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An unusual high-Mg garnet–spinel orthopyroxenite from southern India: evidence for ultrahigh-temperature metamorphism at high-pressure conditions

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Abstract – We report here a garnet–spinel orthopyroxenite in close association with an ultrahigh-temperature (UHT) granulite from the central part of the Madurai Granulite Block in southern India. The garnet–spinel orthopyroxenite is almost entirely composed of orthopyroxene, spinel and rare garnet in a granular texture. Spinels in the rock are characterized by high Mg ($X_{Mg} = 0.69–0.71$) with low Cr and Fe^{3+}, consistent with compositions reported from spinels occurring within xenoliths in kimberlites and high pressure–temperature (*P–T*) Alpine complexes. The orthopyroxenes have high Al content (Al_2O_3 up to 4.85 wt %), typical of equilibration under high *P–T* conditions. The *P–T* estimates derived for the garnet–spinel orthopyroxenite indicate temperatures of around 1000 °C and pressures exceeding 17 kbar. The data indicate that UHT metamorphism in this locality traversed from above 17 kbar to 11 kbar prior to the final stage of isothermal decompression. Our study reports the highest pressures obtained by far, for extreme crustal metamorphism in southern India and elsewhere in Gondwana. The multi-stage decompression observed in the UHT rocks associated with the high *P–T* garnet–spinel orthopyroxenite could be correlated to extension of the crust and possibly of the lithospheric mantle and/or its delamination, with the asthenospheric mantle as the ultimate heat source, during the final stage of amalgamation of the Gondwana supercontinent.

Keywords: garnet–spinel orthopyroxenite, UHT granulite, *P–T* evolution, southern India.

1. Introduction

Southern India comprises a collage of Proterozoic granulite facies blocks that are welded onto an Archaean craton in the north along a system of late Proterozoic mega-shears termed as the Palghat–Cauvery Shear Zone System (Drury & Holt, 1980; Braun & Kreigsman, 2003; Santosh & Collins, 2003; Chetty, Bhaskar Rao & Narayana, 2003). The largest of the granulite blocks south of the Palghat–Cauvery Shear Zone System is the Madurai Block (Fig. 1). The northern Madurai Block and the Palghat–Cauvery Shear Zone region are dominantly composed of variably migmatized hornblende–biotite gneiss carrying supracrustal slivers of pelitic and aluminous granulites, along with massive charnockites, mafic granulites, calc-silicate rocks and quartzite. Intercalated sapphirine-bearing lithologies have been reported previously from a number of localities in the Madurai Block, including Panrimalai (Grew, 1984), Ganguvarpatti (Grew, 1982; Mohan & Windley, 1993; Sajeev, Osanai & Santosh, 2004; Tamashiro *et al.* 2004), Perumalmalai (Brown & Raith, 1996; Raith, Karmakar, & Brown, 1997; Prakash & Arima, 2003), Usilampatti (Prakash & Arima, 2003), Kiranur (Lal *et al.* 1984), Kodaikanal (Sajeev, Santosh & Kim, 2006) and Rajapalaiyam (Tateishi *et al.* 2004). The sapphirine–corundum association, mostly found only along the Palghat–Cauvery Shear Zone System, has also been reported in some recent studies, such as those from the Lachmanapatti–Malappatty area (Tsunogae & Santosh, 2003), Paramati and Manavadi (Koshimoto, Tsunogae & Santosh, 2004; Santosh, Tsunogae & Koshimoto, 2004), among other localities. A rare corundum–garnet–kyanite–sapphirine–spinel association has also been discovered recently from the northern domain of the Palghat–Cauvery Shear Zone System (Shimpo, Tsunogae & Santosh, 2006).

The mineral assemblages and pressure–temperature estimates reported from the Mg–Al granulites in the Madurai Block provide evidence for peak metamorphism at UHT conditions. Brown & Raith (1996) and Raith, Karmakar & Brown (1997) reported UHT peak metamorphic conditions of *c.* 900–1000 °C and 10–11 kbar from sapphirine-bearing Mg–Al granulites from the Palni hills in the central Madurai Block. Sajeev, Osanai & Santosh (2004) and Tamashiro *et al.* (2004) also reported $T > 1000$ °C UHT peak metamorphism and a multi-stage decompressional *P–T* path for sapphirine-bearing Mg–Al granulites from Ganguvarpatti in the central Madurai Block. Tateishi

