

Crustal anatexis and formation of two types of granitic magmas in the Kontum massif, central Vietnam: Implications for magma processes in collision zones

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Abstract

Asia grew in the Late Permian by the collision of a number of micro-continents. Syn- to post-collisional magmatism occurred along the continental collision zones. In this study, we report two types of granitic rocks, garnet granite (Grt granite) and orthopyroxene granite (Opx granite), from the Kontum massif, central Vietnam, which is situated on the continental collision zone between the South China and Indochina cratons. These granitic rocks were formed at ca. 250 Ma when high-temperature (HT) and ultrahigh-temperature (UHT) metamorphism took place in the same zone. Based on the petrological and geochemical features compared with previously reported experimental results, garnet-bearing granite is derived from pelitic gneisses by partial melting, whereas orthopyroxene-bearing granite is produced by the partial melting of garnet-bearing mafic granulites. We inferred that a significantly high-geothermal gradient is required to produce Vietnamese granitic magmatism and related HT to UHT metamorphism. This geotherm may be attributed to upwelling mantle plume beneath the Kontum massif during the Late Permian.

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Keywords: Central Vietnam; The Kontum massif; The Late Permian; Adakite; Collision zone

1. Introduction

The formation of adakite magmas can be generally explained by the partial melting of the subducting oceanic crust under eclogite-facies conditions (Defant and Drummond, 1990; Martin et al., 2005). In this case, the subducting slabs possess high-geothermal gradients. Therefore, slab melting, including the process of ridge subduction, takes place in hot and young slabs (Martin, 1999).

Ultrahigh-temperature (UHT) metamorphic rocks are found locally in collision zones where metamorphic conditions are above 900 °C and 1000 MPa (Osanai et al., 2006). If partial melting occurs in collision zones, it is expected that the anatectic melt can

be characterized by compositions similar to adakite, for example, southern Tibet and the north China cratons (Chung et al., 2003; Gao et al., 2004). In these cases, UHT metamorphic rocks and adakitic magma should occur in the same collision zones.

The Asian continent was formed by the amalgamation of micro-continents during the Late Permian to Triassic (Metcalf, 1999; Ishiwatari and Tsujimori, 2003) (Fig. 1). Plume-related basaltic rocks, e.g., Emeishan basalt in south China and Song Da komatiite in northern Vietnam, erupted around the collision zone between the South China and Indochina cratons during the transition from the Permian to the Triassic (Chung and Jahn, 1995; Hanski et al., 2003) (Fig. 1). The formation of the Kontum massif has been explained as an Archean core complex within the Indochina craton (Hutchison, 1989). However, recent petrological and geochronological studies have revealed that the Kontum massif can be regarded as reworked

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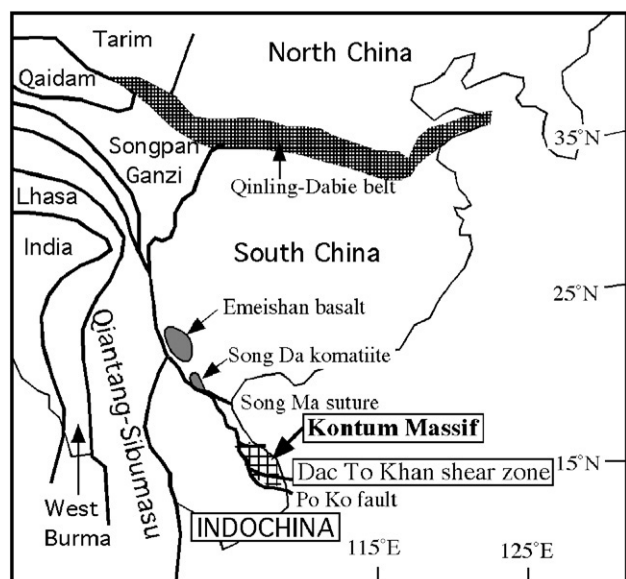


