures of anhydrous and high-pressure ultrahigh-temperature (HP-UHT) granulites that formed in the lower crust during Neoproterozoic regional metamorphism related to the amalgamation of Gondwana. We present unique, dry (hydrous mineral–absent), garnet-clinopyroxene-quartz granulites from the central Highland Complex, Sri Lanka, that preserve evidence of HP-UHT metamorphism. The stability of the mineral assemblages is examined through thermodynamic modeling. The timing of HP-UHT metamorphism is determined by U-Pb zircon dates using laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) spot dating, and the cooling age is determined by Sm-Nd internal (mineral) isochron ages. In this study, we estimate the pressure-temperature-time (P-T-t) relations of this relatively rare rock compared with those of surrounding mafic and pelitic granulites.

Geological Outline

The first geological subdivision of Sri Lankan basement was carried out by Adams (1929); later studies proposed further subdivision and nomenclature (e.g., Coates 1935; Wadia 1942; Cooray 1962, 1984, 1994). The Southwestern Group defined in previous studies (e.g., Hapuarachchi 1983) is now considered a part of the Highland Complex (Kröner et al. 1991) because of petrological, metamorphic, and geochronological similarities. Many recent workers consider the Kaduganawa Complex a part of the Wanni Complex on the basis of their lithological and structural relations (Kehelpannala 1997). In this study, we follow the widely accepted classification of Cooray (1994), which is based on the isotopic mapping of Milisenda et al. (1988) and the geochronological results of Kröner et al. (1991). Cooray (1994) divided the basement complexes of Sri Lanka into four units (fig. 1): the Vijayan Complex in the east, the Highland Complex in the center, the Wanni Complex in the west (fig. 1), and an area in central Sri Lanka (northwest of the city of Kandy), formerly known as the "Arena" (Vitanage 1972), now named the Kaduganawa Complex. Sajeev (2003) suggested that the eastern part of the Wanni Complex belongs to the western Highland Complex because both western and eastern Highland complexes underwent Neoproterozoic granulite facies metamorphism despite their different protolith ages.

The eastern Highland Complex yields 2000–3000-Ma model ages (Milisenda et al. 1988), whereas the other complexes have relatively younger 1000–2000 Ma model ages. This result is well supported by U-Pb zircon ages reported from various recent studies (e.g., Kröner et al. 1991). All the Sri Lankan complexes experienced a later Neoproterozoic regional metamorphic event related to the amalgamation of the Gondwana supercontinent.

The Vijayan Complex experienced amphibolite-grade metamorphism, whereas the Highland, Wanni, and Kaduganawa complexes experienced granulite-grade metamorphism with a retrograde amphibolite facies overprint. The boundary between the Highland and Vijayan complexes is well defined because of the variations in the metamorphic grade and model ages, whereas the boundary between the Highland and Wanni complexes is still under debate (Kehelpannala 1997; Sajeev 2003 and references therein).

Of the various complexes, the highest-grade metamorphic rocks occur in the Highland Complex. A recent regional study by Sajeev and Osanai (2005) on garnet-biotite gneiss from the Highland Complex, using the Fe-Mg distribution coefficient between garnet and biotite, documents an increase in metamorphic grade toward the central part of the Highland Complex (central Highland Complex). This is consistent with other studies (Sajeev and Osanai 2004*a*, 2004*b*) because regional temperature zoning is based on the distribution coefficient and follows a strict procedure for attaining garnet and biotite composition close to the peak metamorphism. Faulhaber and Raith (1991) reported a gradual increase in metamorphic pressure toward the eastern Highland Complex. Thus, high-P-T granulites are to be expected in the east-central Highland Complex.

The pelitic granulites of the Highland Complex have been widely studied (e.g., Osanai 1989; Faulhaber and Raith 1991; Hiroi et al. 1994; Raase and Schenk 1994; Kriegsman and Schumacher 1999; Osanai et al. 2000; Sajeev and Osanai 2004*a*, 2004*b*, 2005), whereas studies of mafic granulites are rare. From mafic granulites in the Highland Complex, Sandiford et al. (1988) reported a P-T range of 6–8 kbar at about 700°–750°C. Schenk et al. (1988) reported a nearly isobaric cooling evolution for mafic granulites at P = 9–8 kbar and from $T > 900$°C to T = 700°C, using the orthopyroxene-clinopyroxene thermometer of Lindsley (1983). In addition, using garnet-orthopyroxene and garnet-clinopyroxene pairs, Schumacher et al. (1990) obtained tem-

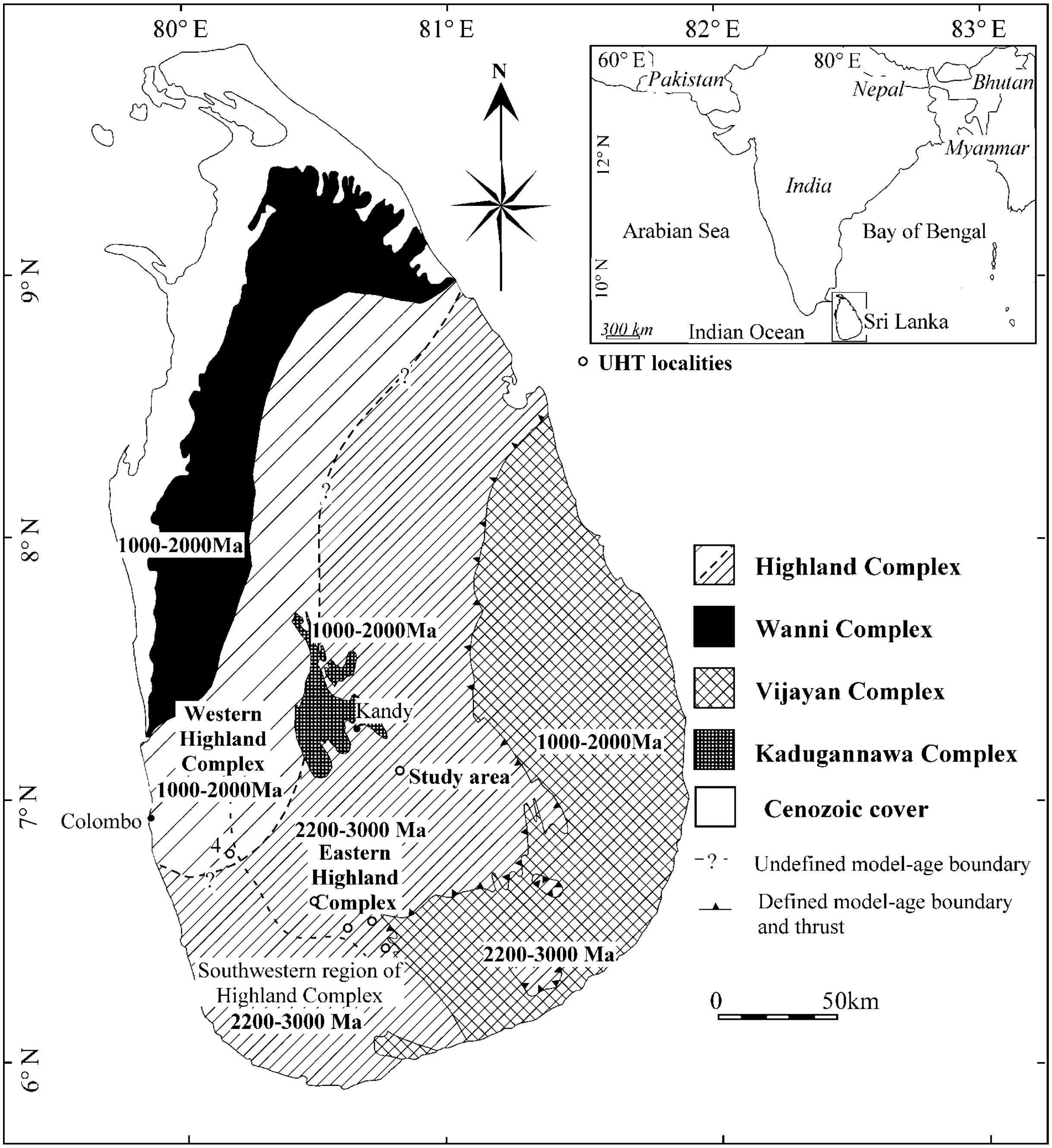


Figure 1. Schematic map of Sri Lankan basement geology, modified after Schumacher and Faulhaber (1994) and Sajeev and Osanai (2004*b*). Boundaries after Milisenda et al. (1988). Ultrahigh-temperature (*UHT*) rock localities are indicated.

peratures of $T = 820$°C and pressure of 8 kbar. Schumacher and Faulhaber (1994) estimated that garnet-pyroxene-plagioclase-quartz-bearing granulites of the central Highland Complex formed at around 800°–850°C under pressures above 9 kbar. Many of the previous studies gave relatively low temperatures even though the sample locations are in the high–temperature-pressure zone (Faulhaber and Raith 1991; Sajeev and Osanai 2005); this was probably due to lack of correction for retrograde exchange (e.g., Fitzsimons and Harley 1994; Pattison and Bégin 1994; Pattison et al. 2003).

