Permo-Triassic ultrahigh-temperature metamorphism in the Kontum massif, central Vietnam

Yasuhito OSANAI^{*}, Nobuhiko NAKANO^{*}, Masaaki OWADA^{**}, Tran Ngoc NAM^{***},
Tsuyoshi TOYOSHIMA^{****}, Toshiaki TSUNOGAE^{*****} and Pham BINH^{*****}

^{*}*Division of Evolution of Earth Environments, Kyushu University, Fukuoka 810-8560, Japan*

^{**}*Department of Earth Sciences, Yamaguchi University, Yamaguchi 753-8512, Japan*

^{***}*Department of Geosciences, Hue University of Science, Hue, Vietnam*

^{****}*Department of Earth Sciences, Niigata University, Niigata 950-2181, Japan*

^{*****}*Department of Earth Sciences, University of Tsukuba, Tsukuba 305-8571, Japan*

^{*****}*Research Institute of Geology and Mineral Resources, Hanoi, Vietnam*

The Kontum massif in central Vietnam consists of low-grade schists and amphibolite- to granulite-facies metamorphic rocks, that have been intruded by S-type and I-type granites. This terrane was formerly considered to be composed mainly of Archean granulites (the Kannak Complex), Proterozoic amphibolite-facies metamorphic rocks (the Ngoc Linh Complex) and low-grade schists (the Kham Duc Complex). They were thought to be the basement of the Indochina Craton in south-east Asia.

The Kannak Complex is dominated by pelitic-semipelitic gneisses metamorphosed under high- to ultrahigh-temperature (UHT) conditions into granulite-facies. A minor amount of mafic and calc-silicate rocks are also intercalated within the gneisses. The major types of ultrahigh-temperature pelitic metamorphic rocks in this complex are garnet-orthopyroxene-sillimanite-cordierite gneiss, orthopyroxene-bearing garnet-cordierite-sillimanite-biotite gneiss and garnet-orthopyroxene charnockitic gneiss. The highest-grade metamorphic condition is determined from garnet-orthopyroxene-sillimanite-cordierite gneiss, which indicates that multi-stage symplectite formation during retrograde stage started from isothermal decompression in UHT condition (1000°C<). Because of the high amount of pyrope (up to 59 mole%) in garnet and high-Al₂O₃ in orthopyroxene (up to 10 wt%), these minerals were unstable in the P-T conditions during the retrograde stage.

On the other hand, the newly found garnet-clinopyroxene-orthopyroxene granulites (eclogitic ultrahigh-temperature mafic granulite) from the Ngoc Linh Complex shows a series of changes in divariant assemblages from garnet-clinopyroxene-quartz to hornblende-quartz through clinopyroxene-orthopyroxene-plagioclase-(garnet). It was identified that these rocks were formed as a result of their metamorphic evolution of isothermal decompression followed by nearly isobaric cooling.

The ultrahigh-temperature metamorphic rocks in the Kontum massif, which are exposed along the Dac To Kan shear zone, show a clockwise pressure-temperature path with the peak metamorphic condition of *ca.* 12 kbar and *ca.* 1050°C (M1 metamorphism). High-pressure M0 metamorphism (*ca.* 17 kbar<, *ca.* 1000°C) as part of the prograde metamorphism and low-pressure (but still ultrahigh-temperature) M2 metamorphism (9–10 kbar, *ca.* 1000°C) as part of the retrograde metamorphism during the clockwise pressure-temperature evolution are also recognized. The widely reported Permo-Triassic metamorphic event (*ca.* 240–260 Ma) from the ultrahigh-temperature metamorphic rocks would indicate a rapid metamorphic evolution from M0 stage to low-pressure and low-temperature retrograde stage (later M2 stage). The recently determined Sm-Nd internal isochron age of 670 Ma for the garnet amphibolite and monazite-CHIME age of *ca.* 480–500 Ma for the pelitic granulites from the Kannak Complex would also indicate that the Kontum massif had also undergone the Pan-African metamorphic event. The present results indicate that ultrahigh-temperature metamorphic rocks from the Kontum massif are remnants of previously metamorphosed rocks that might be derived from the Gondwana super continent and then re-metamorphosed by the Permo-Triassic metamorphism during the continents collision in eastern Asia.

Introduction

The metamorphic basement of the Kontum massif in central Vietnam has been subdivided into three major units: the Kham Duc Complex in the north and west, the Ngoc Linh Complex in the central-west and the Kannak Complex in the central-east (e.g. Tran Quoc Hai, 1986) (Fig. 1). The Kham Duc Complex consists of metamorphic rocks of greenschist- to blueschist-facies (Trinh Long, 1995) and low-grade amphibolite-facies, while the Kannak Complex is composed of various types of high- to ultrahigh-temperature granulite-facies metamorphic rocks, that are pelitic, mafic, quartzofeldspathic, calc-silicate gneisses and granulites with subordinate charnockitic rocks. Both amphibolite- and high- to ultrahigh-temperature granulite-facies rocks occur within the Ngoc Linh Complex. Part of the ultrahigh-temperature mafic granulites also indicates remaining traces of previous high-pressure eclogite-facies metamorphism (Nakano et al., 2003; 2004; Osanai et al., 2003). These high-grade metamorphic rocks are intruded by S-type and I-type granitic rocks (e.g. Plei Man Ko granite: Tran Quoc Hai, 1986).

One of the most important geological topics in southeastern Asia is to understand the metamorphic evolutionary process of the Kontum massif as a key terrane. Understanding this process provides a reality for the tectonic evolution of the Indochina Craton as well as the growth of the Asian continent. The high-grade supracrustal metamorphic and related intrusive rocks exposed in the central part of the Kontum massif are still considered to be of Precambrian basement including Archean granulite-facies rocks (the Kannak Complex) and Proterozoic amphibolite-facies rocks (the Ngoc Linh Complex) of the Indochina Craton (Phan Truong Thi et al., 1986; Hutchison, 1989; Sengor and Natal' in, 1996; Metcalfe, 1999). However recent geochronological studies of metamorphic and intrusive rocks from these complexes have shed light on the Permo-Triassic tectonic evolution in the Kontum massif (Tran Ngoc Nam et al. 2001; Nagy et al., 2001; Carter et al., 2001; Osanai et al., 2001a; Lan et al., 2003).

In this paper, we discuss a possible pressure-temperature evolution for the orthopyroxene-sillimanite-quartz assemblage coexisting with ultrahigh-temperature pelitic granulites from the Kannak Complex. Geochronological

Figure 1. Simplified geologic map of the Kontum massif in central Vietnam modified after United Nations (1990). Sample locations of ultrahigh-temperature metamorphic rocks studied are shown as open squares. Broken lined area indicates the map area of Figure 8.

investigation for the ultrahigh-temperature metamorphic rocks from the Kontum massif is also discussed to analyze the tectonic evolution during Permo-Triassic continental growth in East Asia.

Geological outline of the Kontum massif

The present study area, called the southern Kontum massif, is located in the south-central part of Vietnam around the Kontum-Quy Nhon area at $107^{\circ}30'-109^{\circ}15'E$ and $15^{\circ}30'-13^{\circ}15'N$. This region can be classified into the Kannak Complex and the Ngoc Linh Complex, as explained above. Various localities in the southern part of the Kontum massif consist of extremely high-grade metamorphic rocks. They occur mainly as blocks, disrupted layers or lenses. In this section we will describe the

modes of occurrence of some selected major high-grade metamorphic rocks within the Kannak and the Ngoc Linh Complexes. The distribution of the studied localities is shown in Figure 1.

Kannak Complex

The Kannak Complex is dominated by pelitic-semipelitic gneisses metamorphosed in high- to ultrahigh-temperature granulite-facies conditions. A minor amount of mafic and calc-silicate rocks are also intercalated within the gneisses. Ultrahigh-temperature metamorphic rocks are distributed mainly in An Khe area in the central part of Kannak complex, where three stratigraphic units can be recognized: the Kon Cot, Xa Lam Co and Dak Lo Formations (e.g. Tran Quoc Hai, 1986). The most widely ex-

Figure 2. Modes of occurrence of ultrahigh-temperature metamorphic rocks from the Kontum massif.

(a) exposure of layered pelitic gneisses near Kannak area in the Kannak Complex, (b) close-up view of knotty garnet-orthopyroxene-sillimanite-cordierite gneiss. A knot contains multi-phase symplectite surrounding garnet, (c) close-up view of garnet-cordierite-sillimanite-biotite gneiss. Note garnet porphyroblasts are surrounded by symplectite composed of sillimanite, spinel, cordierite and orthopyroxene, (d) layered calc-silicate gneisses at Kbang area in the Kannak Complex, (e) layered pelitic gneisses from the Ngoc Linh Complex at Dac To Kan area, (f) highly mylonitized felsic gneiss including eclogitic mafic granulite from the Ngoc Linh Complex at Dac To Kan area.