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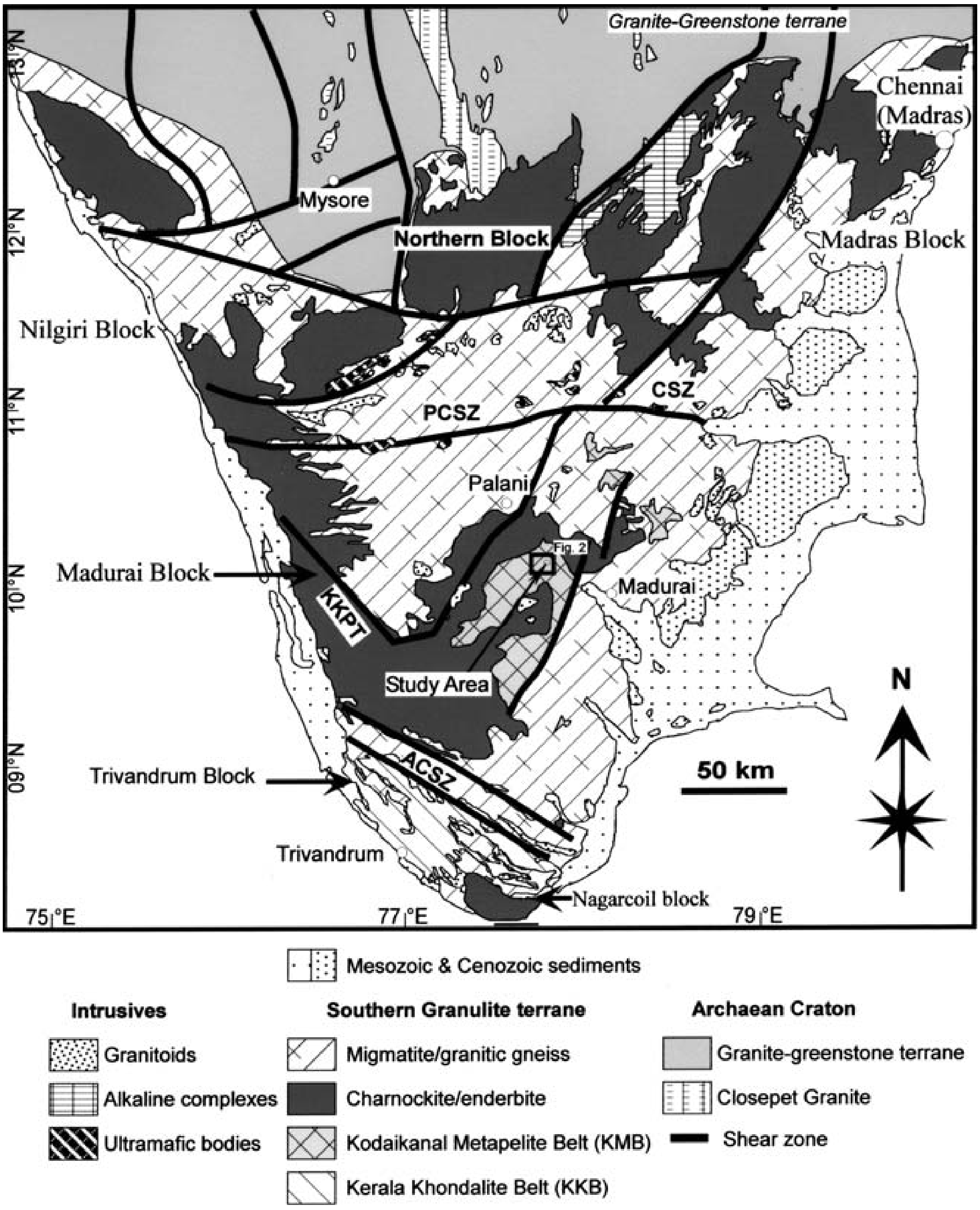

Figure 1. Generalized geology and tectonic framework of southern India. Compiled from Geological Survey of India (1995), with additional data from Drury & Holt, 1980, Santosh *et al.* 2003, Ghosh, de Wit & Zartman, 2004, Rajesh, 2004 and Sajeev, Santosh & Kim, 2006. PCSZ – Palghat–Cauvery Shear Zone; CSZ – Cauvery Shear Zone; KKPT – Karur-Kambam-Painavu-Trichur shear zone; ACSZ – Achankovil Shear Zone.

et al. (2004) recently discovered equilibrium sapphirine + quartz assemblages enclosed in garnet in pelitic granulites from the southern part of the Madurai Block around Rajapalaiyam. Their results suggest that the rocks in this area experienced temperatures exceeding 1050 °C (at 8–10 kbar), consistent with UHT metamorphism (Hensen & Green, 1973; Harley, 1998).

Available geochronological data (Santosh *et al.* 2003, 2006) indicate that the timing of UHT metamorphism coincides with the late Proterozoic–Cambrian collisional orogeny associated with the final amalgamation of the Gondwana supercontinent. However, the extreme thermal conditions attained in parts of the Madurai Granulite Block and elsewhere in the Proterozoic granulite blocks require additional heat input, potentially from underplated magmas. In this report, we document a unique high-Mg garnet–spinel orthopyroxenite in association with UHT granulites in the central part of the Madurai Granulite Block. We report the highest pressures for UHT metamorphism yet recorded from southern India and elsewhere in Gondwana.