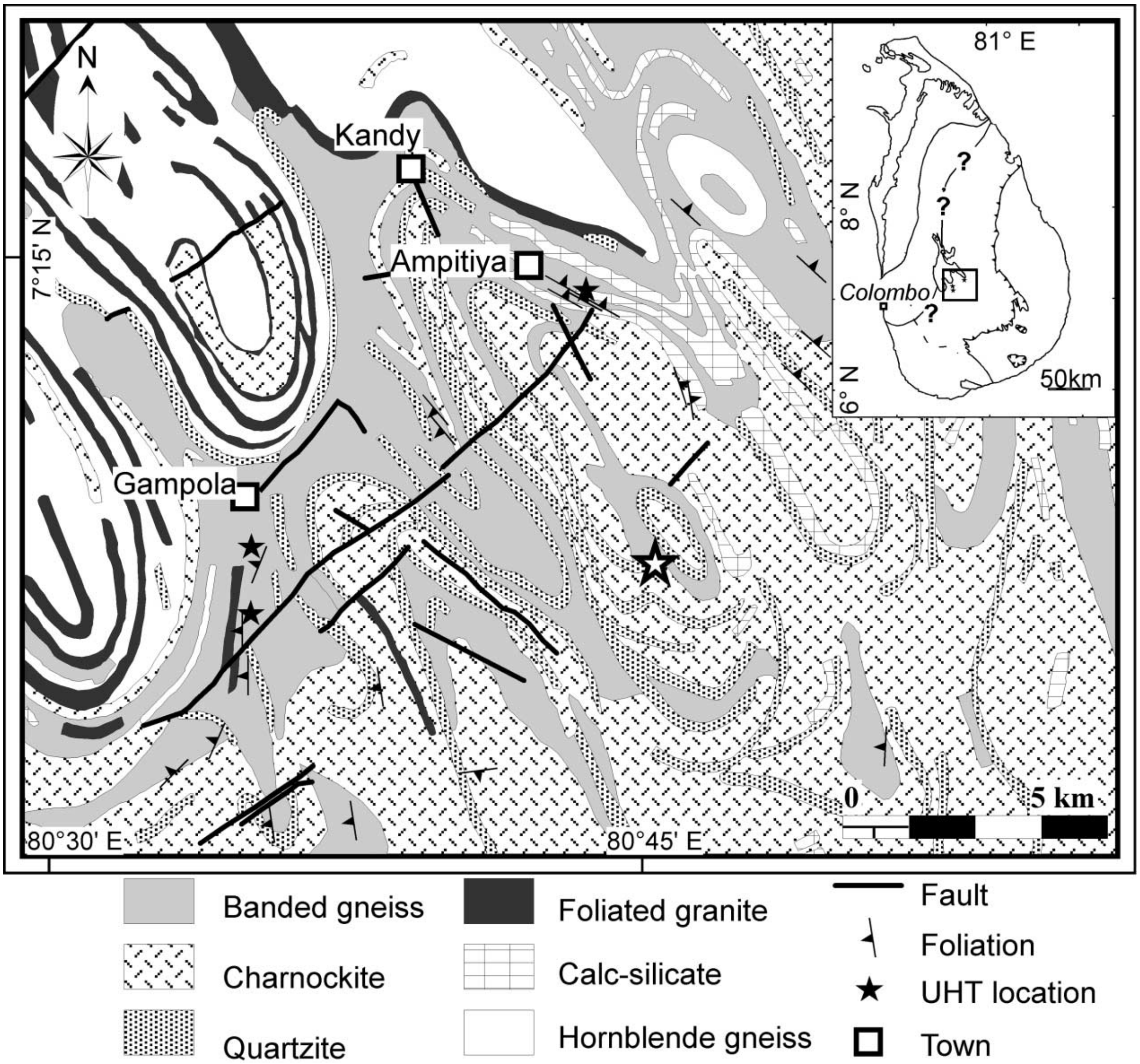


Figure 2. Geological map of the study area, modified after Geological Survey Department of Sri Lanka (1982). Position of the locality of the analyzed ultrahigh-temperature (UHT) rock is indicated by the open star. Filled stars represent previously studied UHT localities (after Kriegsman and Schumacher 1999; Sajeev and Osanai 2004*b*).

Hölzl et al. (1991) summarized the metamorphic and cooling ages of metabasites from the Highland Complex: a 608 ± 3-Ma U-Pb zircon date probably represents peak metamorphism, while a Sm-Nd internal isochron date of (561 ± 12)–(481 ± 8) Ma and a Rb-Sr date of 465 ± 11 Ma probably record cooling. Kröner et al. (1987) reported detrital zircon ages of 3.2–2.4 Ga and Pb loss at 1.1 Ga, which they correlated with a granulite-grade metamorphic event. Sajeev et al. (2003) reported a Sm-Nd internal isochron based on garnet core, clinopyroxene, felsic fraction, and whole rock that suggested an older event (ca. 1500 Ma), whereas an isochron on whole rock and orthopyroxene gave a reference age of 550 Ma.

The rocks of the central Highland Complex include some of the highest-grade granulites known in Sri Lanka. Ultrahigh-temperature sapphirine-bearing granulites were first recognized by Osanai (1989); various localities with UHT assemblages are

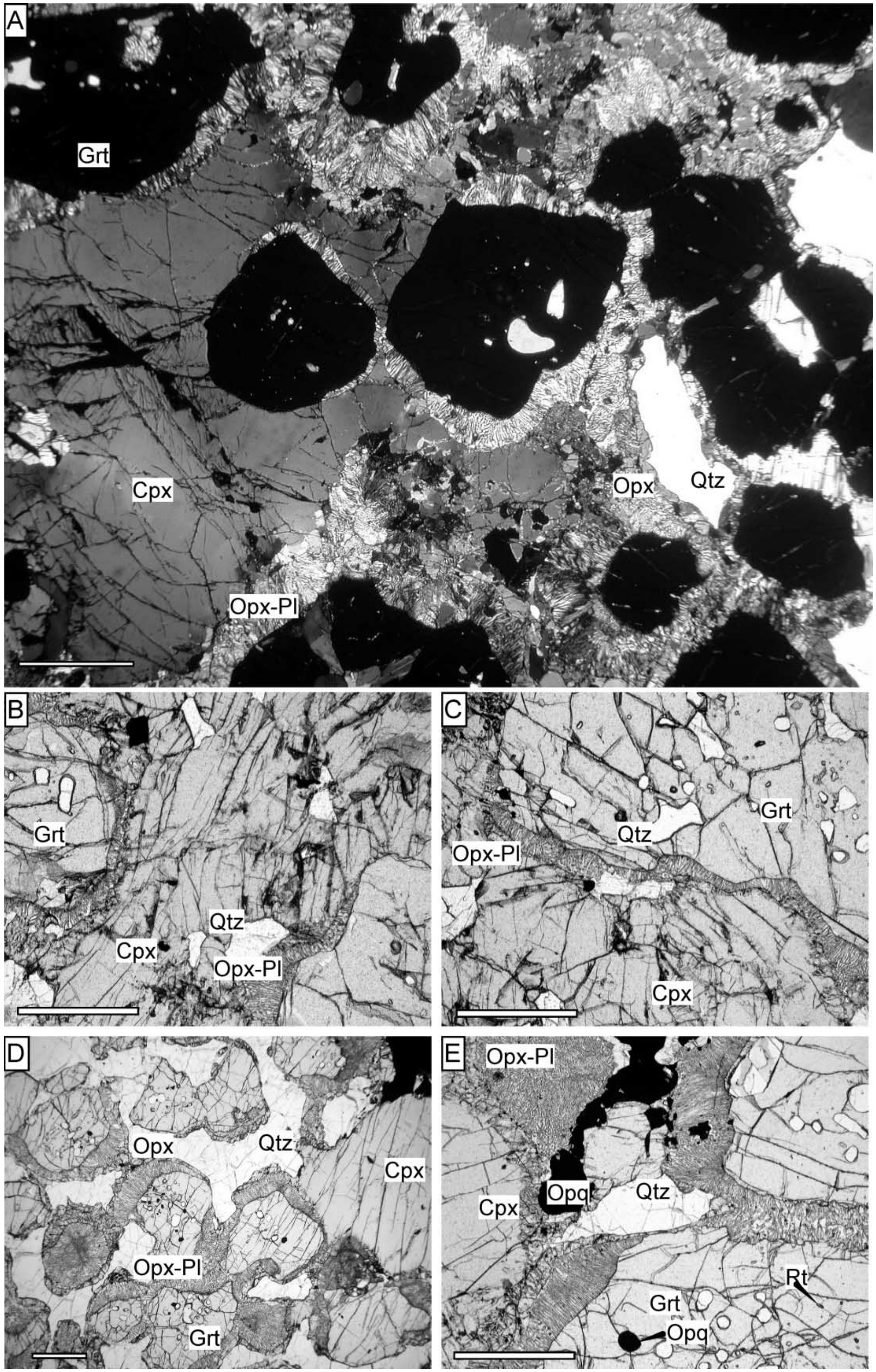
Figure 3. Roadside photos of intercalated mafic and pelitic granulite. *A*, Garnet-clinopyroxene-quartz (Grt-Cpx-Qtz) granulite conformable with metapelitic layers. *B*, Close-up of Grt-Cpx-Qtz granulite with disrupted layers.

now known (e.g., Kriegsman and Schumacher 1999; Osanai et al. 2000, 2006; Sajeev and Osanai 2004*a*, 2004*b*).