Table 1. Representative bulk chemical compositions

	2001A1	2001A2	2001B	1902A2	1902B	1902D1	2001G	2003	2010
	GOSC gn	GOSC gn	GOSC gn	GCSB gn	GCSB gn	GCSB gn	GCSB gn	GOB gn	GOB gn
(Major elements in wt %)									
SiO ₂	75.25	74.43	75.16	65.92	51.12	61.75	60.29	65.49	63.50
TiO ₂	0.47	0.68	0.46	0.94	1.51	0.99	0.91	1.58	0.95
Al ₂ O ₃	10.61	12.92	12.66	15.08	23.73	19.41	18.04	11.17	11.53
FeO	5.89	3.96	4.15	11.08	14.28	10.13	8.56	13.37	13.43
MnO	0.02	0.01	0.01	0.14	0.15	0.12	0.07	0.31	0.81
MgO	5.83	5.49	5.50	3.23	3.83	3.64	4.10	5.18	3.78
CaO	0.31	0.17	0.18	0.32	0.56	0.45	0.54	0.35	1.53
Na ₂ O	0.29	0.22	0.19	0.40	0.76	0.57	0.98	0.09	0.41
K ₂ O	1.28	2.11	1.64	2.87	4.05	2.93	6.49	2.38	3.27
P ₂ O ₅	0.07	0.00	0.04	0.02	0.02	0.02	0.03	0.09	0.80
ASI	4.37	4.37	5.23	3.47	3.56	3.94	1.88	3.33	1.65
Mg#	63.8	71.2	70.3	34.2	32.3	39.0	46.0	40.8	33.4
(Trace elements in ppm)									
Ba	317	436	393	577	821	521	722	476	1183
Co	10	9	8	19	13	19	19	20	29
Cr	115	109	98	137	175	153	123	127	136
Ga	11	19	17	20	36	28	24	17	13
Hf	4	6	4	7	13	9	8	23	6
Nb	12	10	9	19	18	17	15	17	11
Ni	86	67	59	61	39	61	60	28	68
Rb	46	80	64	102	120	119	169	85	71
Sr	9	10	8	40	72	57	61	11	99
V	51	71	57	135	271	136	124	189	138
Y	51	27	26	85	110	80	61	76	56
Zn	39	57	47	105	148	195	172	59	98
Zr	125	203	148	204	369	309	243	1000	179
F	830	1200	780	660	680	740	910	1700	1350
(REEs in ppm)									
La	26.5	31.0	25.5	14.5	11.5	19.0	59.0	80.5	43.5
Ce	62.5	77.0	64.0	21.0	17.5	35.5	115.5	175.0	106.5
Pr	6.5	7.7	6.4	2.2	1.7	3.7	12.6	19.6	13.4
Nd	23.5	28.5	23.5	8.5	6.0	15.0	46.0	75.0	53.0
Sm	5.0	5.4	4.7	3.3	4.0	3.3	9.4	17.4	12.0
Eu	1.0	0.7	0.8	1.0	1.2	1.0	1.2	2.5	1.5
Gd	6.4	5.0	5.6	8.5	10.3	6.1	9.7	19.9	11.4
Tb	1.3	0.8	1.0	2.0	2.1	1.4	1.5	2.6	1.7
Dy	9.9	4.5	5.6	13.5	12.8	11.2	8.7	13.2	9.6
Ho	2.5	0.9	1.1	3.1	2.7	2.7	1.7	2.4	2.2
Er	8.3	3.1	3.0	8.6	7.2	7.5	5.1	6.3	6.5
Tm	1.3	0.5	0.4	1.4	1.0	1.2	0.7	0.9	1.0
Yb	9.5	3.5	2.5	9.0	6.3	7.8	5.1	6.1	6.3
Lu	1.5	0.6	0.3	1.4	1.1	1.3	0.7	1.0	1.0

Abbreviations for rock names: G, Garnet; O, Orthopyroxene; S, Sillimanite; C, Cordierite; B, Biotite; gn, gneiss.

ASI (Alumina Saturation Index), $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$; Mg#, $100\text{MgO}/(\text{FeO} + \text{MgO})$.

posed syn-metamorphic granitic intrusive in this area is the Plei Man Ko granitic complex, which includes garnet- and orthopyroxene-bearing S-type tonalitic rocks and gabbroic to noritic rocks (Owada et al., 2000). Part of the intrusive boundaries disturb the foliation of the host gneisses and show highly migmatized structures.

The major pelitic metamorphic rocks of this complex

are garnet-orthopyroxene-sillimanite-cordierite granulite, garnet-cordierite-sillimanite-biotite gneiss, garnet-orthopyroxene±biotite charnockitic gneiss and graphite-bearing garnet-sillimanite gneiss (Khondalitic gneiss), which generally make layered gneisses (Fig. 2a). The garnet-orthopyroxene-sillimanite-cordierite granulite characteristically contains garnet porphyroblasts sur-

rounded by multi-stage symplectite (Fig. 2b), which can be identified by the naked eye, and orthopyroxene-sillimanite-quartz assemblages, which will be described in detail below. The well-foliated garnet-cordierite-sillimanite-biotite gneiss is relatively fresh and occurs as thin layers including porphyroblasts of garnet surrounded by symplectite composed of sillimanite, spinel and cordierite (Fig. 2c), which can also be identified by the naked eye. Minor amounts of sapphirine-corundum-cordierite granulite, sapphirine-corundum-spinel-phlogopite granulite and sapphirine-bearing quartzofeldspathic gneiss are also exposed as blocks within the gneisses. The general foliation trend varies from N17°W-S17°E with a westward dip of *ca.* 60° to N39°E-S39°W with an eastward dip of *ca.* 55°. The minor amounts of clinopyroxene- and orthopyroxene-bearing mafic granulite, orthopyroxene-biotite enderbite and olivine-spinel-humite or wollastonite-bearing calc silicate rocks are also exposed as thin intercalations within the gneisses (Fig. 2d).

Ngoc Linh Complex

The Ngoc Linh Complex is exposed in the northeastern to southwestern part of the Kontum massif around the Quang Ngai, Dac Glei and Kontum areas (Fig. 1). This complex has been subdivided into the Tac Po Formation in the southwest and the Song Re Formation in the northeast (e.g. Tran Quoc Hai, 1986). The major lithologies of the Tac Po Formation are orthopyroxene-clinopyroxene-hornblende granulite, garnet-orthopyroxene-clinopyroxene granulite, garnet-orthopyroxene-biotite gneiss, garnet-cordierite-sillimanite-biotite gneiss, and quartzofeldspathic garnet-sillimanite-biotite gneiss, which were metamorphosed under granulite-facies conditions (Fig. 2e). Parts of these metamorphic rocks are strongly deformed and highly mylonitized along the NW-SE trending shear zone (Dac To Kan shear zone in Figures 1 and 8). Orthopyroxene-clinopyroxene-hornblende and garnet-orthopyroxene-clinopyroxene granulites, which are exposed as blocks within the mylonitized quartzofeldspathic gneisses (Fig. 2f), collected from Tac Po Formation at Dac To Kan area indicate the previous high-pressure (up to 16 kbar) and ultrahigh-temperature (*ca.* 1000°C) eclogite-facies condition prior to the granulite-facies condition (Nakano et al., 2003; 2004). The Song Re Formation consists mainly of relatively low-grade amphibolite-facies metamorphic rocks of pyroxene-free amphibolite, garnet-amphibolite, hornblende-biotite gneiss, biotite-sillimanite gneiss and garnet-biotite gneiss.