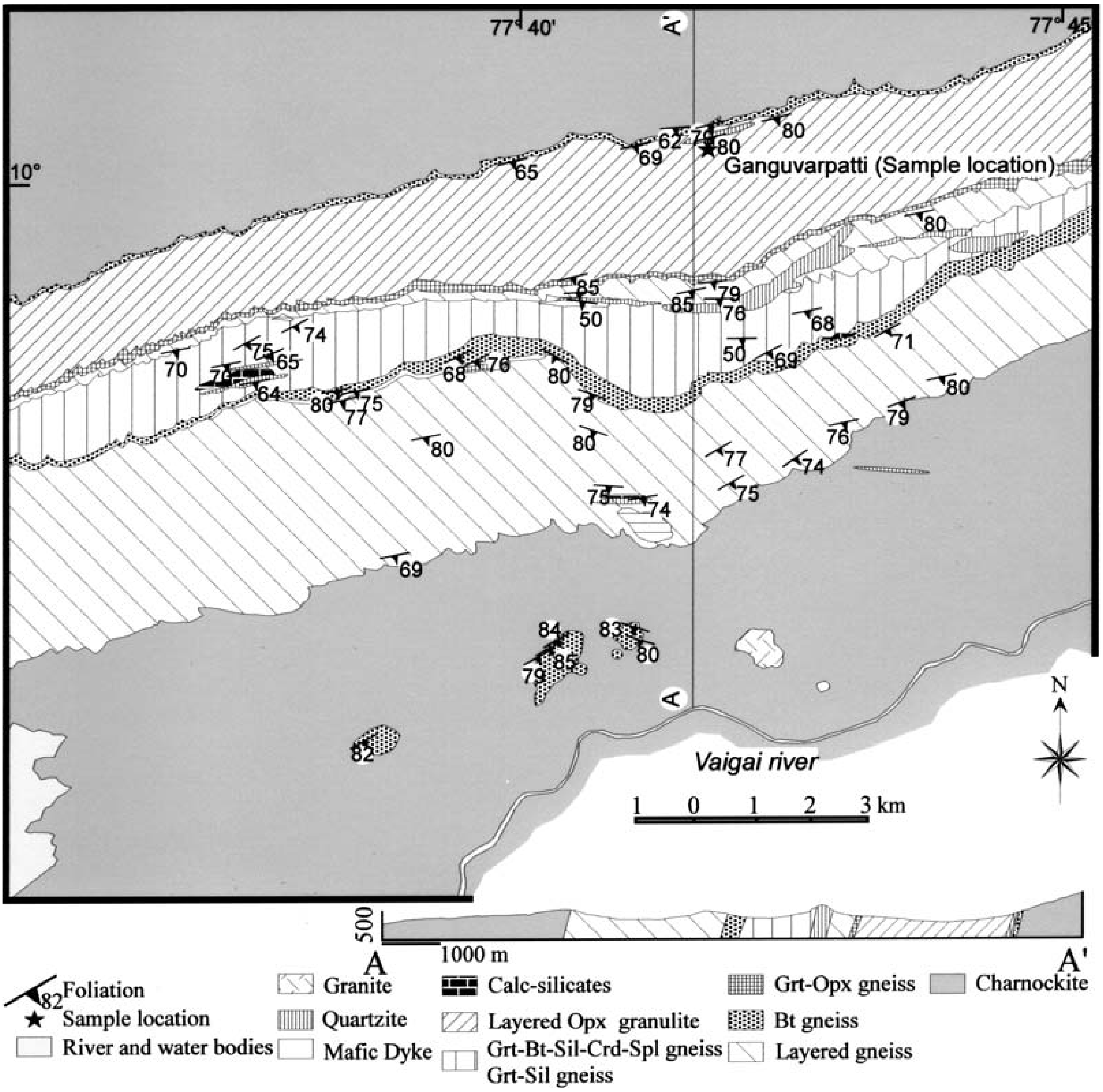

Figure 2. Geological map of central Madurai Granulite Block near Ganguvarpatti (after Sajeev, Osanai & Santosh, 2004).

2. Geological setting

The unusual spinel pyroxenite rock occurs at Ganguvarpatti (10°5′–10°15′ N and 77°35′–77°47′ E) within the central part of the Madurai Granulite Block, where recent geological mapping was carried out by Sajeev, Osanai & Santosh (2004) (Fig. 2). The study area is dominated by massive charnockite (orthopyroxene ± hornblende-bearing orthogneisses) in the northern and southern parts. Pelitic gneisses intercalated with mafic granulites and minor amounts of calc-silicate gneisses are also exposed in the region. Layered garnet–orthopyroxene–sillimanite ± quartz granulites are exposed only in one location, intercalated with spinel–orthopyroxene granulite and two-pyroxene granulites, as identified from a pit near the Ganguvarpatti village. The UHT orthopyroxene–sillimanite–quartz granulite here is interlayered with the garnet–spinel–orthopyroxene rock, although contact relations are obscure in the surface outcrops due to intense weathering.

3. Petrography of garnet–spinel orthopyroxenite

The garnet–spinel orthopyroxenite reported in this study has a fairly simple mineralogy. The rock consists largely of equigranular porphyroblasts of