The central Highland Complex in the area around Kandy (including the study area) consists of interlayered and deformed mafic and pelitic granulites (fig. 2), together with foliated granite, quartzite, and locally intercalated calc-granulite and marble. Our samples were collected from a roadside exposure in the vicinity of the Victoria Dam, near southeastern Kandy (fig. 3*A*). The lithology here consists of quartzite, calc-silicate rocks, and layers of migmatized pelitic granulites (Grt-Sil-Crd-Bt ± Gr gneiss and Grt-Bt gneiss; fig. 3*A*; Sil = sillimanite, Crd = cordierite, Gr = graphite). Garnet-clinopyroxene-quartz granulites form disrupted layers (fig. 3*B*). Coarse garnet and clinopyroxene porphyroblasts are visible in hand specimens. Hornblende and biotite are completely absent in our samples, although they are present in other mafic granulites reported from surrounding areas. The foliation strikes SE to S (140°–185°) and dips steeply to the west (75°–85°).

Mineral Assemblages and Textural Features

Reaction textures in dry mafic granulites are rare, owing to the typically high-variance assemblage and wide *P-T* stability range of the mineral constituents. In all samples studied, porphyroblasts of garnet (3–5 mm) and clinopyroxene (1–7 mm) are preserved with or without medium-grained quartz (1–4 mm; fig. 4*A*). These minerals are interpreted as reflecting the peak metamorphic mineral assemblage, which is still preserved in some microdomains (fig. 4*B*). Orthopyroxene is present only as a secondary phase, commonly forming a symplectite with plagioclase along grain boundaries between garnet, clinopyroxene, and quartz (fig. 4*C*), and as medium-to-coarse-grained moats rimming quartz grains in the matrix (fig. 4*D*). Locally, the symplectites form pods in a quartz matrix (fig. 4*D*) and are interpreted as indicating the presence of preexisting garnet. We have defined at least three subtypes of orthopyroxene-plagioclase (Opx-Pl) symplectite on the basis of x-ray (chemical) mapping (fig. 5). The first consists of medium-grained intergrowths (Opx-Pl_1) in the center of symplectite rims. The orthopyroxene and plagioclase volumes in this texture are relatively similar; these could represent the first stage of symplectite formation, when garnet, clinopyroxene, and quartz were in grain contact. This means that an adequate amount of reactants was present during symplectite formation. The second subtype consists of fine-grained symplectites near garnet rims (Opx-Pl_2), in which both orthopyroxene and plagioclase are fine grained but the volume of plagioclase is greater than that of orthopyroxene. This could represent the breakdown of garnet in the presence of quartz and an absence of chemical communication with clinopyroxene in localized microdomains, leading to a deficit in Fe and Mg and reducing the abundance of orthopyroxene. Considering the mass balance constraints, a deficit in Fe and Mg in this domain indicates a surplus of these elements elsewhere.


A
Grt
Cpx
Opx-Pl
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Qtz
B
Grt
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C
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One possible explanation is the formation of orthopyroxene moats with an absence of plagioclase in nearby microdomains (fig. 4*D*). The third subtype consists of coarse-grained orthopyroxene with minor fine-grained plagioclase intergrowths, mantling clinopyroxene porphyroblasts (Opx-Pl_3). These symplectites probably formed later than Opx-Pl_1 and Opx-Pl_2, where limits such as the width of preexisting symplectitic coronas, coupled with decreasing temperature during retrogression, limited the availability of slower diffusing Al from garnets but still received Fe-Mg because of faster diffusion. Other components, except Al, were also supplied by the other reactants; clinopyroxene restricted the formation of plagioclase.

A second important type of reaction texture comprises medium-grained orthopyroxene moats separating quartz grains associated with Opx-Pl symplectites (fig. 4*D*). This texture may have resulted from early reaction between the peak assemblage phases (Grt + Cpx + Qtz) or originated with the earliest symplectite formation during decompression.

Microprobe analysis shows that orthopyroxene is present in clinopyroxene as lamellae that are too fine to be discerned under an optical microscope. Fe-Ti oxides and rutile are accessory phases. Rutile occurs only as inclusions in clinopyroxene and garnet, whereas opaque phases are present in the matrix and as inclusions in garnet and clinopyroxene (fig. 4*E*). The textural features described above are compatible with reactions between garnet, clinopyroxene, and quartz to form orthopyroxene and plagioclase, similar to

$$\mathrm{Grt} + \mathrm{Cpx} + \mathrm{Qtz} = \mathrm{Opx} + \mathrm{Pl}. \quad (1)$$

Mineral Chemistry

Electron microprobe analyses were carried out using a JEOL JED2140-JSM 5301S electron probe at Okayama University (now at Kyushu University), Japan. The "MINM 53" standard was used for analyzing SiO_2, TiO_2, Cr_2O_3, Al_2O_3, FeO, MgO, MnO, CaO, Na_2O, and K_2O. The data were reduced using ZAF correction procedures. Fe^{3+} was calculated by charge balance following the procedure of Droop (1987). Results from representative analyses are given in tables A1–A3, which are available in the online edition or from the *Journal of Geology* office. A summary of mineral chemistry and thermometric calibrations (explained in "Thermodynamic Modeling and Pressure-Temperature Estimates") is given in tables 1 and 2. The compositions of garnet, clinopyroxene, orthopyroxene, and plagioclase are illustrated in an Al_2O_3-CaO-FeO (ACF) projection (fig. 6). The x-ray (chemical) mapping described in figure 5 was made with a JEOL JXA-8900R superprobe at Okayama University of Science, Japan.

Garnet compositions are mainly a grossular-almandine-pyrope (Grs-Alm-Prp) mixture. Garnet core compositions are typically $Prp_{32.5–34.7}$, $Alm_{46.7–47.7}$, $Grs_{16.1–19.3}$. In contrast, garnet rims are zoned within 200–300 μm of their grain boundary and show slightly different compositions, depending on the associated mineral. Garnet rims that are associated with clinopyroxene (e.g., fig. 4*A*) are slightly more Fe rich ($Prp_{28.9–29.5}$, $Alm_{49.4–52.3}$, $Grs_{19.1–20.5}$) than those that are associated with Opx-Pl symplectites or orthopyroxene moats ($Prp_{27.7–29.5}$, $Alm_{47.8–49.9}$, $Grs_{20.7–20.9}$). Pattison and Bégin (1994) explained similar neighbor dependence of garnet zoning from garnet-orthopyroxene granulites. Clinopyroxenes are slightly aluminous (3.6–4.2 wt% Al_2O_3), with an X_{Mg} [Mg/(Mg + Fe)] of 0.582–0.800 in cores and 0.740–0.846 in rims. Orthopyroxene lamellae in clinopyroxene have the highest Al_2O_3 (up to 3.80 wt%) and X_{Mg} (up to 0.575) content of all textural types of orthopyroxene. The symplectites and moat orthopyroxenes contain 2.15–2.40 wt% Al_2O_3, and X_{Mg} varies from 0.530 to 0.564. Orthopyroxene lamellae have the highest (1.7 wt%) CaO content, whereas symplectite phases associated with garnet-clinopyroxene layers have only 0.5–0.7 wt% CaO. Plagioclase in the studied samples has a high anorthite content ($An_{91.5–84.1}$, $Ab_{0.085–0.142}$; Ab = albite).

Figure 4. Photomicrograph of garnet-clinopyroxene-quartz (Grt-Cpx-Qtz) granulite. *A*, Major mineral assemblages of the Grt-Cpx-Qtz granulite of the Highland Complex, Sri Lanka. *B*, Grt-Cpx-Qtz association. *C*, Garnet and clinopyroxene porphyroblasts associated with quartz. Note the fine rim of orthopyroxene-plagioclase symplectite along the grain boundaries of porphyroblasts. *D*, Complete replacement of garnet by orthopyroxene-plagioclase symplectite. Note the orthopyroxene moat on the quartz rim. *E*, Clinopyroxene and garnet porphyroblasts of various sizes, with rare inclusions of rutile (*Rt*) and Fe-Ti oxides (*Opq*). *Opx* = orthopyroxene; *Pl* = plagioclase. Scale bars = 1 mm. A color version of this figure is available in the online edition of the *Journal of Gology*.