Whole rock chemistry

Major and trace element contents of high-grade pelitic metamorphic rocks (9 samples) from the An Khe area in the Kannak Complex were determined by X-ray fluorescence spectrometry (Rigaku RIX-2100) at the Kurashiki University of Science and Arts. The contents of volatiles were determined by the weight loss on ignition. Rare Earth elements (REE) analyses were also performed by using an ICP-MS at Actlabs Ltd., Canada. Representative data are presented in Table 1. The garnet-orthopyroxene-sillimanite-cordierite gneisses, including rocks showing the coexistence of orthopyroxene-sillimanite-quartz (2001A1, 2001A2, 2001B), show characteristically higher contents of SiO₂ (73–75 wt%) and MgO (4.3–7.0 wt%, 100MgO/(FeO + MgO): Mg# = 63.8–71.2) than the other pelitic granulites (garnet-cordierite-sillimanite-biotite gneisses: 1902A2, 1902B, 1902D1, 42001G: SiO₂ = 51–65 wt%, Mg# = 32.3–46.0; garnet-orthopyroxene-biotite charnockitic gneisses: 2003, 2010: SiO₂ = 63–66 wt%, Mg# = 33.4–41.2) (Table 1). Al₂O₃, CaO, Na₂O and K₂O contents are lower than the others. The alumina saturation index (ASI = Al₂O₃/(CaO + Na₂O + K₂O)) is high in the garnet-orthopyroxene-sillimanite-cordierite gneisses (ASI = 4.4–5.2) and low in other pelitic granulites (ASI = 1.6–3.9). Differences in trace element compositions among these gneisses are as follows; garnet-orthopyroxene-sillimanite-cordierite gneisses are systematically lower in Ba, Rb, Sr, V, Zn and Cu than the garnet-cordierite-sillimanite-biotite and garnet-orthopyroxene-biotite charnockitic gneisses.

Whole rock compositions of high-grade (ultrahigh-temperature as described below) pelitic gneisses from the Kannak Complex and their relevant mineral assemblages are shown in an SiO₂-(FeO + MgO)-Al₂O₃ (FMAS) diagram (Fig. 3). In this figure the gneisses are compared with those of other sapphirine-bearing ultrahigh-temperature granulites (Tonagh Island, Antarctica: Osanai et al., 1999; Bunt Island, Antarctica: Osanai et al., 2001b; Mt. Liiser Larsen, Antarctica: Suzuki et al., 1999; Eastern Ghats, India: Sengupta et al., 1991; Forefinger point, Antarctica: Harley et al., 1990; Spot Hight 945 etc., Antarctica: Sheraton et al., 1987; Limpopo belt, South Africa: Horrocks, 1983; Sipiweski, Canada: Arima and Barnett, 1984; Sør Rondane, Antarctica: Ishizuka et al., 1995; Gage ridge etc.: Grew, 1982; Highland Complex, Sri Lanka: Osanai et al., 1996; Namaqualand, South Africa: Clifford et al., 1981; Higo, Japan: Osanai et al., 1998). As shown in Figure 3, sapphirine-bearing ultrahigh-temperature metamorphic rocks from the various places in the world can be classified into three types: quartz-bearing (type-1), quartz- and corundum-free (type-2) and corun-

Figure 3. SiO_2 -(FeO+MgO)- Al_2O_3 diagram for the bulk chemical compositions of ultrahigh-temperature pelitic gneisses from the Kontum massif. Data sources for the other compiled data are cited in the text. Types-1 to -3 show quartz-bearing, quartz- and corundum-free and corundum-bearing ultrahigh-temperature sapphirine granulites, respectively (Osanai et al., 2001b). Note the studied ultrahigh-temperature pelitic gneisses mainly plot within the type-1 field.

Figure 4. Chondrite-normalized REE patterns of ultrahigh-temperature pelitic gneisses from the Kannak Complex. Normalized values are after Sun and McDonough (1989).

dum-bearing (type-3) sapphirine granulites (Osanai et al., 2001b). The studied ultrahigh-temperature pelitic gneisses mainly plot within the type-1 field (Fig. 3), which is indicative of coexistence of sapphirine and quartz.

Chondrite-normalized REE patterns of high-grade pelitic gneisses from the Kannak Complex are shown in Figure 4. Most of the samples have remarkable depletion

patterns in Eu and they can be subdivided into two groups, (1) a light-REE (LREE) enrichment and heavy-REE (HREE) slightly depleted pattern (group-1: 2001A2, 2001B, 2001G, 2003, 2010) and (2) a slightly enriched LREE and nearly constant or slightly enriched HREE pattern (group-2: 1902A2, 1902B, 1902D1, 2001A1). The normalized patterns of group-1 are similar to those of

bulk upper crust or “post-Archean average shales” (PAAS, NASC, ES) (Taylor and McLennan, 1985). The patterns of group-2 may be explained by an abundance of HREE concentrated metamorphic minerals (garnet, orthopyroxene, etc.), the normalized pattern of 1902B especially bears some resemblance to the chondrite-normalized pattern of garnet.

Petrography, reaction textures and mineral chemistry

In this section we describe the petrographic and chemical characteristics of the minerals of the following three-types of high-grade pelitic metamorphic rocks from the Kannak Complex: (1) magnesian garnet-orthopyroxene-sillimanite-cordierite gneisses (samples 2001A1, 2001A2, 2001B), which contains characteristic textures of decompression and cooling reactions from ultrahigh-temperature down to normal granulite-facies conditions; (2) relatively aluminous garnet-cordierite-sillimanite-biotite gneisses (1902A2, 1902B, 1902D1, 2001G) containing some retrograde reaction textures; and (3) relatively iron-rich garnet-orthopyroxene-biotite charnockitic gneisses (2003, 2010) without any remarkable reaction textures. Detailed descriptions for ultrahigh-temperature mafic granulites from the Ngoc Linh Complex have already been described by Nakano et al. (2003, 2004).

Chemical compositions of minerals in these three-types of high-grade metamorphic rocks were determined by using the energy dispersive electron microprobe system of the JEOL JSM-5310S with JED-2100 at Okayama University. The data were obtained under 15 kV of accelerating voltage and using a data processing correction program by Oxide-ZAF. Natural mineral samples (ASTIMEX MINM25-53) were used as standard for analyses. Representative data are listed in Table 2. Mineral abbreviations in the reaction equations are after Kretz (1983).

Garnet-orthopyroxene-sillimanite-cordierite gneiss

The garnet-orthopyroxene-sillimanite-cordierite gneiss is relatively coarse grained, homogeneous and rather massive in appearance. This type of gneiss consists mainly of garnet, orthopyroxene, sillimanite, cordierite, spinel and quartz with subordinate plagioclase, K-feldspar, phlogopite/biotite, rutile, ilmenite, apatite, corundum, zircon and monazite. The gneiss shows various significant reaction textures indicating multi-phase symplectite formation during their metamorphic evolution started from ultrahigh-temperature conditions. Anhedral to subhedral garnet porphyroblasts (Grt 1: 2–10 mm in diameter; $\text{Alm}_{43.0-50.2}\text{Sps}_{0-0.1}\text{Prp}_{48.4-55.1}\text{Grs}_{1.4-2.8}$ at the core), including sillimanite

needles (fibrolite), are generally surrounded by fine-grained multiple symplectites composed of orthopyroxene (Opx 2: X_{Mg} : $\text{Mg}/(\text{Fe}+\text{Mg}) = 0.62-0.69$, 6.0–7.6 wt% Al_2O_3) + cordierite (Crd 2: $X_{\text{Mg}} = 0.84-0.86$) and orthopyroxene (Opx 3: $X_{\text{Mg}} = 0.66-0.70$, 5.8–7.6 wt% Al_2O_3) + spinel (Spl 2: $X_{\text{Mg}} = 0.46-0.51$). A thin moat of orthopyroxene (Opx 4: $X_{\text{Mg}} = 0.67-0.71$, 4.7–5.3 wt% Al_2O_3), which coexists with K-feldspar and plagioclase, was identified along the boundary between these symplectites and adjacent quartz (Fig. 5a). Sometimes a garnet porphyroblast (Grt 1) is completely consumed and orthopyroxene (Opx 4) mantled orthopyroxene (Opx 2)-cordierite symplectite is formed as a garnet pseudomorph (Fig. 5b). At the rim of garnet porphyroblast ($\text{Alm}_{57.6-60.2}\text{Sps}_{0-0.2}\text{Prp}_{34.5-38.0}\text{Grs}_{3.9-5.4}$), fine symplectite composed of rather magnesian garnet (Grt 2: $\text{Alm}_{55.1-56.7}\text{Sps}_{0-0.3}\text{Prp}_{39.2-40.6}\text{Grs}_{4.0-4.3}$) and spinel (Spl 3: $X_{\text{Mg}} = 0.57-0.60$) was observed. Coarse-grained subhedral orthopyroxene porphyroblasts (Opx 1: 9–15 mm; $X_{\text{Mg}} = 0.73-0.78$, 7.5–10.2 wt% Al_2O_3) include anhedral high-fluorine phlogopite ($X_{\text{Mg}} = 0.86-0.90$, $X_{\text{F}}: \text{F}/(\text{F} + \text{Cl} + \text{OH}) = 0.21-0.27$) and quartz inclusions (Fig. 5c). Another type of fine-grained anhedral and aluminous orthopyroxene porphyroblast (Opx 1': 1–5 mm; $X_{\text{Mg}} = 0.73-0.77$, 6.3–7.5 wt% Al_2O_3) coexists with sillimanite and quartz, even though cordierite (Crd 1: $X_{\text{Mg}} = 0.88-0.91$) and cordierite (Crd 1': $X_{\text{Mg}} = 0.84-0.86$)-spinel (Spl 1: $X_{\text{Mg}} = 0.55-0.57$) symplectite separate grains of orthopyroxene (Opx 1'), sillimanite and quartz (Fig. 5d). This type of gneiss contains excess quartz as described above, while any direct contact of spinel-quartz and corundum-quartz is not detected. These textures suggest the following reactions took place during the retrograde-process:

Reactions (1) to (5) suggest a sequential, nearly isothermal decompression process under the ultrahigh-temperature conditions.