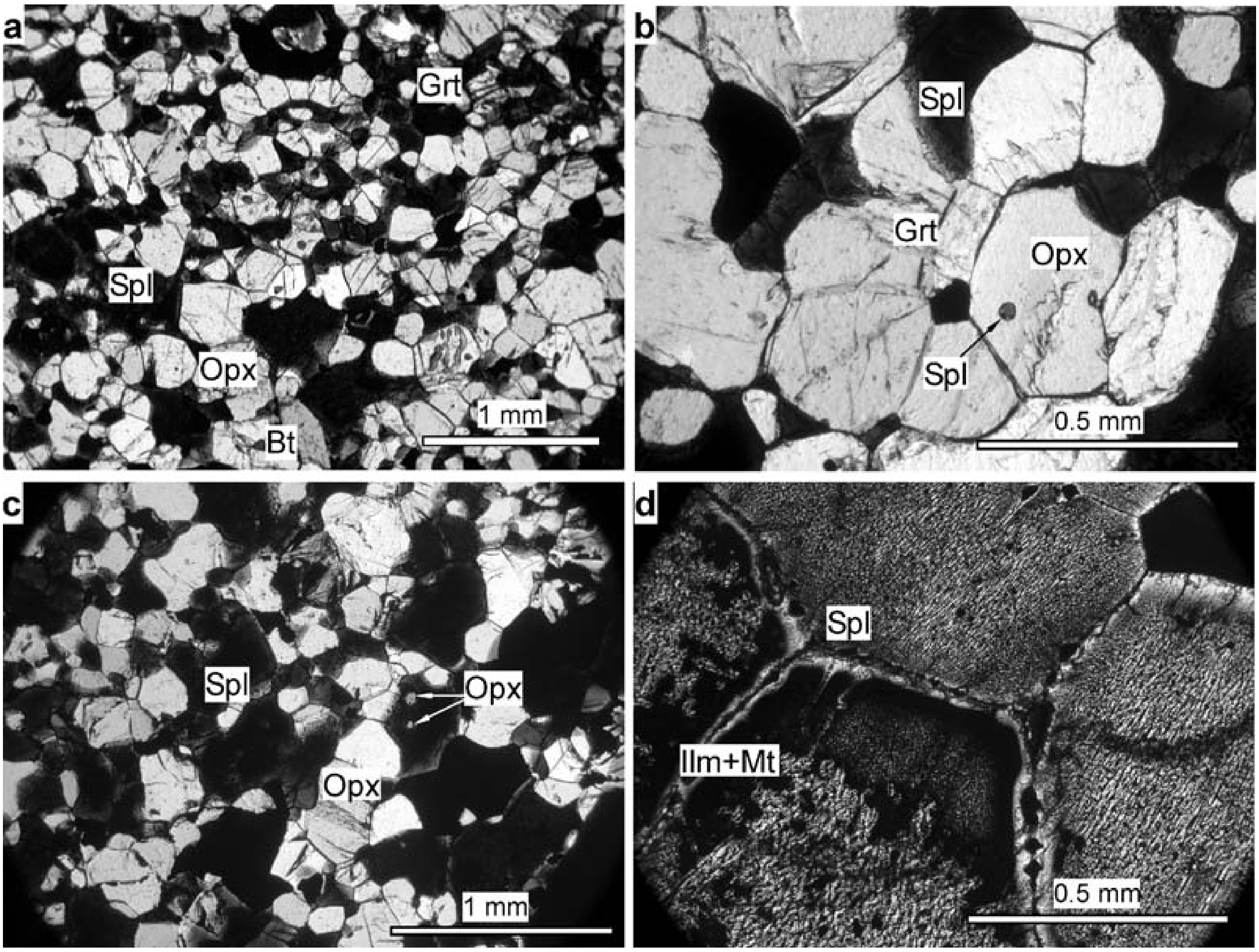

Figure 3. Photomicrographs showing mineral assemblages and textures from garnet–spinel orthopyroxenite. (a) Photomicrograph of garnet–spinel orthopyroxenite showing equigranular texture. (b) Photomicrographs of relict garnet observed in association with orthopyroxene and spinel porphyroblasts in the matrix. (c) Spinel and orthopyroxene porphyroblasts in garnet–spinel orthopyroxenite. (d) Late exsolution of Fe–Ti oxides in spinel porphyroblasts. All photomicrographs with plane polarized light.

orthopyroxene and spinel (Fig. 3a). Garnet is rare and occurs in the matrix associated with orthopyroxene and spinel megacrysts (Fig. 3b). Inclusions of spinel occur within orthopyroxene (Fig. 3b) and vice versa (Fig. 3c). No reaction textures are present in any of the observed thin-sections. The grain boundaries of minerals (orthopyroxene and spinel) are in direct contact and also form triple junctions defining typical granular texture. Exsolution of ilmenite is observed in all spinel grains (Fig. 3d). Due to varying degrees of exsolution, some spinel grains show textures similar to compositional zoning. Opaque minerals are also observed in the matrix. Biotite is extremely rare and only three to four grains were observed in a total of ten thin-sections examined (Fig. 3a). The grain size of spinel varies from very fine (0.1 mm) inclusions to megacrysts (> 1 cm). Orthopyroxene also shows similar variations in grain size. Garnet grains are relatively small, with a size less than 0.01 mm.

4. Mineral chemistry

Mineral chemical data were obtained for all the major minerals present in the rock. Representative analytical data are given in Table 1. Electron microprobe analyses were carried out using a JEOL JXA-8900R microprobe housed at Okayama University of Science, operating with an accelerating voltage of 15 kV, beam current of 12 nA. Natural and synthetic silicates and oxides are used for calibration. SiO_2, TiO_2, Cr_2O_3, Al_2O_3, FeO, MgO, MnO, CaO, Na_2O and K_2O were analysed for all minerals. ZnO was analysed for spinel and F and Cl for biotite. The data were reduced using ZAF correction procedures. Fe^{3+} was calculated by normalizing analyses to respective cation totals through charge balance considerations (Droop, 1989).