Fig. 1. Tectonic framework of east Asia (after Metcalfe, 1999). The time of magma activity of Emeishan basalt shows in the range of 251–253 Ma by Ar–Ar (Lo et al., 2002) and 259±3 Ma by U–Pb zircon (Zhou et al., 2002). Rb–Sr whole-rock isochron for Song Da komatiite gives an age of 257±24 Ma (Polyakov et al., 1998).

continental crust comprising rocks metamorphosed under high-temperature (HT) to ultrahigh-temperature conditions at the end of the Permian (Nagy et al., 2001; Carter et al., 2001; Tran Ngoc Nam et al., 2001; Osanai et al., 2001), during the formation of the Asian continent. The analyzed metamorphic P – T – t paths of the Kontum massif show the deep crustal process during continental collision (Osanai et al., 2004; Nakano et al., 2004). However, the relationship between HT to UHT metamorphism and magmatism is not understood completely.

In this paper, we describe the metamorphic and igneous rocks that appear in the highest-grade metamorphic region in the Kontum massif and focus on the petrogenetic relationship between HT and UHT metamorphism and granite magmatism. Implications for the crustal evolution of the Kontum massif are also discussed. This paper uses the mineral abbreviations recommended by Kretz (1983).

2. Geological outline of the Kontum massif

The Kontum massif is located in central Vietnam (Fig. 2). The massif comprises both high- P /low- T and low- P /high- T metamorphic rocks and is divided into three complexes from northwest to southeast—Kham Duc, Ngoc Linh, and Kannak (Tran Quoc Hai, 1986) (Fig. 2). The Kham Duc Complex is composed of green-schist-to blueschist-facies and low amphibolite-facies metamorphic rocks (Trinh Van Long, 1995). HT to UHT granulite occur in the Ngoc Linh and the Kannak Complexes (Osanai et al., 2004; Nakano et al., 2004). A part of the UHT mafic granulites from the Ngoc Linh Complex preserves localized evidence of the previous eclogite-facies metamorphism (Nakano et al., 2004). The Kannak Complex is composed of high-grade metamorphic rocks, including the UHT metamorphic rocks (Osanai et al., 2004). Both the Ngoc Linh and the Kannak Complexes are accompanied by intrusive rocks. The peak metamorphic conditions of the Ngoc Linh and the

Kannak Complexes are recorded at 1.2 GPa and 1050 °C (Osanai et al., 2004; Nakano et al., 2004). These UHT metamorphic rocks are situated along the Dac To Khan shear zone; however, the main section of the Ngoc Linh and the Kannak Complexes, located outside the shear zone, does not comprise UHT metamorphic rocks (Osanai et al., 2004).

Chronological data reveal that the metamorphic rocks from the Kontum massif have a complex history from the Mesoproterozoic to the Early Paleozoic, and were reworked during the Late Permian (Osanai et al., 2004). The U–Pb zircon dating of the HT to UHT metamorphic rocks and igneous rocks (Ngoc Linh and Kannak Complexes) found along the Dac To Khan shear zone in the southern part of the Kontum massif, reveal ages between 250 and 260 Ma from the rims of zircon grains (Tran Ngoc Nam et al., 2001; Carter et al., 2001; Nagy et al., 2001; Nakano et al., 2005). The UHT metamorphic rocks and granitic rocks also yield monazite; moreover, the chemical Th–U total Pb isochron method (CHIME) also reveals ages between 250 and 260 Ma (Osanai et al., 2001, 2004). Therefore, the igneous activity and HT to UHT metamorphism coincide with each other at 250 to 260 Ma. Although the random Proterozoic and Paleozoic ages obtained by various methods (U–Pb inherited zircon, Ar–Ar hydrous minerals, etc.) were reported by many workers, a large peak in age determinations at around 250 Ma was interpreted as the metamorphic age (Tran Ngoc Nam et al., 2001; Carter et al., 2001; Nagy et al., 2001; Osanai et al., 2004; Nakano et al., 2005). The distributions of isotopic ages were illustrated in Osanai et al. (2004).