High-fluorine phlogopite consuming melting reactions could also have taken place during the prograde process before forming the highest-grade assemblage of orthopyroxene-sillimanite-quartz±garnet through the following reaction at high-pressure:

Interstitally existed melt, which might be produced by reaction (7) at the primary stage, was consumed by the

Table 2. Representative microprobe analyses for ultrahigh-

Rock type Grt-Opx-Sil-Crd gneiss													
Mineral	Grt 1 Core	Grt 1 Rim	Grt 2 Core	Opx 1 Core	Opx 2 Core	Opx 3 Core	Opx 4 Core	Crd 1 Core	Crd 2 Core	Spl 1 Core	Spl 2 Core	Spl 3 Core	Phl Core
SiO ₂	40.31	38.76	39.34	49.86	51.45	50.61	51.84	50.58	50.07	0.00	0.00	0.00	38.79
TiO ₂	0.00	0.00	0.09	0.24	0.00	0.09	0.19	0.03	0.00	0.00	0.00	0.09	0.92
Al ₂ O ₃	22.94	22.08	22.35	10.16	6.24	7.57	5.11	32.60	32.52	64.39	63.33	64.94	15.47
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.10	0.04	0.00
FeO	20.52	26.99	25.74	15.16	19.68	19.98	20.26	2.31	3.56	19.76	24.38	19.02	6.28
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	14.77	9.73	10.51	24.83	22.74	21.87	22.39	13.22	11.84	13.83	11.56	14.88	21.85
CaO	0.73	1.68	1.52	0.06	0.10	0.18	0.24	0.06	0.02	0.00	0.00	0.00	0.00
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.11	0.00	0.00	0.00	0.28
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.18
ZnO	---	---	---	---	---	---	---	---	---	1.37	0.27	0.62	0.00
F	---	---	---	---	---	---	---	---	---	---	---	---	2.13
Cl	---	---	---	---	---	---	---	---	---	---	---	---	0.00
F=O	---	---	---	---	---	---	---	---	---	---	---	---	0.90
Cl=O	---	---	---	---	---	---	---	---	---	---	---	---	0.00
Total	99.27	99.24	99.55	100.31	100.21	100.30	100.03	98.92	98.12	99.55	99.64	99.59	95.00
H ₂ O*	---	---	---	---	---	---	---	---	---	---	---	---	3.11
Total*	---	---	---	---	---	---	---	---	---	---	---	---	98.11
O	12	12	12	6	6	6	6	18	18	4	4	4	22
Si	3.002	2.992	3.004	1.783	1.878	1.849	1.902	5.040	5.052	0.000	0.000	0.000	5.655
Ti	0.000	0.000	0.005	0.006	0.000	0.002	0.005	0.002	0.000	0.000	0.000	0.002	0.101
Al	2.014	2.009	2.012	0.428	0.268	0.326	0.221	3.829	3.868	1.994	1.992	1.994	2.658
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.002	0.001	0.000
Fe	1.278	1.743	1.644	0.453	0.601	0.610	0.622	0.192	0.300	0.434	0.544	0.414	0.766
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	1.639	1.120	1.196	1.323	1.237	1.191	1.224	1.963	1.780	0.542	0.460	0.578	4.749
Ca	0.058	0.139	0.124	0.002	0.004	0.007	0.009	0.006	0.002	0.000	0.000	0.000	0.000
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.022	0.000	0.000	0.000	0.079
K	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.893
Zn	---	---	---	---	---	---	---	---	---	0.03	0.005	0.012	---
Total	7.991	8.003	7.985	3.997	3.988	3.986	3.983	11.055	11.025	3.001	3.003	3.001	15.901
F	---	---	---	---	---	---	---	---	---	---	---	---	0.982
Cl	---	---	---	---	---	---	---	---	---	---	---	---	0.000
Alm	0.430	0.581	0.555	---	---	---	---	---	---	---	---	---	---
Spe	0.000	0.000	0.000	---	---	---	---	---	---	---	---	---	---
Pyr	0.551	0.373	0.403	---	---	---	---	---	---	---	---	---	---
Grs	0.020	0.046	0.040	---	---	---	---	---	---	---	---	---	---
Adr	0.000	0.000	0.002	---	---	---	---	---	---	---	---	---	---
XMg	0.562	0.391	0.421	0.745	0.673	0.661	0.663	0.911	0.856	0.556	0.461	0.584	0.861
XF	---	---	---	---	---	---	---	---	---	---	---	---	0.245

Mineral abbreviations are after Kretz (1983).

Mineral names with number show the produced stage during the evolution. Sy- indicates symplectite composed with minerals after hyphen.

orthopyroxene (Opx 4) moat-producing reaction (6) at the same temperature but relatively low-pressure conditions.

Garnet - cordierite - sillimanite - biotite gneiss

The garnet-cordierite-sillimanite-biotite gneiss is a lay-

ered, well foliated, rather iron-rich and aluminous metapelite. It contains garnet, cordierite, sillimanite, biotite, plagioclase, K-feldspar and quartz with subordinate amounts of orthopyroxene, corundum, ilmenite, rutile, zircon, monazite and apatite (Fig. 5e). Orthopyroxene occurs only in coronas surrounding garnet porphyroblast, and intergrew with cordierite (Fig. 5f), the feature is simi-

temperature metamorphic rocks from the Kontum massif

Rock type	Grt-Crd-Sil-Bt gneiss								Grt-Opx charno. gneiss		
Mineral	Grt	Grt	Crd	Crd	Crd	Opx	Spl	Bt	Grt	Grt	Opx
	Core	Rim	Sy-Spl	Sy-Opx	Sy-Sil	Sy-Crd	Sy-Crd	Core	Core	Rim	Core
SiO ₂	39.71	38.47	47.45	47.69	49.86	49.12	0.00	35.60	37.75	37.31	49.07
TiO ₂	0.15	0.16	0.14	0.10	0.31	0.24	0.30	2.70	0.25	0.05	0.04
Al ₂ O ₃	23.06	22.33	34.32	34.13	32.51	6.77	61.80	15.00	21.30	21.06	1.02
Cr ₂ O ₃	0.08	0.00	0.15	0.10	0.21	0.03	0.29	0.10	0.12	0.00	0.16
FeO	20.70	28.51	6.00	4.59	6.20	23.04	28.90	20.00	31.91	33.43	37.07
MnO	0.77	1.55	0.00	0.55	0.00	0.68	0.26	0.00	1.27	1.09	0.69
MgO	13.77	8.34	10.54	10.32	9.78	20.14	8.47	12.50	4.31	3.05	11.05
CaO	1.60	1.23	0.11	0.00	0.00	0.00	0.15	0.10	3.64	3.24	0.41
Na ₂ O	0.00	0.00	0.03	0.21	0.15	0.00	0.00	0.00	0.00	0.06	0.21
K ₂ O	0.00	0.00	0.10	0.00	0.00	0.00	0.00	10.70	0.00	0.00	0.00
ZnO	---	---	---	---	---	---	0.27	0.00	---	---	---
F	---	---	---	---	---	---	---	0.00	---	---	---
Cl	---	---	---	---	---	---	---	0.10	---	---	---
F=O	---	---	---	---	---	---	---	0.00	---	---	---
Cl=O	---	---	---	---	---	---	---	0.02	---	---	---
Total	99.84	100.59	98.84	97.69	99.02	100.02	100.44	96.78	100.55	99.29	99.72
H ₂ O*	---	---	---	---	---	---	---	3.90	---	---	---
Total*	---	---	---	---	---	---	---	100.68	---	---	---
O	12	12	18	18	18	6	4	22	12	12	6
Si	2.965	2.968	4.828	4.881	5.047	1.837	0.000	5.432	2.985	3.006	1.977
Ti	0.008	0.009	0.011	0.008	0.024	0.007	0.006	0.310	0.015	0.003	0.001
Al	2.030	2.030	4.116	4.117	3.879	0.298	1.976	2.697	1.985	2.000	0.048
Cr	0.005	0.000	0.012	0.008	0.017	0.001	0.006	0.012	0.008	0.000	0.005
Fe	1.293	1.839	0.511	0.393	0.525	0.720	0.656	2.552	2.110	2.252	1.249
Mn	0.049	0.101	0.000	0.048	0.000	0.022	0.006	0.000	0.085	0.074	0.024
Mg	1.532	0.959	1.598	1.574	1.475	1.122	0.342	2.843	0.508	0.366	0.664
Ca	0.128	0.102	0.012	0.000	0.000	0.000	0.004	0.016	0.308	0.280	0.018
Na	0.000	0.000	0.006	0.042	0.029	0.000	0.000	0.000	0.000	0.009	0.016
K	0.000	0.000	0.013	0.000	0.000	0.000	0.000	2.083	0.000	0.000	0
Zn	---	---	---	---	---	---	0.005	0.000	---	---	---
Total	8.009	8.008	11.107	11.070	10.996	4.007	3.003	15.945	8.004	8.001	4.003
F	---	---	---	---	---	---	---	0.000	---	---	---
Cl	---	---	---	---	---	---	---	0.026	---	---	---
Alm	0.431	0.613	---	---	---	---	---	---	0.700	0.758	---
Spe	0.016	0.034	---	---	---	---	---	---	0.028	0.025	---
Pyr	0.510	0.319	---	---	---	---	---	---	0.169	0.123	---
Grs	0.039	0.030	---	---	---	---	---	---	0.092	0.093	---
Adr	0.004	0.004	---	---	---	---	---	---	0.010	0.001	---
XMg	0.542	0.343	0.758	0.800	0.74	0.609	0.347	0.527	0.194	0.140	0.347
XF	---	---	---	---	---	---	---	0.000	---	---	---