4.a. Orthopyroxene

Orthopyroxene has an X_{Mg} range of 0.832–0.825 without any marked compositional variation. The

Table 1. Representative mineral chemistry of garnet–spinel orthopyroxenite

	Opx				Spl			Grt	
SiO_2 (wt%)	53.11	53.52	55.12	54.59	0.00	0.01	0.95	41.51	41.77
TiO_2	0.44	0.27	0.19	0.20	0.30	0.45	0.27	0.00	0.00
Al_2O_3	4.85	4.81	4.01	4.25	64.92	65.91	64.10	23.50	23.54
Cr_2O_3	0.01	0.20	0.00	0.00	0.08	0.06	0.00	0.00	0.00
FeO	12.46	11.51	11.14	11.61	16.50	16.13	14.00	14.00	15.00
MnO	0.00	0.33	0.14	0.12	0.00	0.00	0.00	0.30	0.70
MgO	28.56	29.11	30.90	30.62	17.52	17.52	19.90	19.52	18.74
CaO	0.36	0.19	0.09	0.10	0.00	0.00	0.08	0.50	0.81
Na_2O	0.02	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00
K_2O	0.00	0.06	0.00	0.00	0.00	0.00	0.03	0.00	0.00
ZnO	nd	nd	nd	nd	0.00	0.00	0.03	0.00	0.00
Total	99.81	100.04	101.61	101.48	99.3	100.1	99.36	99.33	100.57
Oxygens	6	6	6	6	4	4	4	12	12
Si (pfu)	1.887	1.892	1.909	1.898	0.000	0.000	0.024	2.998	3.000
Ti	0.012	0.007	0.005	0.005	0.006	0.009	0.005	0.000	0.000
Al	0.203	0.200	0.164	0.174	1.972	1.981	1.923	2.001	1.993
Cr	0.000	0.006	0.000	0.000	0.002	0.001	0.000	0.000	0.000
Fe	0.370	0.340	0.323	0.338	0.356	0.344	0.298	0.846	0.901
Mn	0.000	0.010	0.004	0.003	0.000	0.000	0.000	0.019	0.043
Mg	1.512	1.533	1.595	1.587	0.673	0.666	0.755	2.101	2.006
Ca	0.014	0.007	0.003	0.004	0.000	0.000	0.002	0.039	0.062
Na	0.001	0.003	0.001	0.000	0.000	0.000	0.000	0.000	0.000
K	0.000	0.003	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Zn	nd	nd	nd	nd	0.000	0.000	0.001	0.000	0.000
Total cation	4.000	4.001	4.004	4.009	3.008	3.000	3.009	8.002	8.004
Fe^{3+}	0.000	0.003	0.013	0.028	0.021	0.009	0.024	0.006	0.012
Fe^{2+}	0.370	0.337	0.309	0.309	0.335	0.335	0.274	0.840	0.889
X^*_{Mg}	0.803	0.820	0.838	0.837	0.668	0.666	0.717	0.714	0.693
X_{Mg}	0.803	0.818	0.832	0.825	0.654	0.659	0.734	0.713	0.690

nd – not determined.
Fe^{3+} calculated after charge balance.

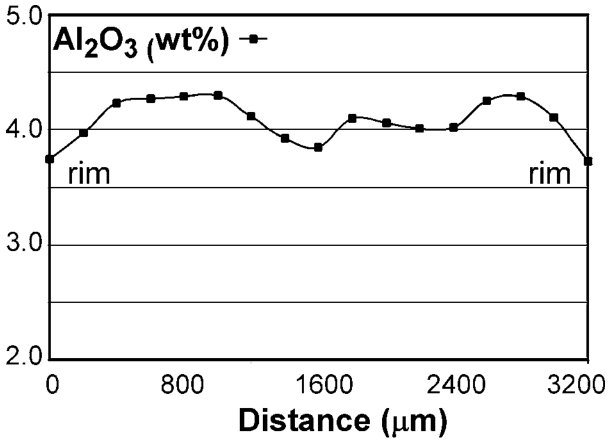

Figure 4. Al_2O_3 compositional profile of orthopyroxene porphyroblast.

mineral shows high Al content with Al_2O_3 ranging from 4.85–3.72 wt %. A profile analysis of large grains indicates a depletion of Al in the rims compared to the cores (Fig. 4). The high Al content in orthopyroxene is considered as an indication of equilibration under high *P–T* conditions as will be discussed in a later section.

4.b. Spinel

Spinels are typically Mg-rich with X_{Mg} (Mg/(Fe + Mg)) ranging from 0.713 to 0.621. Slight enhancement in X^*_{Mg} (Mg/(Fe^{2+} + Mg)) is noted due to the presence of minor Fe^{3+}. Although some spinel grains show apparent colour zoning under the microscope, their compositional profiles do not bring out any marked variation. Relatively fine-grained spinels show a slight increase in X_{Mg} in the rims while the coarser grains possess almost flat patterns (Fig. 5a, b). This suggests that the initial spinel composition is more Fe–Ti rich, and exsolution might have taken place during retrogression. Compositions of spinels from mafic rocks are conventionally represented by using X_{Fe3+}(Fe^{3+}/(Fe^{3+} + Cr + Al)) v. X_{Fe2+}(Fe^{2+}/(Fe^{2+} + Mg)) relations so that our data can be compared with the fields described in the spinel dataset of Barnes & Roeder (2001). The Cr–Al–Fe^{3+} triangular plot, TiO_2 v. X_{Fe3+} and Y_{Cr} (Cr/(Cr + Al)) v. X_{Fe2+} plots of Barnes & Roeder (2001) were not used because of the low Cr, Ti and Fe^{3+} content in these spinels. In the X_{Fe3+} v. X_{Fe2+} diagram the composition falls in the compositional fields identified for spinels from xenolith in kimberlites and high *P–T* Alpine Complexes, characterized by low Fe^{3+} (Fig. 6) as noted by Barnes & Roeder (2001). The chemical maps (not presented here) indicate that the initial spinel could be more Fe–Ti-rich. The integrated spinel composition from chemical mapping of spinel grains indicate 80–83 % spinel, 15–16 % magnetite and 2–3 % ilmenite components.