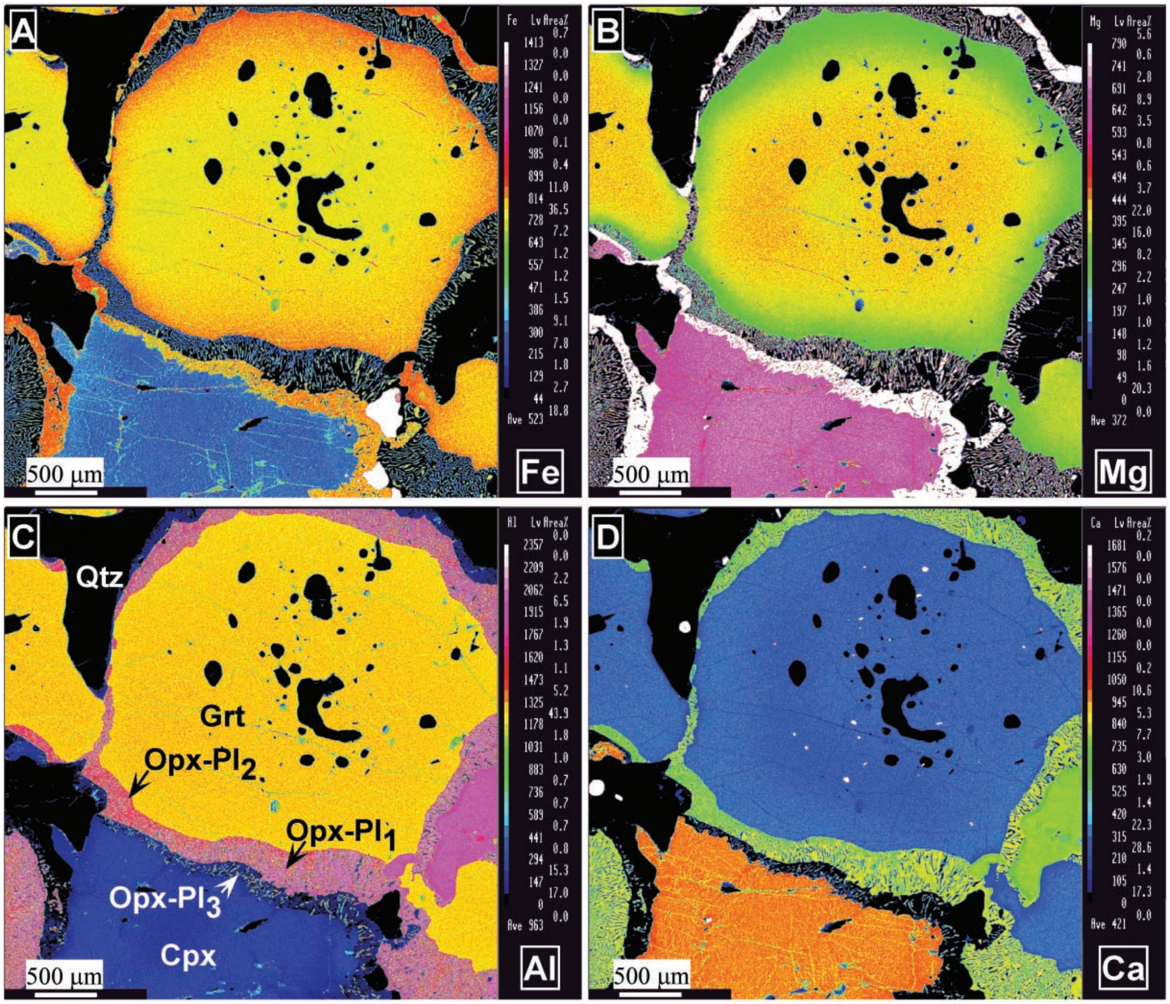


Figure 5. X-ray intensity (chemical) maps of Fe, Mg, Al, and Ca, differentiating the three types of orthopyroxene-plagioclase (*Opx-Pl*) symplectite associated with garnet (*Grt*) and clinopyroxene (*Cpx*). The three types of Opx-Pl symplectite are labeled in *C*; see "Mineral Assemblages and Textural Features" for explanation.

Metamorphic Evolution

U-Pb Zircon In Situ Dating. Zircons were separated from a garnet-clinopyroxene-quartz granulite sample for geochronology, and U-Pb measurements were performed with LA-ICPMS at the Tokyo Institute of Technology using analytical procedures outlined by Iizuka and Hiratha (2004). The analytical results are given in table 3.

Rare zircons in the studied sample occur only within garnet porphyroblasts (fig. 7); none were observed in the retrograde symplectites. So we assume that the separated zircons were initially situated within the garnet. The zircon grains were separated following the procedure of Katayama et al. (2001), using facilities at the Tokyo Institute of Technology. Crushed samples were dispersed in water followed by panning and magnetic and heavy-liquid separation. The grains were handpicked with the aid of a fluorescent system microscope, and they were mounted on 25-mm epoxy disks. Polished zircon mounts were carefully examined under polarized and reflected light to trace the inclusions. All the inclusions were later checked using a laser-Raman spectroscope at the Tokyo Institute of Technology. Inclusion-free areas were selected for laser ablation analysis. Cathodoluminescence (CL) images were taken of all zircons before and after the geochronological studies in order to check the zoning and overgrowth patterns for the exact analysis points (fig. 7).

Table 1. Summary of Representative Mineral Chemistry for the Grt-Cpx-Qtz Granulite, Sri Lanka

	Peak assemblage			Retrograde assemblage		
	Grt		Cpx		Opx	Pl
Texture	X_{Mg}	X_{Grs}	X_{Mg}	Texture	X_{Mg}	X_{An}
Prb core:						
	.426	.189	.582	Sym	.535	.895
	.422	.200	.589	Sym	.555	.846
	.419	.167	.610	Sym	.553	
	.415	.189	.613	Sym	.567	
	.404	.187	.630	Sym	.572	
	.427	.187	.694	Lamella	.584	
	.425	.193	.700	Moat	.542	
	.421	.161	.712			
	.416	.188	.738			
	.406	.180	.736			
			.762			
			.745			
			.783			
			.824			
Prb rim:						
	.357	.207	.859			
	.382	.209	.810			
	.394	.186	.793			
	.365	.194	.770			
	.350	.191	.758			
	.374	.205				

Note. Mineral chemistry is based on tables A1–A3, available in the online edition. Grt = garnet; Cpx = clinopyroxene; Qtz = quartz; Prb = porphyroblast; Opx = orthopyroxene; Pl = plagioclase; Sym = Opx-Pl symplectite.

The zircon grains in the analyzed sample are mostly rounded, typical of granulites, and contain very few fluid and mineral inclusions, which are mainly of CO_2-, H_2O-, and CO_2 + H_2O-fluids and apatite confirmed by laser-Raman spectroscopy. The CL images reveal oscillatory zoning patterns throughout the grains, and it is difficult to identify any inherited cores. Most of the analyzed core and rim values cluster together in the lower part of the concordia diagram, with no upper intercept (fig. 8). The cores and rims yield a lower intercept age of ca. 580 Ma, with a concordance above 99%. The analytical results plot on the concordia, suggesting a major thermal event in the late Neoproterozoic (fig. 8).

Sm-Nd Geochronology. Garnet, clinopyroxene, orthopyroxene, a felsic fraction, and a whole-rock fraction were separated using the procedure of Nakano (2002), with Sm-Nd isotopes measured using an isotope dilution–thermal ionization mass spectrometer (ID-TIMS; MAT-262) equipped with nine Faraday cups at the Graduate School of Science and Technology, Niigata University, Japan. The method for extracting Sm and Nd from mineral grains and rock powder follows the procedure of Kagami et al. (1982, 1989). The process for dissolving garnet closely follows the method of Krogh (1973) and Hamamoto et al. (1999). Isotope measurements were made by adding a ^{149}Sm-^{150}Nd mixed spike. The ^{143}Nd/^{144}Nd ratios were corrected to 0.512116 for JNdi (Geological Society of Japan standard), which corresponds to 0.511858 of La Jolla (Tanaka et al. 1997). Isochrons and age calculations were computed using the computer program of Kawano (1994) based on the equation of York (1966), with the following decay constant: $\lambda(^{147}\text{Sm}) = 6.54 \times 10^{-12}\ \text{yr}^{-1}$ (Lugmair and Marti 1978).

The isotope compositions of all major minerals (garnet, clinopyroxene, orthopyroxene), a felsic fraction (Pl + Qtz), and a whole-rock fraction were obtained for the geochronological studies. Zhou and Hensen (1995) and Unnikrishna-Warrier et al. (1995) noted the effect of inclusions in garnet on the Sm-Nd system. In our analyzed sample, the only major inclusion in garnet is quartz, and extreme care was taken during handpicking to select the garnets with the fewest inclusions. The most important potential contaminating materials in the matrix of this sample are opaque phases, which were separated magnetically using an isodynamic separator followed by handpicking. Because of the lack of multimineral phases and complex reaction textures, the Sm-Nd system is considered to be a reliable method for geochronological calculations in this type of mafic granulite.

The Sm and Nd concentrations, isotope ratios, and resultant ages for the whole rock and separated minerals are presented in table 4. Uncertainties on individual ^{143}Nd/^{144}Nd values are quoted at the 2σ levels and are typically 0.000014 or less. An internal isochron including all mineral fractions and the whole rock gives an age of 534 ± 12 Ma (fig. 9).