lar to the garnet-orthopyroxene-sillimanite-cordierite gneiss from reaction (3). Subhedral garnet porphyroblasts (3–10 mm: Alm_{43.0-54.0}Sps_{0.3-3.0}Prp_{42.0-51.3}Grs_{2.0-5.0}), with inclusions of sillimanite, biotite ($X_{\text{Mg}} = 0.60-0.67$, $X_{\text{F}} = 0-0.08$) and quartz, are generally surrounded by fine-grained cordierite ($X_{\text{Mg}} = 0.71-0.80$) – spinel ($X_{\text{Mg}} = 0.29-0.35$) $\pm$ sillimanite symplectite as an outer corona and

cordierite ($X_{\text{Mg}} = 0.78-0.83$) – orthopyroxene ($X_{\text{Mg}} = 0.58-0.63$, 3.7–6.8 wt% Al₂O₃) symplectite as an inner corona (Fig. 5e). Spinel-cordierite intergrowths are also included in garnet porphyroblasts, which would be reaction products of sillimanite inclusions with garnet. Biotite, sillimanite and cordierite coexistence is also formed at the garnet rim or outer portion of the corona around

Figure 5. Photomicrographs of ultrahigh-temperature metamorphic rocks from the Kannak Complex.

(a)–(d): garnet-orthopyroxene-sillimanite-cordierite gneiss, (e)–(g): garnet-cordierite-sillimanite-biotite gneiss, (h): garnet-orthopyroxene. Orthopyroxene moat situated at the boundary between corona and surrounding quartz, (b) deformed garnet pseudomorph replaced by orthopyroxene and quartz, (d) coexisting orthopyroxene-sillimanite-quartz replaced by retrograde cordierite and spinel, (e) biotite, sillimanite close-up of orthopyroxene-cordierite symplectite surrounding garnet porphyroblast, (g) a domain composed of cordierite, sillimanite and quartz, 0.5 mm.

garnet porphyroblast. In the garnet-free portion, micro domains of characteristic cordierite ($X_{Mg} = 0.72\text{--}0.74$) – sillimanite – spinel ($X_{Mg} = 0.29\text{--}0.31$) symplectite were also observed (Fig. 5g), which may indicate pseudomorph after garnet. These textural relationships suggest the following reactions through the prograde and retrograde processes:

Garnet-orthopyroxene-biotite charnockitic gneiss

The garnet-orthopyroxene-biotite charnockitic gneiss is a fine-grained, well-foliated melanocratic rock containing

garnet, orthopyroxene, plagioclase, quartz, biotite and gedrite. Minor constituents are ilmenite, zircon, apatite and monazite (Fig. 5h). Subhedral to anhedral garnet porphyroblasts (2–6 mm: $\text{Alm}_{62.0\text{--}68.9}\text{Sps}_{1.1\text{--}2.8}\text{Prp}_{15.2\text{--}17.3}\text{Grs}_{9.7\text{--}17.6}$) include fine anhedral quartz and biotite. Weak-pleochroic orthopyroxene porphyroblasts (2–5 mm, $X_{Mg} = 0.34\text{--}0.37$, 0.9–1.2 wt% Al_2O_3) often coexist with garnet and are elongated along the gneissic foliation. Gedrite, biotite and minor chlorite replace orthopyroxene and some garnet rims as secondary retrograde minerals.

P-T conditions and metamorphic evolution

Reaction textures and chemical features of minerals in some specific very high-grade metamorphic rocks from the Kannak Complex described above are useful to determine the metamorphic evolution processes that have oc-

charnockitic gneiss. (a) garnet is generally surrounded by fine-grained multiple symplectites composed of orthopyroxene, spinel and cordierite, pyroxene-cordierite intergrowth, which surrounded by orthopyroxene moat, (c) primary orthopyroxene porphyroblast including anedral high-limanite and quartz included garnet porphyroblast surrounded by corona of orthopyroxene-cordierite and spinel-cordierite symplectites, (f) spinel, (h) garnet and orthopyroxene porphyroblasts with minor biotite. Scale bar indicates 1 mm in each photomicrograph excepting (d) and (f):

curred in the region. Some well-defined petrogenetic grids, isopleth of chemical compositions of the minerals and melting reaction curves are used for the estimation of pressure-temperature (P - T) paths.

The mineral reactions observed in the very high-grade magnesian and aluminous metamorphic rocks can be explained using the petrogenetic grids in the model FMAS and KFMASH systems (e.g. Harley, 1998; McDade and Harley, 2001). On the basis of petrographic observations of the garnet-orthopyroxene-sillimanite-cordierite gneiss described above, the highest-grade divariant assemblage of orthopyroxene (Opx 1 and Opx 1') + sillimanite + quartz was stabilized at c. 1000–1050°C and c. 11–12 kbar (Fig. 6). This is suggested by the evidence of partial melting reactions accompanied with the consumption of high- F phlogopite ($X_F = 0.2$ – 0.3) (reaction (7): Hensen and Osanai, 1994; Osanai et al., 1998) and no ob-

servation of sapphirine-quartz coexistence. Estimated pressure-temperature conditions for the iron-rich garnet-orthopyroxene-biotite charnockitic gneiss obtained by using garnet-orthopyroxene geothermometers (e.g. Lee and Ganguly, 1988; Bhattacharya et al., 1991; Lal, 1993) and garnet-orthopyroxene-plagioclase-quartz geobarometers (e.g. Perkins and Chipera, 1985; Moecher et al., 1988; Bhattacharya et al., 1991) indicate these ultrahigh-temperature metamorphic conditions (9.0–12.5 kbar, 990–1100°C). The reactions to produce the divariant assemblage of garnet (Grt 1) + cordierite (Crd 1) + sillimanite (through the reaction (1)) and the coexistence of cordierite (Crd 1') + spinel (Spl 1) (through the reaction (2)) in the garnet-orthopyroxene-sillimanite-cordierite gneiss indicate a nearly isothermal decompression path at ultrahigh-temperature conditions. This reaction passes the position between [Spl, Bt] and [Qtz, Bt] invariant points. Accord-

Figure 6. Inferred P - T path and estimated metamorphic conditions of ultrahigh-temperature pelitic gneisses from the Kannak Complex. Petrogenetic grid is compiled from Harley (1998) and Spear (1993). Open square shows the assumed emplacement P - T condition of syn-metamorphic intrusion of S-type tonalite (Plei Man Ko granite) (Osanai et al., 2001a). Biotite-consuming melting curves for $Mg\# = 0.5$ ($X_F = 0$), $Mg\# = 0.75$ ($X_F = 0$) and $Mg\# = 0.75$ ($X_F = 0.1$ and 0.3) are after Vielzeuf and Holloway (1988), Carrington and Harley (1995) and Hensen and Osanai (1994), respectively.

ing to McDade and Harley (2001), the P - T conditions of the invariant points [Spl, Bt] and [Qtz, Bt] in the FMAS system lie around 10.5–11 kbar and 1050°C and near 9.5 kbar and 980°C, respectively (Fig. 6). These ultrahigh-temperature conditions are also suggested by the high-alumina content ($X_{Al} = 0.18$ – 0.21) in orthopyroxene (Opx 1 and Opx 1') (Fig. 7). Multi-phase symplectites of orthopyroxene (Opx 2) + cordierite (Crd 2) and orthopyroxene (Opx 3) + spinel (Spl 2) could be produced during the decompression and cooling stage below *ca.* 1000°C by reactions (3) and (4), respectively. Equilibrium pressure and temperature conditions of retrograde orthopyroxenes (Opx 2 and Opx 3) are also estimated by the isopleths in terms of X_{Al} and X_{Mg} of orthopyroxene (Fig. 7), which show a nearly isobaric cooling path from 9 kbar, 1000°C

to 6.5 kbar, 800°C in the divariant orthopyroxene-cordierite-spinel stability field.