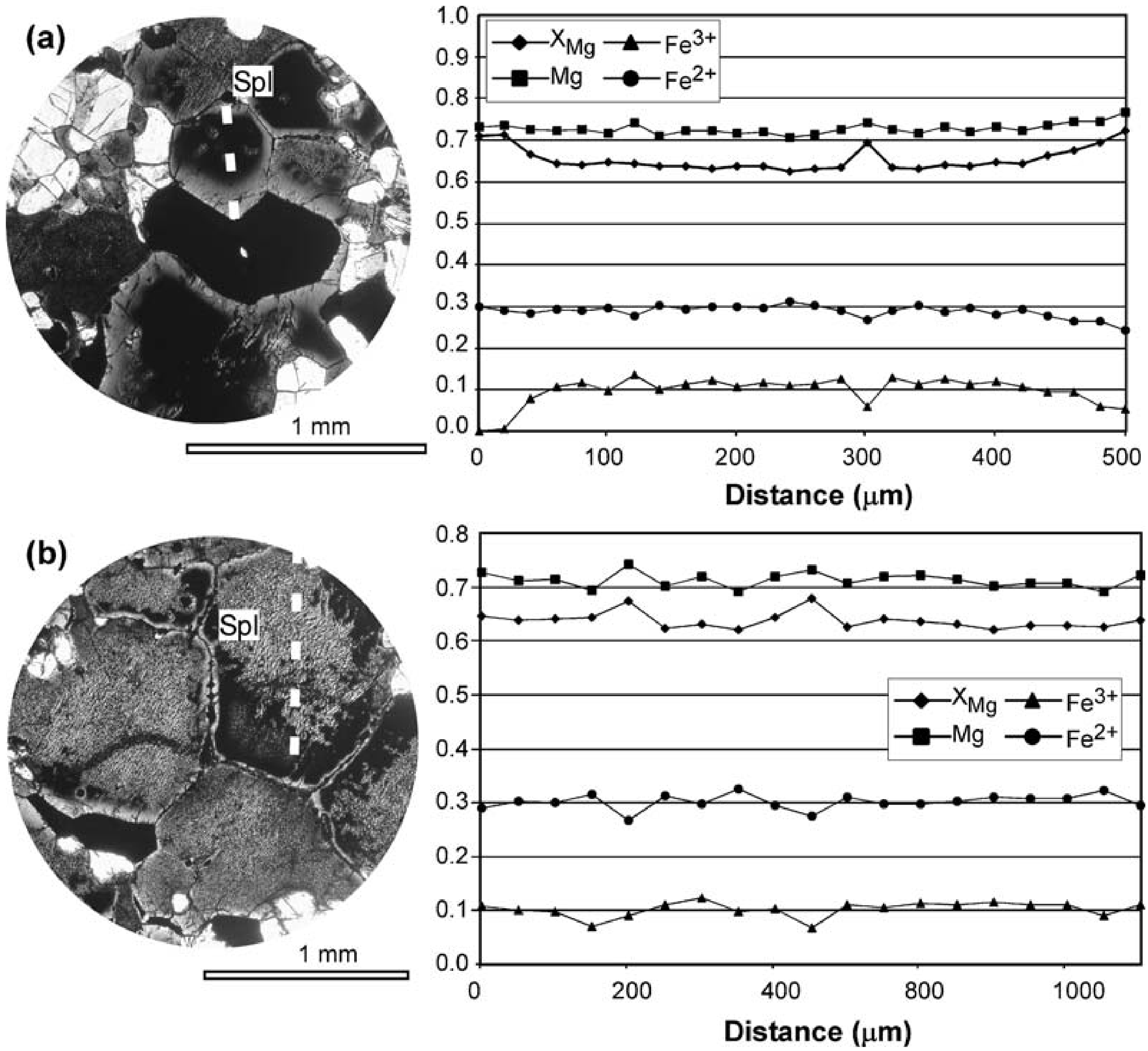

Figure 5. (a, b) Compositional zoning profile for Mg, Fe^{2+}, Fe^{3+} (in pfu) and X_{Mg} of two different porphyroblast in spinel. Fe^{3+} calculated by charge balance considerations (Droop, 1989).

4.c. Garnet

The rare garnets found in the rock are characterized by high Mg contents and correspond to almandine–pyrope solid solution. The composition of these relict garnet grains varies from $Prp_{70.1–66.9}$, $Alm_{29.6–28.0}$, $Grs_{0.16–0.10}$.

4.d. Biotite

There are only a few grains of biotite present in the studied rock with textures indicating retrograde origin. The X_{Mg} of biotites ranges from 0.870 to 0.867, and F content is uniformly low with a range between 0.31 and 0.21. The biotites have moderate TiO_2 ranging from 2.59 to 2.60 wt %.

4.e. Fe–Ti oxide

The major exsolution phases in spinel are ilmenite and magnetite. From the chemical mapping results, the dominant phase in the studied spinels is magnetite. Due to the nature of the very fine lamellae, it was difficult to analyse these using a microprobe. In the matrix there are a few large grains of Fe–Ti oxides which are mainly ilmenite with exsolution lamellae of late magnetite.