Isotopic mineral ages are sensitive to the representative closure temperature of minerals (Dodson 1973). In an internal isochron, garnet is the strongest controlling factor. Despite numerous studies on the closure temperature of Sm-Nd diffusion in garnet, estimates for closure are in the range 500°–900°C, with an apparent dependence on garnet composition (Humphries and Cliff 1982; Cohen et al. 1988; Jagoutz 1988; Mezger et al. 1992; Paquette et al. 1994; Hensen and Zhou 1995; Maboko and Nakamura 1995; Schmädicke et al. 1995; Wang et al. 1998). We conclude that the 534 ± 12 Ma date given by the internal isochron is a cooling age, indicating the timing of decompression after peak metamorphism. The isochron represented in figure 9 for initial minerals, retrograde minerals, and the whole-rock fraction defines a coherent isochron, indicating that the rock experienced rapid cooling after peak metamorphism or complete resetting to

Table 2. Summary of the Grt-Cpx Thermometric Calculations for the Selected Core Composition

	Peak assemblage				Temperature (°C)[a]						
	Grt		Cpx								
	X_{Mg}	X_{Grs}	X_{Mg}	K_D	EG74	P85	K88	A94	K00	G96	B95
P(ref) = 12.5 kbar:											
	.426	.189	.582	2.800	1006	996	988	943	936	1050	1044
	.422	.200	.589	3.182	964	952	943	888	885	1008	970
	.419	.167	.610	3.300	916	901	870	827	843	982	951
	.415	.189	.613	3.778	888	872	849	794	811	946	884
	.404	.187	.630	4.024	863	847	820	767	774	925	859
Average					928	913	894	844	850	982	942
SD					58	60	69	71	63	50	74
P(ref) = 10 kbar:											
				2.800	997	987	978	922	917	1042	1038
				3.182	955	943	933	869	867	1000	963
				3.300	908	893	860	807	825	974	944
				3.778	879	864	840	775	794	939	876
				4.024	863	847	820	767	774	925	859
Average					920	907	886	828	836	976	936
SD					55	58	67	66	58	47	72

Note. Grt = garnet; Cpx = clinopyroxene; Opx = orthopyroxene; Pl = plagioclase; P_{ref} = reference pressure.
[a] Sources for temperatures are as follows. EG74: Ellis and Green (1974); P85: Powell (1985); K88: Krogh (1988); A99: Ai (1999); K00: Ravna (2000); B95: Berman et al. (1995); G96: Ganguly et al. (1996).

the time of closure. It should also be noted that when cooling is very rapid, the effect of closure temperature is minor.

Thermodynamic Modeling and Pressure-Temperature Estimates. The interpretation of the mafic granulites is complicated by the high variance and refractory nature of the mineralogy. However, quartz-bearing assemblages tend to be more reactive during metamorphism. Although it is difficult to estimate peak pressures for the present assemblage (Grt-Cpx-Qtz) using geobarometric parameterizations, the absence of plagioclase in the peak assemblage suggests that the assemblage must have equilibrated outside the plagioclase stability field, most probably at pressures above the plagioclase decomposition reaction suggested by Green and Ringwood (1967). To quantify this inference, phase relations for a bulk composition in the system $CaO-Na_2O-K_2O-FeO-MgO-Al_2O_3-SiO_2$, estimated from the mineral modes and compositions of a Grt + Cpx + Qtz-rich domain, were computed as a function of pressure and temperature (fig. 10) using free-energy minimization (Connolly 2005), with end-member thermodynamic data given by Kelsey et al. (2004) and solution models as summarized in table 5. Because the clinopyroxene solution model does not incorporate K_2O, sanidine is present as a minor phase (<1 vol%), with the Grt-Cpx-Qtz assemblage in the high-pressure plagioclase-absent field of the resulting phase diagram. As the plagioclase mode increases with decompression, sanidine is absorbed into plagioclase. The X_{Mg} isopleths for garnet and clinopyroxene (fig. 11) in the phase diagram section provide a basis for establishing peak metamorphic conditions. Based on the highest X_{Mg} in garnet core (0.43) and clinopyroxene core (0.80), the P-T conditions fall on the plagioclase-out line at 12 kbar at 925°C (fig. 7), which is in agreement with the bulk chemical composition (with minor orthopyroxene and plagioclase) used for the thermodynamic modeling. Thus, we infer that the minimum pressure for the plagioclase-absent Grt-Cpx-Qtz assemblage must be above the resultant conditions, at a pressure of around 12.5 kbar and a temperature above 925°C (figs. 10, 11).

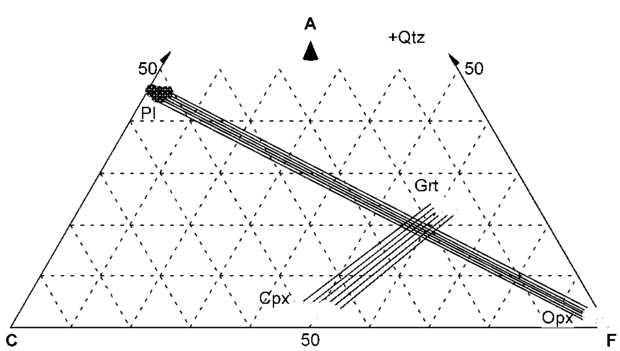


Figure 6. ACF (Al_2O_3-CaO-FeO) diagram showing mineral composition projected from quartz. Tie lines represent the associated phases and reactions. *Cpx* = clinopyroxene; *Grt* = garnet; *Opx* = orthopyroxene; *Pl* = plagioclase; *Qtz* = quartz.

Table 3. U-Pb Compositions of Zircons and Metamorphic Ages for Garnet-Clinopyroxene-Quartz Granulite from Sri Lanka

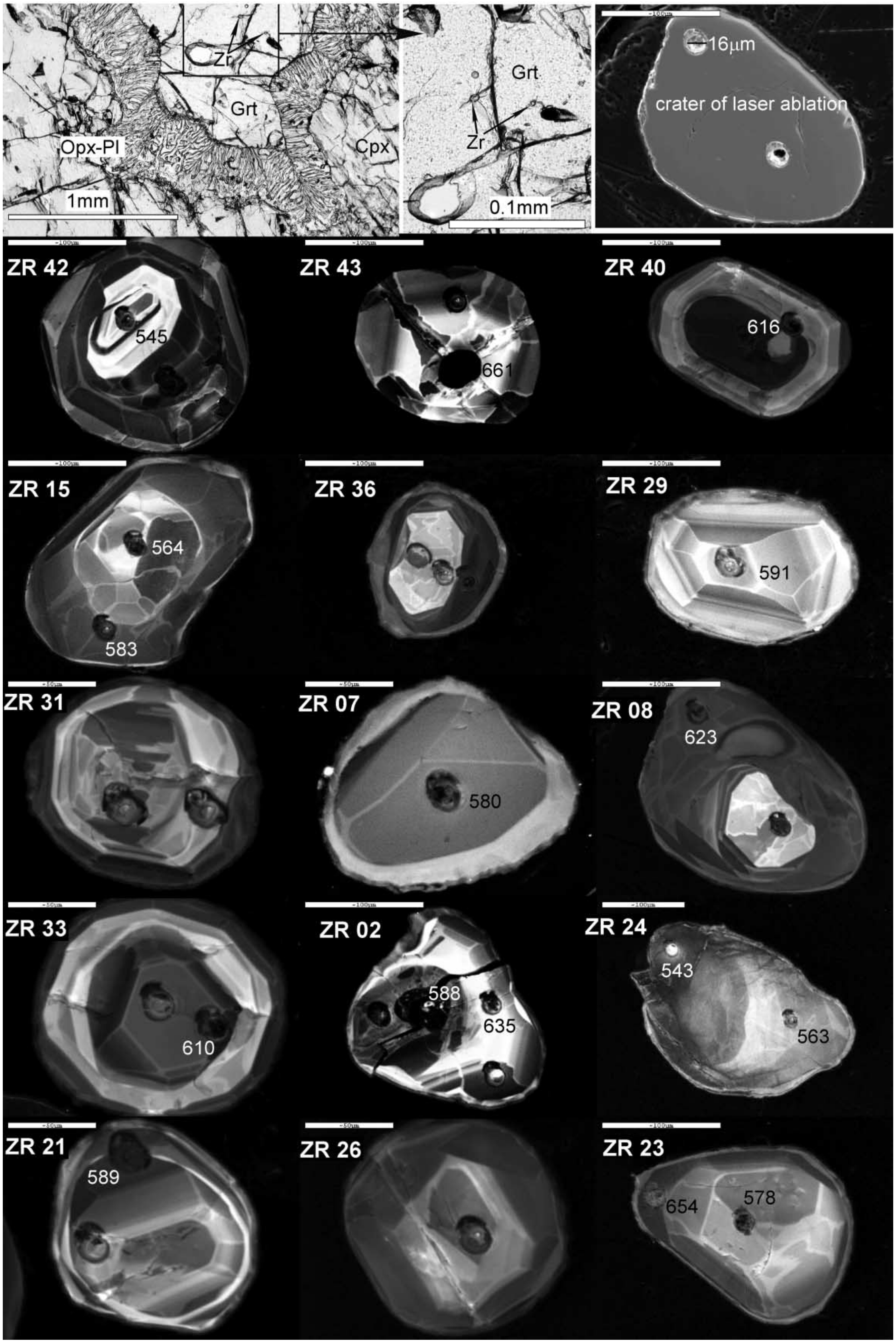
	$^{207}Pb/^{206}Pb$		$^{206}Pb/^{238}U$		$^{207}Pb/^{235}U$		$^{206}Pb/^{238}U$		$^{207}Pb/^{235}U$				
	Ratio	Err.	Ratio	Err.	Ratio	Err.	Age (Ma)	Err.	Age (Ma)	Err.	Conc. (%)	Th (ppm)	U (ppm)
Zr2 core	.059639	.000332	.095449	.001323	.784874	.011719	588	8	588	7	100	84.72484	270.0906
Zr2 rim	.062611	.000348	.100683	.001395	.869178	.012978	618	8	635	7	97	104.2093	409.6184
Zr3 core	.05818	.000324	.093114	.00129	.746944	.011153	574	8	566	6	101	45.76174	319.1513
Zr3 rim	.057321	.000319	.094467	.001309	.746619	.011148	582	8	566	6	103	62.92494	391.0539
Zr6	.057808	.000322	.099513	.001379	.793171	.011843	612	8	593	7	103	40.22832	246.0533
Zr7	.058092	.000323	.096166	.001333	.770257	.011501	592	8	580	7	102	102.2807	539.6831
Zr8-2	.061754	.000344	.099465	.001378	.846905	.012646	611	8	623	7	98	87.89866	507.1907
Zr15 core	.057286	.000319	.094092	.001304	.743198	.011097	580	8	564	6	103	53.26667	267.1255
Zr15 rim	.057355	.000319	.098186	.001361	.776467	.011594	604	8	583	7	103	122.0524	598.8715
Zr21 rim	.060469	.000234	.094388	.001084	.786958	.009539	581	6	589	5	99	67.33754	572.7571
Zr22 rim	.058501	.000227	.094425	.001085	.761644	.009233	582	6	575	5	101	87.88698	530.4495
Zr22 core	.061186	.000237	.096977	.001114	.818134	.009917	597	7	607	6	98	50.49421	421.0197
Zr23 core	.059941	.000232	.092878	.001067	.767604	.009305	573	6	578	5	99	59.03948	437.3448
Zr23 rim	.059724	.000231	.107848	.001239	.888098	.010765	660	7	645	6	102	240.5175	1016.553
Zr24 core	.05912	.000229	.090913	.001044	.741078	.008983	561	6	563	5	100	71.68386	417.9739
Zzr24 rim	.05465	.000212	.093733	.001077	.706289	.008562	578	6	543	5	106	268.0873	377.0529
Zr29	.061242	.000237	.09361	.001075	.790456	.009582	577	6	591	5	98	40.62909	386.1604
Zr33 rim	.057088	.000129	.097651	.001395	.768637	.011121	601	8	579	6	104	60.71333	339.4639
Zr40-2	.062978	.000519	.096138	.002393	.834807	.021889	592	14	616	12	96	126.6176	583.2644
Zr41-1	.059734	.000493	.087831	.002186	.723383	.018968	543	13	553	11	98	58.47165	415.4575
Zr42-1	.059963	.000495	.085868	.002137	.709929	.018615	531	13	545	11	97	80.53976	216.5223
Zr43-1	.062553	.000516	.106326	.002646	.917047	.024046	651	15	661	13	99	138.2377	5123.467