Reaction textures in the garnet-cordierite-sillimanite-biotite gneiss clearly indicate the later stage of metamorphic evolution after the orthopyroxene+cordierite symplectite producing reaction (reaction (3)). Chemical compositions of orthopyroxene ($X_{Al} = 0.085$ – 0.138) from the symplectite indicate a P - T condition of 5.5–7.5 kbar and 780–900°C (Fig. 7), which is equivalent to Opx 2 and Opx 3 in the garnet-orthopyroxene-sillimanite-cordierite gneiss. Later retrograde-stage is estimated using garnet-biotite geothermometry and reaction (10) that the evolution path would pass the condition of *ca.* 4.5 kbar and 730°C (Fig. 6). This pressure-temperature condition is equivalent to that of syn-metamorphic intrusion of the

Figure 7. Inferred P - T path using orthopyroxene compositions from ultrahigh-temperature pelitic gneisses fitted on the calculated X_{Mg} and X_{Al} isopleths (Hensen and Harley, 1990) for orthopyroxene. Note the alumina and magnesium contents of orthopyroxene decrease systematically from primary stage to retrograde stage reflecting reaction textures.

Plei Man Ko granite, which was estimated using garnet-orthopyroxene geothermobarometry and the isopleths for garnet and orthopyroxene compositions (Fig. 7). Biotite + sillimanite + quartz intergrowth surrounding garnet porphyroblasts (reaction (11)) would be produced as the final reaction product at around 4 kbar and 700°C.

Discussion and concluding remarks

Timing of ultrahigh-temperature metamorphism

According to the traditional ideas and inaccurate geochronological data, the Kontum massif was considered to be the Precambrian basement in the Indochina Craton (e.g. Phan Truong Thi et al., 1986; Hutchison, 1989; Sengor and Natal'in, 1996; Metcalfe, 1999). Recently, however, detailed geochronological works for the metamorphic rocks from the wide area of the Kontum massif have been established (e.g. Tran Ngoc Nam, 1998; Nagy et al., 2001; Carter et al., 2001; Tran Ngoc Nam et al., 2000; 2001) (Table 3). But geochronological investigations on the ultrahigh-temperature metamorphic rocks from the massif have not been well established, except Osanai et al. (2001a; 2003) for the Kannak Complex and Nakano et al. (2003) for the Ngoc Linh Complex. Osanai et al. (2001a)

reported a monazite-CHIME age of 248 ± 16 Ma for garnet-orthopyroxene-sillimanite-cordierite gneiss, but a Pan-African age (*ca.* 480–500 Ma) was also detected using some specific monazite grains. They also reported the preliminary CHIME ages of 240–260 Ma for the garnet-cordierite-sillimanite-biotite gneiss and the Plei Man Ko granite (Table 3). Considering the isotopic closure temperature of monazite (700°C), these new results could be from after the biotite-producing retrograde stage. However these ages are comparable to those of charnockite and pelitic gneiss from the Kannak Complex (Carter et al., 2001; Tran Ngoc Nam et al., 2001), determined by zircon ages using a SHRIMP. A closure temperature of zircon for SHRIMP would be as high as 900–1000°C. K-Ar biotite ages for the garnet-cordierite-sillimanite-biotite gneiss yields 242 Ma (Tran Ngoc Nam, 1998). The ultrahigh-temperature eclogitic mafic granulite and related pelitic granulite from the Ngoc Linh Complex are also dated as 240–250 Ma using an Sm-Nd internal isochron method (Nakano et al., 2003). Therefore, ultrahigh-temperature metamorphism and succeeding retrograde metamorphism would have taken place rapidly during the Permo-Triassic (240–260 Ma).

Figure 8 shows a distribution of the recent age-determined localities in the Kontum massif. The metamorphic rocks including high- to ultrahigh-temperature metamorphic rocks along the Dac To Kan shear zone in the Kannak (8–12 in Fig. 8) and the Ngoc Linh (4, 5 in Fig. 8) Complexes indicate Permo-Triassic metamorphic age (240–260 Ma), except undeformed garnet amphibolite in the Kannak Complex (678 ± 23 Ma; Nakano et al., 2002; Osanai et al., 2003), which is located far from the shear zone. It may indicate that the Pan-African metamorphic event would have taken place in the Kontum massif mainly in the Kannak Complex and afterward a very high-grade metamorphic event also took place in the Kannak and the Ngoc Linh Complexes during Permo-Triassic Asian continent growth. The geochronological data from the northern and southwestern Kham Duc Complexes (Carter et al., 2001; Nagy et al., 2001; Tran Ngoc Nam et al., 2000) show ages of *ca.* 300–450 Ma, which may show a different metamorphic event from the Kannak and the Ngoc Linh Complexes.

Metamorphic evolution of ultrahigh-temperature metamorphic rocks from the Kontum massif

To get a better understanding of the metamorphic evolution of ultrahigh-temperature metamorphic rocks from the Kontum massif, well-established petrogenetic grids obtained by experimental and thermodynamical studies and isopleths for minerals are useful. We combined two

Figure 8. Distribution of the recent age-determined localities in the Kontum massif. Age data and their sources for each locality are listed in Table 3.

types of petrogenetic grids not only for pelitic granulites but also for mafic granulites (Fig. 9). The proposed pressure-temperature path for the pelitic granulites from the Kannak Complex is mentioned above, in which the peak metamorphic conditions can be assumed to be *ca.* 11–12 kbar and 1000–1050°C (stage M1 in Fig. 9). However, the high-pressure side of this evolution path is not explained due to the lack of any evidence of reaction textures and available mineral inclusions. On the contrary, a series of changes in divariant assemblages of garnet-clinopyroxene-quartz, clinopyroxene-orthopyroxene-plagioclase-(garnet) and hornblende-quartz in the garnet-clinopyroxene-orthopyroxene granulites (eclogitic ultrahigh-temperature mafic granulite) from the Ngoc Linh Complex was found as a result of their metamorphic evolution. The first high-pressure assemblage (stage M0 in Fig. 9) indicates conditions of 18 kbar and 950–1000°C. Certain low-grade assemblages show the metamorphic condition at around 8–9 kbar and 800–900°C (stage M2 in Fig. 9) estimated by geothermobarometry using garnet rim and orthopyroxene compositions in retrograde phases (Nakano et al., 2003; 2004). Based on observations made in mafic granulites, the simplified connection between these two conditions would correspond to a steep, nearly isothermal decompression path. The ultrahigh-temperature metamorphosed pelitic and mafic metamorphic rocks from the Kontum massif characteristically exposed along the Dac To Kan shear zone show the same isotopic age of

Figure 9. Combined P-T paths for ultrahigh-temperature pelitic gneisses from the Kannak Complex studied here and mafic granulites from the Ngoc Linh Complex (Nakano et al., 2004) in the Kontum massif.

Plagioclase-out and garnet-in lines for mafic granulites are after Green and Ringwood (1967). Hornblende producing univariant line is from Spear (1993). Background petrogenetic grid for pelitic metamorphic rocks is the same to Figure 6. Estimated emplacement P-T condition of S-type tonalite (Plei Man Ko granite) is after Osanai et al. (2001a).

240–250 Ma (Fig. 8). This would indicate that the metamorphic evolution process of these two types of ultrahigh-temperature metamorphic rocks would be identical. If we adopt the same P-T path for both mafic granulite and pelitic metamorphic rocks, divariant assemblage evolution in the mafic granulite immediately after the stage M0 and before the stage M2 would be the same as the clinopyroxene-orthopyroxene-plagioclase-(garnet) (Fig. 9). Then we are able to propose a P-T path for the high-pressure side of the evolution path of pelitic metamorphic rocks, which estimated by using the path of mafic granulite. Evolution process of mafic granulite at lower-temperature and -pressure side after M2 stage is also estimated using the P-T path derived from pelitic metamorphic rocks (Fig. 9).