5. Evolution and relationship with UHT metamorphism

We calculate the near-peak temperature for the garnet–spinel orthopyroxenite by using the orthopyroxene–spinel geothermometer of Liermann & Ganguly (2001). The reference pressure for the calculation is

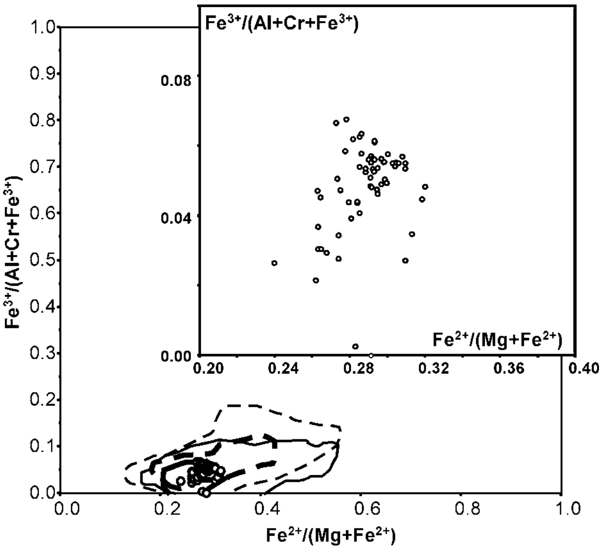

Figure 6. Spinel composition plotted in the X_{Fe3+} ($Fe^{3+}/(Fe^{3+}+Cr+Al)$) v. X_{Fe2+} ($Fe^{2+}/(Fe^{2+}+Mg)$) plot. Dotted line indicates field of xenoliths in kimberlites and the plain line indicates high-*P*–*T* Alpine Complexes (after Barnes & Roeder, 2001). See text for description.

taken as 12 kbar based on the approximate phase transition of garnet and spinel pyroxenite suggested by O'Reilly & Griffin (1985) and Roach (2004). The estimated average temperature at this reference pressure using the core composition is 932 °C. The highest estimated temperature for the spinel–othopyroxene pair with $X_{Mg}^{(Spl)} = 0.642$, $Y_{Cr}^{Spl} = 0.0$, $X_{Mg}^{Opx} = 0.825$ and $K_D = 1.979$ is 959 °C. The factors such as diffusion of Fe^{2+} and Mg with Y_{Cr} of spinel (Liermann & Ganguly, 2002) and effect of Cr^{3+}, Fe^{3+} and Ti^{4+} content on calculated *T* (Liermann & Ganguly, 2003) were also considered, and the high Mg, low Fe and low Cr of the spinels from the present study yielded consistent results. The estimate using integrated spinel compositions give low temperatures, probably due to the effect of Fe^{3+} and Ti^{4+} as discussed above, and are hence not considered further. The temperature estimates obtained from the garnet–spinel orthopyroxenite are broadly comparable with the *P*–*T* estimates from the associated pelitic UHT granulites reported in Sajeev, Osanai & Santosh (2004; 1000 ± 50 °C, 11 kbar) and Tamashiro *et al.* (2004; 1050 ± 50 °C, > 10 kbar).

Temperatures were also estimated from garnet–orthopyroxene pairs based on Fe–Mg exchange and Mg–Fe–Al thermometry (Table 2). Assuming a pressure of 12 kbar derived from the same criteria explained above, the Fe–Mg exchange thermometer of Lee & Ganguly (1988) provided a range of 1098–1193 °C for the core compositions. The method of Bhattacharya *et al.* (1991) yielded a range of 1023–1123 °C, while that of Ganguly, Cheng & Tirone (1996) gave 1095–1190 °C. Garnet–orthopyroxene thermometry of Harley (1984) gave a temperature range of 1006–1097 °C. Rim compositions yielded temperature ranges of 946–1017, 882–948, 945–1015 and 866–932 °C respectively (Table 2). Application of Mg–Fe–Al thermometry of Harley & Green (1982) and Aranovich & Berman (1997) to core compositions yielded temperatures of 865–880 °C and 895–943 °C respectively, while rim compositions yielded a range of 814–870 °C and 796–865 °C. The striking feature is that the Fe–Mg exchange thermometers at 12 kbar yield higher *T* than those obtained from the Mg–Fe–Al thermometry method. We also estimated pressures based on Al in orthopyroxene method following Wood (1974), Harley (1984) and Harley & Green (1982). At a reference temperature of 975 °C, core compositions yield pressures of around 17 kbar from all these methods (Table 2). In order to get a good fit between the Fe–Mg and Mg–Fe–Al thermometry methods for the previous estimate of 12 kbar at 975 °C, the Al_2O_3 in orthopyroxene should exceed 6 wt %. However, the maximum Al_2O_3 content of orthopyroxene in the present case is only 4.85 wt %. This clearly indicates that the assumed 12 kbar pressure is an underestimate, and that the mineral chemistry provides robust evidence for high-pressure metamorphism exceeding 17 kbar and 950–1000 °C in our locality.