Note: Err. = error; Conc. = concordance.

The peak temperature for the plagioclase-orthopyroxene-absent assemblage (Grt-Cpx-Qtz) was also calculated by using the Fe-Mg exchange thermometer for the core compositions of the coexisting garnet and clinopyroxene. Garnet rim and clinopyroxene rim thermometers have not been attempted because the textural features indicate that the consumption of garnet is greater than that of clinopyroxene. Thus, the present garnet and clinopyroxene rims may not be in equilibrium. Moreover, the retrograde Fe-Mg exchange between garnet and clinopyroxene may hamper the peak equilibrium condition. As explained above, it is clear that the pressure of the peak assemblage must be on the high-pressure side of the plagioclase-out reaction curve at around 12.5 kbar.

Temperature calibration using coexisting garnet (core) and clinopyroxene (core) gives a maximum estimate of 1050°C (average 982° ± 50°C) with the Ganguly et al. (1996) method at 12.5 kbar (table 2; fig. 11). The methods of Ellis and Green (1974), Berman et al. (1995), Powell (1985), and Krogh (1988) yield similar maximum temperature limits of 1006°C (928° ± 58°C), 1044°C (942° ± 74°C), 996°C (913° ± 60°C), and 988°C (894° ± 69°C), respectively. Ai's (1999) and Ravna's (2000) methods yield slightly lower temperature maxima of 943°C (844° ± 71°C) and 936°C (850° ± 63°C), respectively.

P-T-t ***Evolution.*** The petrographic results, thermodynamic modeling, thermometric estimates, and geochronological results were compiled to trace the metamorphic evolution of the studied dry mafic granulite (fig. 11). The peak assemblage is equilibrated in the plagioclase-absent field followed by the Opx-Pl symplectite overprint that indicates an isothermal decompression path (fig. 11). With our results superimposed, the evolution supports a near-isothermal decompression from a pressure of 12.5 kbar in the plagioclase-absent stability field at a temperature around 925°C within a dry condition at ca. 580 Ma. The rock cooled to 900°C at ca. 530 Ma. Schenk et al. (1988) determined an isobaric cooling and late-decompression *P-T* path for mafic granulites (Grt-Cpx-Opx-Qtz-Pl-Hbl) from the Highland Complex, Sri Lanka. By combining our result of isothermal decompression from high pressures at UHT conditions with the isobaric cooling and decompression path of hydrous mafic granulites, a multistage decompression history can be traced. The present *P-T* path of the mafic granulite can thus be correlated with the evolution of UHT pelitic granulites, as suggested by Sajeev and Osanai (2004*b*) and Osanai et al. (2006).



Zr
Grt
Opx-Pl
Cpx
1mm
Grt
Zr
0.1mm
16μm
crater of laser ablation
ZR 42
545
ZR 43
661
ZR 40
616
ZR 15
564
583
ZR 36
ZR 29
591
ZR 31
ZR 07
580
ZR 08
623
ZR 33
610
ZR 02
588
635
ZR 24
543
563
ZR 21
589
ZR 26
ZR 23
654
578

Discussion and Conclusion

Our study reports the first HP-UHT, Grt-Cpx-Qtz granulites from the Highland Complex, Sri Lanka. Textural relationships indicate that the peak assemblage of Grt-Cpx-Qtz breaks down to form plagioclase and orthopyroxene symplectites during decompression. Thermodynamic modeling indicates a high-pressure stability of the peak Grt-Cpx-Qtz assemblage (fig. 10). The *P-T* conditions derived through the X_{Mg} isopleths of garnet and clinopyroxene gave a peak temperature around 925°C at a minimum peak pressure of 12.5 kbar (fig. 11). The thermometric results of this study, derived from core values of coexisting garnet-clinopyroxene pairs, indicate a UHT peak metamorphism with average temperature ranging from 844°C to 982°C (with a maximum estimate of 1050°C) at a pressure above the plagioclase stability field (around 12.5 kbar). The sample reported here is situated within the highest-temperature zone of Sajeev and Osanai (2005) and is also surrounded by many new UHT localities of the Highland Complex (e.g., Osanai 1989; Kriegsman and Schumacher 1999; Osanai et al. 2000, 2006; Sajeev and Osanai 2004*b*). The total absence of any hydrous minerals (e.g., biotite or hornblende) in the samples studied suggests that the HP-UHT metamorphism occurred locally at low aH_2O with no postpeak hydration, which is rare for mafic rocks of the Highland Complex or elsewhere in eastern Gondwana.

Schumacher and Faulhaber (1994) concluded that the near-peak conditions of mafic granulites from the Highland Complex were around 760°–830°C and 8–10 kbar; these contradict our results. Schenk et al. (1988) proposed a *P-T* segment of near-isobaric cooling followed by isothermal decompression for hornblende-bearing mafic granulites of the Highland Complex. The isothermal decompression path of the dry Grt-Cpx-Qtz granulite (this study) from the peak metamorphism can be connected with the late isobaric cooling and decompression suggested by Schenk et al. (1988). This gives rise to a multistage decompression history similar to that inferred from UHT pelitic granulites of the Highland Complex (Sajeev and Osanai 2004*b*) and other parts of eastern Gondwana (e.g., southern India; Raith et al. 1997; Sajeev et al. 2004, 2006). Our results are

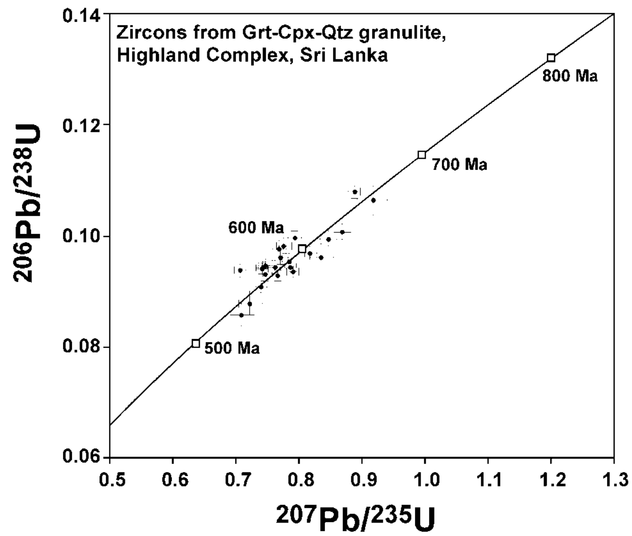


Figure 8. Concordia plot of laser ablation–inductively coupled plasma mass spectrometry U-Th-Pb zircon analysis. See text for explanation. *Grt* = garnet; *Cpx* = clinopyroxene; *Qtz* = quartz.

also supported by the decompression from higher pressure followed by multistage evolution proposed by Osanai et al. (2006) for a suite of pelitic, quartzofeldspathic, and mafic granulites from the Highland Complex.