The metamorphic rocks exposed along the Dac To Khan shear zone are composed of quartzofeldspathic and pelitic to psammitic rocks with traces of mafic and calcsilicate rocks. They show well-defined metamorphic foliation and are locally cut by granitic rocks (Fig. 3a). Some of mafic granulites contain garnet and are associated with granitic rocks (Fig. 3b). The granitic rocks, Plei Man Ko granite (Tran Quoc Hai, 1986), occurring along the Song Ba (Ba River) intrude into the host gneisses and are weakly foliated parallel to the foliation of host pelitic gneisses. A migmatite structure is also observed at the boundary between the granitic rocks and metamorphic rocks (Fig. 3c). The granitic rocks are locally associated with fine-grained gabbro. The field relationship between the granitic rocks and fine-grained gabbro is shown in Fig. 3d. The fine-grained gabbro intrudes the granitic rocks, whereas the leucocratic veins derived from the granitic body also penetrate the fine-grained gabbro. This suggests that both granitic rocks and fine-grained gabbro are coeval intrusive rocks.

3. Description of analyzed samples

Analyzed samples are collected from the Kannak Complex that occurs along the Song Ba (Fig. 2). The granitic rocks (Plei Man Ko granite) are classified into garnet-bearing granite (Grt granite) and orthopyroxene-bearing granite (Opx granite). Opx granite is identical to the previously reported as charnockite from the Kannak Complex (Carter et al., 2001; Tran Ngoc Nam et al., 2001; Nagy et al., 2001; Lan et al., 2003). Charnockite includes the following two-generation charnockites, metamorphic charnockite and igneous charnockite. Lan et al. (2003) argued that the charnockite from the Kontum massif was an igneous charnockite rather than a

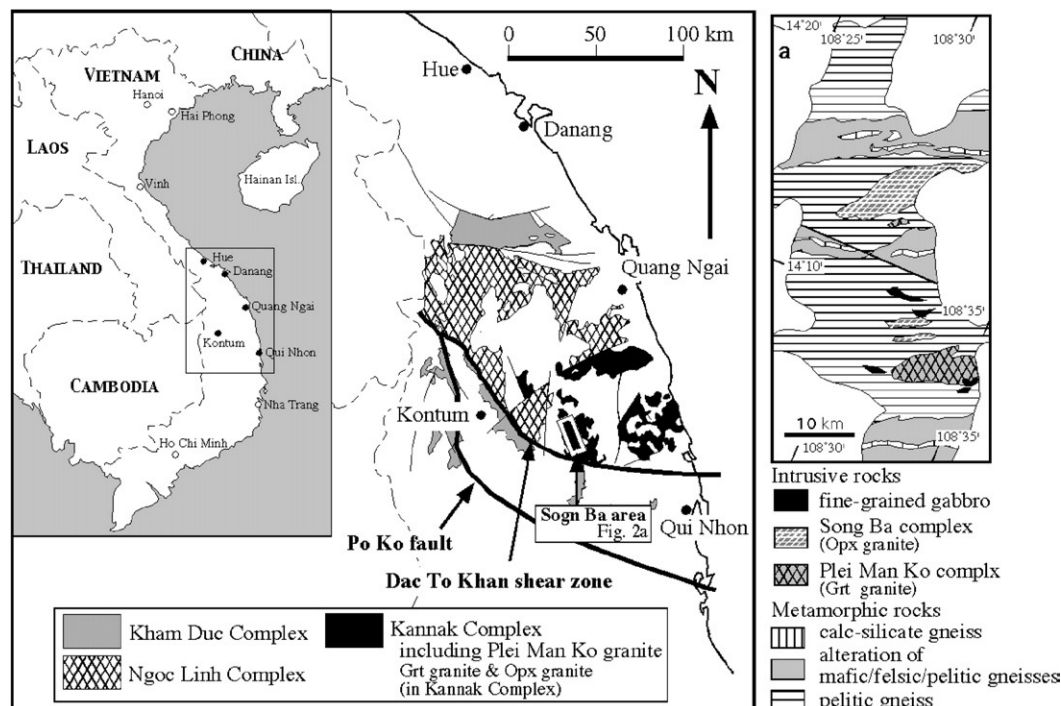


Fig. 2. Geological map of the Kontum massif, central Vietnam (compiled after United Nations, 1990; Lepvrier et al., 2004; Osanai et al., 2004, 2005). a: A detailed geological map along Song Ba river (quoted from Tran Ngoc Nam et al., 2001).