It was concluded that ultrahigh-temperature metamorphic rocks from the Kontum massif, central Vietnam show a clockwise P-T path with the peak metamorphic condition of 12 kbar and 1050°C (M1 metamorphism). High-pressure M0 metamorphism as part of prograde metamorphism and low-pressure (but still ultrahigh-temperature) M2 metamorphism as part of retrograde meta-

Table 3. Recent geochronological results from the Kontum massif

Loc. No.	Age (Ma)	Rock type	Complex	Method (Mineral*)	Reference
1	418	Gneiss	Kham Duc?	U-Pb SHRIMP (Zrn)	Carter et al. (2001)
2	407	Gneiss	Kham Duc?	U-Pb SHRIMP (Zrn)	Carter et al. (2001)
3	298	Bt-Si gneiss	Kham Duc (north)	K-Ar (Bt)	Tran Ngoc Nam (2000)
4	247	Grt-Opx-Bt gneiss	Ngoc Linh	Sm-Nd (Grt, FF, WR)	Nakano et al. (2003)
5	240	Mafic granulite	Ngoc Linh	Sm-Nd (Grt, Cpx, Hbl, WR)	Nakano et al. (2003)
6	451	Granodioritic gneiss	Kham Duc (south)	U-Pb (Zrn)	Nagy et al. (2001)
	339	Granodioritic gneiss	Kham Duc (south)	Ar-Ar (Bt)	Nagy et al. (2001)
7	444	Gneiss	Kham Duc (south)	U-Pb SHRIMP (Zrn)	Carter et al. (2001)
8	249	Charnockite	Kannak	U-Pb (Zrn)	Nagy et al. (2001)
	243	Charnockite	Kannak	Ar-Ar (Bt)	Nagy et al. (2001)
9	258	Charnockite	Kannak	U-Pb SHRIMP (Zrn)	Carter et al. (2001)
10	242	Crd-Sil-Bt gneiss	Kannak	K-Ar (Bt)	Tran Ngoc Nam (1998)
11	250	Grt-Opx-Sil-Crd gneiss	Kannak	U-Th-Pb CHIME (Mz)	Osanai et al. (2001a)
	479	Grt-Opx-Sil-Crd gneiss	Kannak	U-Th-Pb CHIME (Mz)	Osanai et al. (2001a)
	262	S-type granite	Kannak	U-Th-Pb CHIME (Mz)	Osanai et al. (2001a)
	238	Grt-Crd-Sil-Bt gneiss	Kannak	U-Th-Pb CHIME (Mz)	Osanai et al. (2001a)
12	254	Opx-Bt gneiss	Kannak	U-Pb SHRIMP (Zrn)	Tran Ngoc Nam (2001)
13	678	Grt amphibolite	Kannak (Phu My)	Sm-Nd (Grt, Hbl, WR)	Nakano et al. (2002)

Locality numbers are referred to Figure 8.

*Abbreviations; Zrn, Zircon; Bt, Biotite; Grt, Garnet; FF, Felsic fraction (feldspars + quartz); WR, Whole rock; Mz, Monazite; Hbl, Hornblende.

morphism during the clockwise pressure-temperature evolution were also found (Fig. 9). The widely reported Permo-Triassic metamorphic event (*c.* 240–260 Ma) deduced from ultrahigh-temperature metamorphic rocks would indicate rapid metamorphic evolution from M0 stage to a low-pressure and low-temperature retrograde stage. A recently determined Sm-Nd internal isochron age of 670 Ma for the garnet amphibolite and a monazite-CHIME age of 480–500 Ma for the pelitic granulites would also indicate that the Kontum massif had undergone the Pan-African metamorphic event. The present results indicate that ultrahigh-temperature metamorphic rocks from the Kontum massif are remnants of previously metamorphosed rocks, that might be derived from Gondwana super continent and then strongly affected (re-metamorphosed) by the Permo-Triassic metamorphism during continent collision in eastern Asia as well as the high-grade granulites from north Dabieshan and Shandong areas in China, Imjingang belt in the Korean peninsula and the Higo metamorphic terrane in Japan.

Acknowledgments

We are grateful to M. Yoshida, M. Arima, D.D. Kiem and

Tran Van Tri for their assistance during this work. We would like to sincerely thank H. Kagami, T. Hokada, T. Itaya, M. Seno and S. Kobayashi for their collaboration and frequent discussions. Thanks are also due to T. Shimura and an anonymous reviewer for critical reading of this manuscript. This work was partly supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan (No. 14340150: Y. Osanai). This is a contribution to IGCP-368 and -440.

References

- Arima, M. and Barnett, R.L. (1984) Sapphirine bearing granulites from the Sipiweesk Lake area of the late Archean Pikwitonei granulite terrain, Manitoba, Canada. *Contributions to Mineralogy and Petrology*, 88, 102–112.
- Bhattacharya, A., Krishnakumar, K.R., Raith, M. and Sen, S.K. (1991) An improved set of *a*-*X* parameters for Fe-Mg-Ca garnets and refinements of the orthopyroxene-garnet thermometer and the orthopyroxene-garnet-plagioclase-quartz barometer. *Journal of Petrology*, 32, 629–656.
- Carrington, D.P. and Harley, S.L. (1995) Partial melting and phase relations in high-grade metapelites: an experimental petrogenetic grid in the KFMASH system. *Contributions to Mineralogy and Petrology*, 120, 270–291.