The evolution of garnet–spinel orthopyroxenite from the Madurai Granulite Block is shown in Figure 7. The temperature estimate and the *P*–*T* path of the associated ultrahigh-temperature granulite at Ganguvarpatti are also shown (cf. Sajeev, Osanai & Santosh, 2004; Tamashiro *et al.* 2004). The pressure estimates derived for the garnet–spinel orthopyroxenite exceed 17 kbar, translating into a depth of over 50 km. Although Raith, Karmakar & Brown (1997) and Sajeev, Osanai & Santosh (2004) reported pressures exceeding 11 kbar for ultrahigh-temperature metamorphism in the Madurai Granulite Block, our present report gives

Table 2. Thermobarometric estimates summarized for Grt–Opx garnet–spinel orthopyroxenite

		Garnet		Orthopyroxene				Fe–Mg			Mg–Fe–Al			Mg–Fe–Al		
Method	X_{Mg}	X_{Grs}	X_{Mg}	X_{Al}	K_D	$P_{(ref)}$	T_{H84}	T_{LG88}	T_{B91}	T_{G92}	T_{HG92}	T_{AB93}	$T_{(ref)}$	P_{HG82}	P_{H84}	P_{W74}
Core	0.71	0.013	0.803	0.101	1.641	12	1097	1193	1123	1119	875	943	975	15.8	18.6	16.9
	0.71	0.012	0.818	0.100	1.809	12	1012	1101	1035	1098	865	895	975	16.2	17.9	17.1
	0.69	0.021	0.803	0.101	1.831	12	1006	1098	1023	1095	880	910	975	15.6	17.2	16.6
Rim	0.69	0.021	0.818	0.100	2.019	12	932	1017	948	1015	870	865	975	16.0	16.5	16.8
	0.69	0.021	0.832	0.082	2.225	12	866	946	882	945	814	796	1150	18.5	17.9	19.4

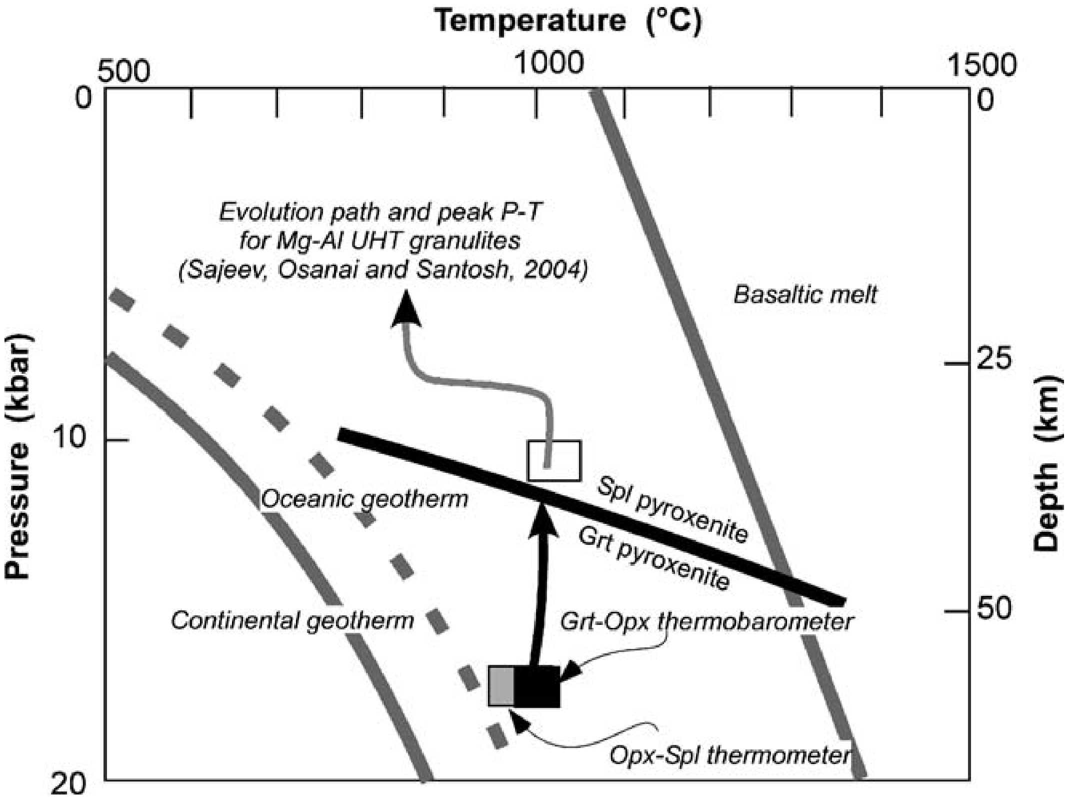

Figure 7. Evolution of the garnet–spinel orthopyroxenite from Madurai Granulite Block; see text for discussion.

the highest pressures obtained by far, for extreme crustal metamorphism in southern India and elsewhere in Gondwana. The garnet–spinel orthopyroxenite plots in a higher pressure field than the field defined for the associated granulites, suggesting that the UHT metamorphism decompressed from 17 kbar to 11 kbar prior to the final stage of isothermal decompression.

The association of the high *P–T* garnet–spinel orthopyroxenite with UHT granulites at Ganguvarpatti suggests a tectonic scenario of crustal thickening and magmatic underplating. The multi-stage decompression observed in the UHT rocks could be correlated to extension of the crust and possibly of the lithospheric mantle and/or its delamination similar to the model proposed by Harley (1989, 1998). If this model is valid, then the anomalous heat source for the UHT metamorphism at high pressures in the Madurai Granulite Block can be attributed to asthenospheric mantle.

Santosh *et al.* (2006) reported electron probe U–Pb–Th data from monazites in the Ganguvarpatti granulite. Spot ages of monazite grains from the UHT granulite show a range of 511–548 Ma for grain cores and 510–450 Ma for outer rims. Compiled probability density plots of ages from monazites in Ganguvarpatti define a sharp peak at 524 ± 13 Ma. The data clearly indicate that the UHT metamorphism at high *P–T* conditions in Ganguvarpatti occurred during Late Neoproterozoic–Early Cambrian times, coinciding with the final phase of assembly of the Gondwana supercontinent.

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