The *P-T* conditions indicate that peak metamorphism probably took place at a depth of around 40–50 km, which can be considered to be the crustal thickness of the central Highland Complex. A review by Schumacher and Faulhaber (1994) assumed a crustal thickness of up to 36 km and that all granulites were metamorphosed below 10 kbar and 830°C.

The U-Pb zircon dating using the LA-ICPMS method yielded an age of ca. 580 Ma. Considering the high closure temperature of zircon in the U-Pb system (above 900°C; Cherniak and Watson 2001, 2003), the derived age could be the time of peak HP-UHT metamorphism (fig. 11). The fact that zircons always occur within garnets (fig. 8) also indicates that the formation of zircons must be associated with the peak metamorphic assemblages.

Figure 7. Zircon photomicrographs showing craters of laser ablation–inductively coupled plasma mass spectrometry analysis (scanning electron microscopy image) and cathodoluminescence images of zircons from garnet-clinopyroxene-quartz granulite, Sri Lanka. Scale bars = 50 μm for ZR 31, ZR 07, ZR 33, ZR 21, and ZR 26; all other scale bars = 100 μm. *Cpx* = clinopyroxene; *Grt* = garnet; *Opx* = orthopyroxene; *Pl* = plagioclase; *Zr* = zircon.

Table 4. Sm-Nd Compositions and Metamorphic Ages for Garnet-Clinopyroxene-Quartz Granulite from Sri Lanka

	Sm (ppm)	Nd (ppm)	$^{143}Nd/^{144}Nd$ Ratio	2σ	$^{147}Sm/^{144}Nd$
Grt	4.740	5.110	.512849	.00001390	.560811615
Cpx	1.620	7.740	.511348	.00001404	.126496910
Opx	10.100	42.900	.511377	.00001355	.142289520
FF	.202	1.390	.511181	.00001181	.087826450
WR	5.280	17.200	.511547	.00001363	.185537508

Note. Age = 532 ± 21 Ma. Grt = garnet; Cpx = clinopyroxene; Qtz = quartz; Opx = orthopyroxene; FF = felsic fraction; WR = whole rock.

Considering the CL analysis in comparison with individual ages, even though the well-rounded zircon grains shows oscillatory zoning, there is no significant difference in the ages derived from the core and the rim, indicating a metamorphic origin for the zircons.

The internal isochron ages in the Sm-Nd system (ca. 530 Ma) represent a minimum age (fig. 11) for the time of UHT granulite-grade metamorphism in the Highland Complex. As mentioned above, determination of the closure temperature of garnet in the Sm-Nd system is problematic. Cohen et al. (1988) suggested a higher closure temperature for garnet from granulites of the Bergen Arc, which have a composition of $Alm_{0.31-0.35}$, $Prp_{0.43-0.49}$, $Grs_{0.15-0.23}$. A temperature of 850°C was calculated by Jagoutz (1988) for eclogites from Nzega and by Paquette et al. (1994) for granulites in Madagascar. Gebauer (1990) and Paquette et al. (1994) suggested that a high closure temperature is reasonable for high-grade terranes that have brief cooling histories. In garnet- and pyroxene-bearing rock types, Sm-Nd diffusion in garnet is strongly affected by associated clinopyroxene, which stops diffusing at higher temperatures (Kalt et al. 1994). Jagoutz (1988) suggested a closure temperature of around 850°C for similar rock types from Tanzania. Results of our study, indicating a temperature above 900°C for coexisting garnet-clinopyroxene pairs and a garnet composition of $Alm_{0.46-0.53}$, $Prp_{0.27-0.34}$, $Grs_{0.20-0.30}$, suggest that a higher closure temperature is also appropriate. Moreover, in the present case, garnet, clinopyroxene, orthopyroxene, a felsic fraction, and a whole rock form a single straight isochron, probably indicating that uplift could have taken place within a short span of time and hence have had less effect on closure temperature.

High-pressure UHT granulites are rarely reported from Neoproterozoic Gondwana terranes. Sajeev and Santosh (2006) described unique occurrences of garnet-bearing spinel orthopyroxenite from southern India; they estimated that peak temperature-pressure conditions of ca. 1000°C at 17 kbar fall well within the HP-UHT granulite field. Our results indicate the possibility of a regional HP-UHT event during the Neoproterozoic metamorphism. The *PT* path reported from the UHT pelitic granulites of eastern Gondwana indicates a complex retrograde (multistage) history after the peak UHT event. The isobaric cooling segment after peak metamorphism reported by Sajeev and Osanai (2004*b*) from the Highland Complex and by Goncalves et al. (2004) from northern Madagascar is not identified in the mafic granulites of the Highland Complex (our study) or from the central Madurai Block (Sajeev and Santosh 2006). These results, coupled with those of previous studies, indicate an isothermal decompression followed by isobaric cooling and a second stage of isothermal decompression path after peak UHT conditions. This *P-T* path is in good agreement with the reported *P-T* evolution from other East Gondwana fragments (e.g., Harley et al. 1990; Goncalves et al. 2004; Sajeev and Osanai 2004*a*, 2004*b*; Sajeev et al. 2004, 2006).

Available geochronological results indicate that the UHT metamorphic event in eastern Gondwana must have taken place in the Neoproterozoic. There are some contradicting data from the Highland Complex, Sri Lanka (ca. 1000-Ma event: Kröner et al. 1987; ca. 1400-Ma event: Sajeev et al. 2003), and from other fragments of eastern Gondwana, but these results are not well constrained regionally and hence require reexamination before discussion. Also, there are a few ages reporting a possible early Neoproterozoic UHT thermal event (ca. 800 Ma; e.g., Goncalves et al. 2004; Motoyoshi et al. 2006) from eastern Gondwana. This indicates the possibility of multiple thermal events within

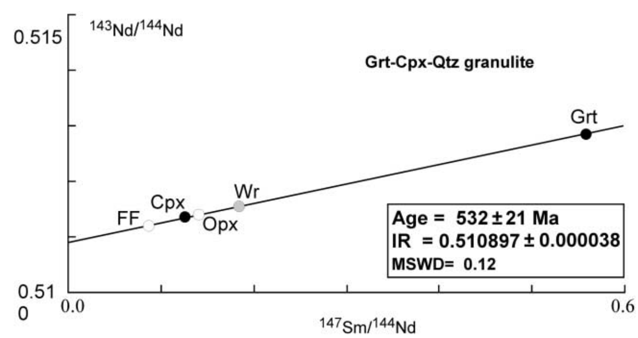


Figure 9. Internal Sm-Nd isochron for mafic minerals (*Cpx* = clinopyroxene; *Grt* = garnet; *Opx* = orthopyroxene), felsic fraction (*FF*), and whole rock (*WR*).