- Carter, A., Roques, D., Bristow, C. and Kinny, P. (2001) Understanding Mesozoic accretion in Southeast Asia: significance of Triassic thermotectonism (Indosinian orogeny) in Vietnam. *Geology*, 29, 211–214.
- Clifford, T.N., Stumpfl, E.F., Burger, A.J., McCarthy, T.S. and Rex, D.C. (1981) Mineral-chemical and isotopic studies of Namaqualand granulites, South Africa: a Grenville analogue. *Contributions to Mineralogy and Petrology*, 77, 225–250.
- Green, D.H. and Ringwood, A.E. (1967) An experimental investigation of the gabbro to eclogite transformation and its petrological applications. *Geochimica et Cosmochimica Acta*, 31, 767–833.
- Grew, E.S. (1982) Osumilite in the sapphirine-quartz terrane of Enderby Land, Antarctica: implications for osumilite petrogenesis in the granulite facies. *American Mineralogist*, 67, 762–787.
- Harley, S.L. (1998) On the occurrence and characterization of ultrahigh-temperature crustal metamorphism. In *What drives metamorphism and metamorphic reactions?* (Treloar, P.J. and O'Brien, P.J. Eds.). Geological Society of London Special Publication, 138, 81–107.
- Harley, S.L., Hensen, B.J. and Sheraton, J.W. (1990) Two-stage decompression in orthopyroxene-sillimanite granulites from Forefinger Point, Enderby Land, Antarctica: implications for the evolution of the Archaean Napier Complex. *Journal of Metamorphic Geology*, 8, 591–613.
- Hensen, B.J. and Osanai, Y. (1994) Experimental study of dehydration melting of biotite in model pelitic compositions. *Mineralogical Magazine*, 58A, 410–411.
- Hensen, B.J. and Harley, S.L. (1990) Graphical analysis of P - T - X relations in granulite facies metapelites. In *High-temperature Metamorphism and Crustal Anatexis* (Ashworth, J.R. and Brown, M. Eds.), Unwin-Hyman, London, 19–56.
- Horrocks, P.C. (1983) A corundum and sapphirine paragenesis from the Limpopo Mobile Belt, southern Africa. *Journal of Metamorphic Geology*, 1, 13–23.
- Hutchison, C.S. (1989) *Geological Evolution of Southeast Asia*. pp. 368, Clarendon, Oxford.
- Ishizuka, H., Suzuki, S. and Kojima, H. (1995) Mineral paragenesis of the sapphirine-bearing rock from the Austkampene area of the Sør Rondane Mountains, east Antarctica. *Proceedings of National Institute of Polar Research Symposium on Antarctic Geosciences*, 8, 65–74.
- Kretz, R. (1983) Symbols for rock-forming minerals. *American Mineralogist*, 68, 277–279.
- Lal, R.K. (1993) Internally consistent recalibrations of mineral equilibria for geothermobarometry involving garnet-orthopyroxene-plagioclase-quartz assemblages and their application to the South Indian granulites. *Journal of Metamorphic Geology*, 11, 855–866.
- Lan, C.-Y., Chung, S.-L., Long, T.V., Lo, C.-H., Lee, T.-Y., Mertzman, S.A. and Shen, J. (2003) Geochemical and Sr-Nd isotopic constraints from the Kontum massif, central Vietnam on the crustal evolution of the Indochina block. *Precambrian Research*, 122, 7–27.
- Lee, H.Y. and Ganguly, J. (1988) Equilibrium compositions of co-existing garnet and orthopyroxene: experimental determination in the system $\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ and applications. *Journal of Petrology*, 29, 93–113.
- McDade, P. and Harley, S. L. (2001) A petrogenetic grid for aluminous granulite facies metapelites in the KFMASH system. *Journal of Metamorphic Geology*, 19, 45–59.
- Metcalfe, I. (1999) Gondwana dispersion and Asian accretion: An overview. In *Gondwana Dispersion and Asian Accretion* (Metcalfe, I. Ed.). Balkema, Rotterdam, 9–28.
- Moecher, D.P., Essene, E.J. and Anovitz, L.M. (1988) Calculation and application of clinopyroxene-garnet-plagioclase-quartz geobarometers. *Contributions to Mineralogy and Petrology*, 100, 92–106.
- Nagy, E.A., Maluski, H., Lepvrier, C., Schärer, U., Thi, P.T., Leyreloup, A. and Thich, V.V. (2001) Geodynamic significance of the Kontum massif in central Vietnam: composite $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb ages from Paleozoic to Triassic. *Journal of Geology*, 109, 755–770.
- Nakano, N., Osanai, Y., Owada, M., Nam, T.N., Binh, P., Kagami, H. and Suzuki, S. (2002) Two different metamorphic ages in the Kontum massif, central Vietnam, Abstract. The 109th Annual Meeting of the Geological Society of Japan, 309.
- Nakano, N., Osanai, Y., Owada, M., Nam, T.N., Suzuki, S. and Kagami, H. (2003) Metamorphic evolution of high-pressure and ultrahigh-temperature mafic granulite from the Kontum massif, central Vietnam, *Earth Monthly*, 25, 236–243.
- Nakano, N., Osanai, Y., Owada, M., Nam, T.N., Tsunogae, T., Toyoshima, T. and Binh, P. (2004) Decompression process of mafic granulite from eclogite to granulite facies under ultrahigh-temperature condition in the Kontum massif, central Vietnam. *Journal of Mineralogical and Petrological Sciences*, 99, 242–256.
- Osanai, Y., Hamamoto, T., Maishima, O. and Kagami, H. (1998) Sapphirine-bearing granulites and related high temperature metamorphic rocks from the Higo metamorphic terrane, west-central Kyushu, Japan. *Journal of Metamorphic Geology*, 16, 53–66.
- Osanai, Y., Owada, M., Kagami, H., Hamamoto, T. and Hensen, B.J. (1996) Sapphirine granulite and related high P - T metamorphic rocks from Highland Complex, Sri Lanka. *Gondwana Research Group Miscellaneous Publication*, 4, 107–108.
- Osanai, Y., Toyoshima, T., Owada, M., Tsunogae, T., Hokada, T. and Crowe, W. A., (1999) Geology of ultrahigh-temperature metamorphic rocks from Tonagh Island in the Napier Complex, East Antarctica. *Polar Geoscience*, 12, 1–28.
- Osanai, Y., Owada, M., Tsunogae, T., Toyoshima, T., Hokada, T., Long, T.V., Sajeev, K. and Nakano, N. (2001a) Ultrahigh-temperature pelitic granulites from Kontum massif, central Vietnam: Evidence for East Asian juxtaposition at ca. 250 Ma. *Gondwana Research*, 4, 720–723.
- Osanai, Y., Toyoshima, T., Owada, M., Tsunogae, T., Hokada, T., Crowe, W.A. and Kusachi, I. (2001b) Ultrahigh temperature sapphirine-osumilite and sapphirine-quartz granulites from Bunt Island in the Napier Complex, East Antarctica –Reconstruction estimation of P - T evolution–. *Polar Geoscience*, 14, 1–24.
- Osanai, Y., Nakano, N., Owada, M., Nam, T.N., Toyoshima, T., Tsunogae, T. and Kagami, H. (2003) Metamorphic and tectonic evolution of Kontum Massif, Vietnam. *Earth monthly*, 25, 244–251.
- Owada, M., Osanai, Y., Tsunogae, T., Toyoshima, T., Hokada, T. and Long, T. V. (2000) Geochemistry of Plei Man Ko complex in Kontum Massif, Central Vietnam. Annual meeting of the Japanese Association of Mineralogists, Petrologists and Economic Geologists, Abstract, 63.
- Perkins, D.I. and Chipera, S.J. (1985) Garnet-orthopyroxene-plagioclase-quartz barometry: Refinement and application to the

- English River subprovince of the Minnesota River Valley. *Contributions to Mineralogy and Petrology*, 89, 69–80.
- Phan Truong Thi, Trinh Van Long, Nguyen Ngoc Lien, Nguyen Xuan Truong and Tran Van Tri (1986) Metamorphic formations and facies series map of S.R. Vietnam on the 1:1000000 scale. *Proceedings of the 1st Conference on Geology of Indochina*, Ho Chi Minh City, 1, 191–200.
- Sengor, A.M.C. and Natal'in, B.A. (1996) Paleotectonics of Asia: fragments of a synthesis. In *The Tectonic Evolution of Asia* (Yin, A. and Harrison, T.M. Eds.). Cambridge University Press, Cambridge, 486–640.
- Sengupta, P., Karmakar, S., Dasgupta, S. and Fukuoka, M. (1991) Petrology of spinel granulites from Araku, Eastern Ghats, India, and a petrogenetic grid for sapphirine-free rocks in the system FMAS. *Journal of Metamorphic Geology*, 9, 451–459.
- Sheraton, J.W., Tingey, R.J., Black, L.P., Offe, L.A. and Ellis, D.J. (1987) Geology of Enderby Land and Western Kemp Land, Antarctica. pp.51, Australian Bureau of Mineral Resources Bulletin, 223.
- Spear, F.S. (1993) Metamorphic Phase Equilibria and Pressure–Temperature–Time Paths, pp. 799, Mineralogical Society of America Monograph, 1, Mineralogical Society of America, Washington.
- Sun, S.-S. and McDonough, W.F. (1989) Chemical and isotopic systematics of ocean basalts: Implications for mantle composition and processes. In *Magmatism in the Ocean Basins* (Saunders, A.D. and Norry, M.J. Eds.). Geological Society of London Special Publication, 42, 313–345.
- Suzuki, S., Hokada, T., Ishikawa, M. and Ishizuka, H. (1999) Geochemical study of granulites from Mount Riiser-Larsen, Enderby Land, East Antarctica: Implication for protoliths of the Archaean Napier Complex. *Polar Geoscience*, 12, 101–125.
- Taylor, S.R. and McLennan, S.M. (1985) *The Continental Crust: its Composition and Evolution*, pp. 312, Blackwell, Oxford.
- Tran Ngoc Nam (1998) Thermotectonic events from early Proterozoic to Miocene in the Indochina craton: implication of K–Ar ages in Vietnam. *Journal of Asian Earth Science*, 16, 475–484.
- Tran Ngoc Nam, Toriumi, M., Itaya, T., Okada, T., Long, T.V. and Kiem, D.D. (2000) Tectonothermal events in Indochinese crystalline basement: evidence from geochronological data. *EOS*, 81, 22, 190.
- Tran Ngoc Nam, Sano, Y., Terada, K., Toriumi, M., Phan Van Quynh and Le Tien Dung (2001) First SHRIMP U–Pb zircon dating of granulites from the Kontum massif (Vietnam) and tectonothermal implications. *Journal of Asian Earth Science*, 19, 77–84.
- Tran Quoc Hai (1986) The evolution of magmatism and metamorphism in Precambrian of Vietnam's territory. *Proceedings of the 1st Conference on Geology of Indochina*, Ho Chi Minh City, 1, 201–207.
- Trinh Van Long (1995) Paired metamorphic belts of Kham Duc complex. *Journal of Geology in Hanoi*, 11, 282–292.
- United Nations (1990) Atlas of mineral resources of the ESCAP region, 6, Vietnam, pp.124, United Nations Publication, Bangkok.
- Vielzeuf, D. and Holloway, J.R. (1988) Experimental determination of fluid-absent melting relations in the pelitic system. Consequences for crustal differentiation. *Contributions to Mineralogy and Petrology*, 98, 257–276.

(Manuscript received; 19 January, 2004)

(Manuscript accepted; 21 April, 2004)