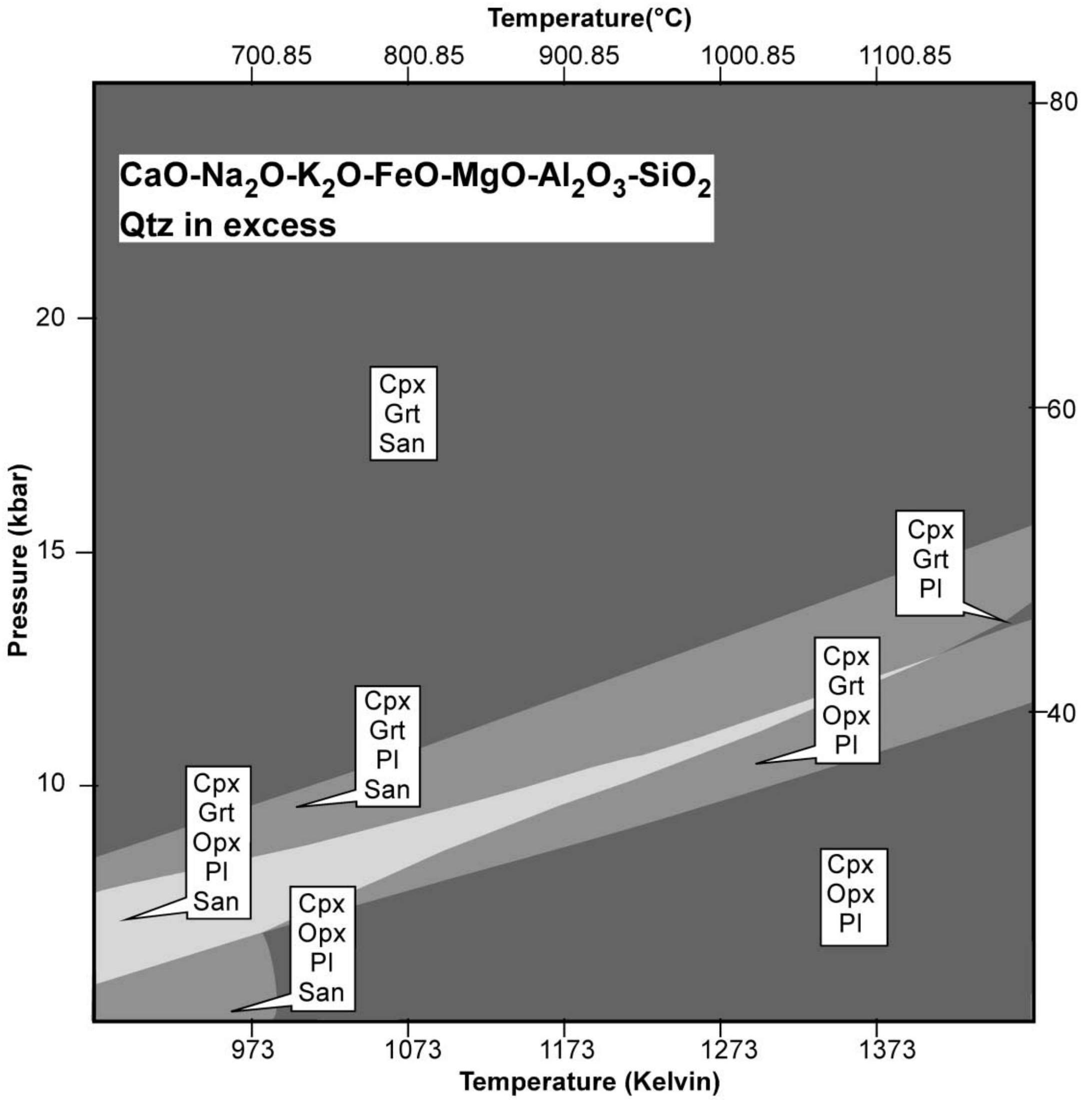


Figure 10. Pseudosection modeled in the CaO-Na_2O-K_2O-FeO-MgO-Al_2O_3-SiO_2 system calculated for a bulk chemical composition of 11.63 : 0.26 : 0.12 : 11.66 : 8.45 : 10.97 : 56.91 for the dry mafic (Grt-Cpx-Qtz) granulite of the Highland Complex, Sri Lanka. See text for explanation. *Cpx* = clinopyroxene; *Grt* = garnet; *Opx* = orthopyroxene; *Pl* = plagioclase; *Qtz* = quartz.

Table 5. Solution Notation, Formulas, and Model Sources for Phase Diagram Calculation

Symbol	Solution	Formula	Source
Cpx	Clinopyroxene	$Ca_{2y}Mg_{4-2x-2y}Fe_{2x}Si_4O_{12}$	Holland and Powell 1996
Grt	Garnet	$Fe_{3x}Ca_{3y}Mg_{3(1-x+y+z/3)}Al_{2-2z}Si_{3+z}O_{12}$, $x + y \leq 1$	Holland and Powell 1998
Opx	Orthopyroxene	$[Mg_xFe_{1-x}]_{4-2y}Al_{4(1-y)}Si_4O_{12}$	Holland and Powell 1996
Pl	Plagioclase	$K_yNa_xCa_{1-x-y}Al_{2-x-y}Si_{2+x+y}O_8$, $x + y \leq 1$	Fuhrman and Lindsley 1988
San	Sanidine	$K_yNa_xCa_{1-x-y}Al_{2-x-y}Si_{2+x+y}O_8$, $x + y \leq 1$	Fuhrman and Lindsley 1988

Note. Unless otherwise noted, the compositional variables x, y, and z can vary between 0 and unity and are determined as a function of the computational variables by free-energy minimization.

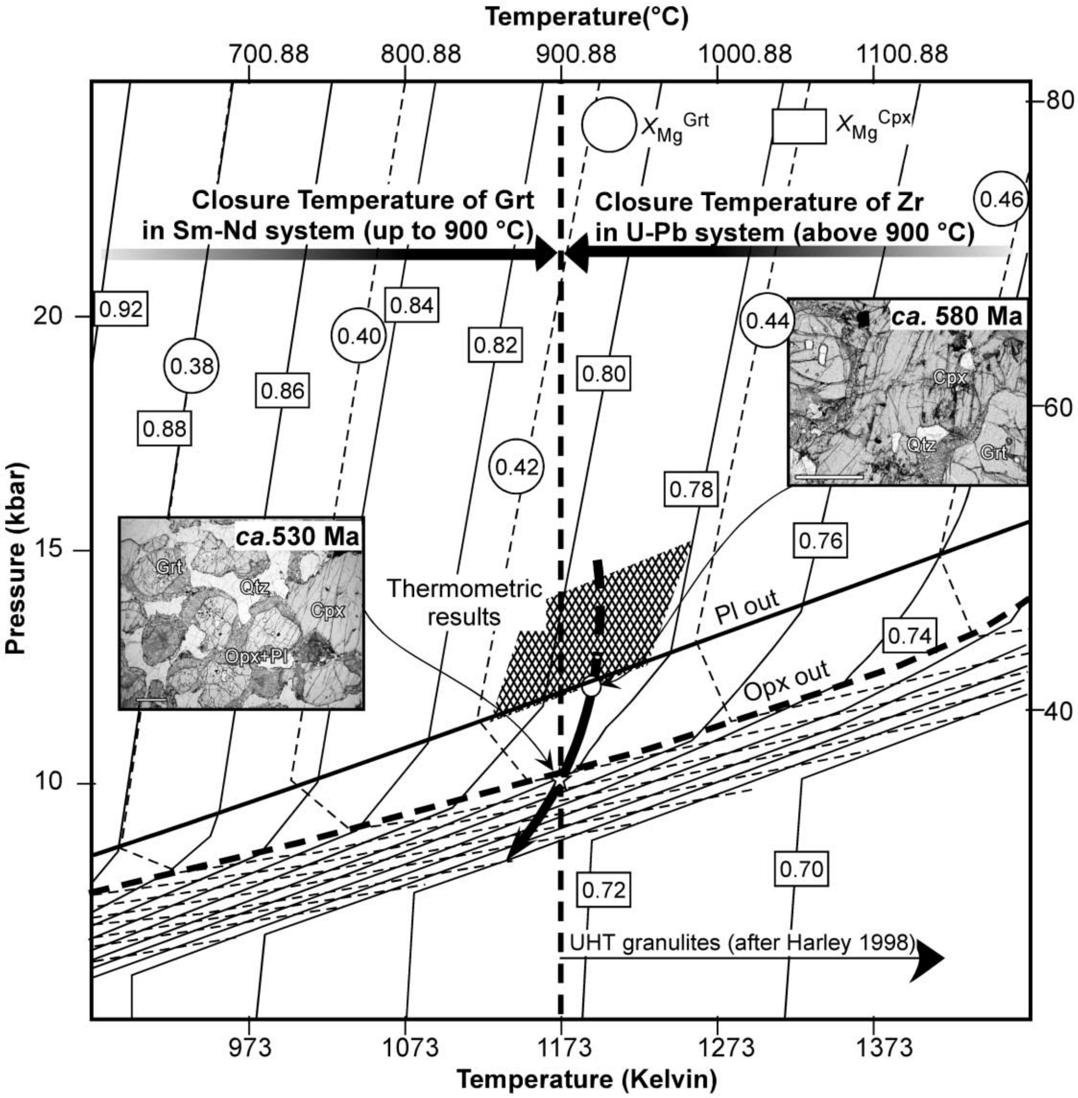


Figure 11. *P-T-t* evolution path for garnet (*Grt*)-clinopyroxene (*Cpx*)-quartz granulite, marked along with the X_{Mg} isopleths for garnet and clinopyroxene. The closure temperatures for U-Pb zircons and Sm-Nd garnets are also marked. *Opx* = orthopyroxene; *Pl* = plagioclase. *UHT* = ultrahigh temperature. See text for explanation.

Neoproterozoic time, but more region-scale *P-T-t* studies on various high-grade rock types are required. Most geochronological results from central eastern Gondwana (the Highland Complex, Sri Lanka, and the Madurai Block, southern India) indicate a peak event at ca. 550–580 Ma (e.g., Santosh et al. 2006). The 550–580-Ma event is also reported from high-grade rocks of the Lützow-Holm Complex (Fraser et al. 2000) and part of the Rayner Complex (e.g., Forefinger Point; Shiraishi et al. 1994; Motoyoshi et al. 2006) in eastern Antarctica and from northern Madagascar (Goncalves et al. 2004). It should also be noted that HP-UHT metamorphism is not yet identified from these eastern and western peripheral terranes of eastern Gondwana. We thus propose that more regional petrological and geochronological studies on mafic granulites are required to find the distribution and time of HP-UHT metamorphism within eastern Gondwana in order to understand the tectonometamorphic evolution of these continental fragments.

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