metamorphic charnockite in terms of its mineralogical and geochemical features. In order to avoid confusing charnockite with its petrogenesis, we use the term “Opx granite” in this paper. The mutual relationship between Grt granite and Opx granite is not understood completely. Grt granite locally forms a migmatite structure accompanied by a garnet–orthopyroxene gneiss (Grt–Opx gneiss) (Fig. 3c). Both Grt granite and Opx granite contain fine-grained gabbro as coeval intrusive rocks (Fig. 3d) or as enclaves.

Grt granite consists mainly of Pl, Qtz, Kfs, Grt, and Bt (Fig. 4a,b). Opaque minerals, apatite, zircon, and monazite occur as accessory minerals. Anhedral Grt contains anhedral Bt inclusions, whereas euhedral to subhedral Grt is inclusion-free (Fig. 4a,b). The estimated emplacement P – T conditions of Grt granite are 500–600 MPa and 700 °–800 °C (Osanai et al., 2004). Opx granite comprises Pl, Qtz, Opx, Bt, Hbl, Cpx, and Kfs (Fig. 4c,d). The opaque minerals and apatite are present as accessory minerals. Anhedral Bt and Hbl appear locally in pyroxenes as inclusions. Euhedral to subhedral Opx also includes euhedral Pl (Fig. 4d).

Metamorphic rocks in this area typically underwent retrograde metamorphism after UHT metamorphism (Osanai et al., 2004) and UHT mineral assemblages are only observed in limited lithologies (Osanai et al., 2004). Therefore, most of the metamorphic rocks that occur in this area do not preserve UHT mineral assemblages. Mafic granulite is composed of Pl, Cpx, and Opx with traces of Hbl, Bt, and Qtz, and includes opaque minerals and apatite as accessory minerals. Garnet-bearing mafic granulite, described by Nakano et al. (2004), comprises Cpx, Grt, Opx, Pl, and Hbl. Pelitic gneiss is divided into a Grt–Opx gneiss and a Grt–Bt gneiss. The Grt–Opx gneiss comprises Pl, Qtz, Opx, and Grt with small amounts of Bt, Crd, and Kfs. The opaque minerals, apatite, and zircon appear as

accessory minerals. Opx and Grt include tiny subhedral biotite and quartz crystals. The Bt and Qtz intergrowth replaces euhedral to subhedral Opx. The Grt–Bt gneiss comprises Pl, Qtz, Bt, Grt, and Kfs. The opaque minerals, apatite, and zircon are included as accessory minerals.

4. Whole-rock chemistry and Sr–Nd isotope characteristics

4.1. Analytical procedure

The analyses of major and some trace elements in igneous and metamorphic rocks from the Kannak Complex were determined using XRF (RIX-3000) at the Center for Instrumental Analyses, Yamaguchi University. Some trace elements and REE analyses were also performed using an ICP-MS at Actlabs Ltd., Canada.

Isotopic separation was performed at Yamaguchi University using an experimental procedure adopted from Kagami et al. (1987). Isotopic analyses were carried out using a thermal ionization mass spectrometer (MAT 262) equipped with nine dynamic Faraday cups at Niigata University. $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$, respectively. The normalized $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were corrected using the NBS-987 standard of $^{87}\text{Sr}/^{86}\text{Sr}=0.710241$. The $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were corrected with the Japanese standard JNdi-1 (Nd isotopic reference of the Geological Survey of Japan) of $^{143}\text{Nd}/^{144}\text{Nd}=0.512106$, which was well documented using the international standard La Jolla of $^{143}\text{Nd}/^{144}\text{Nd}=0.511849$ (Tanaka et al., 2000). The analytical errors for $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were 0.01% (1 σ) and 0.01% (1 σ), respectively. Detailed isotopic analytical procedures were reported by Miyazaki and Shuto (1998).

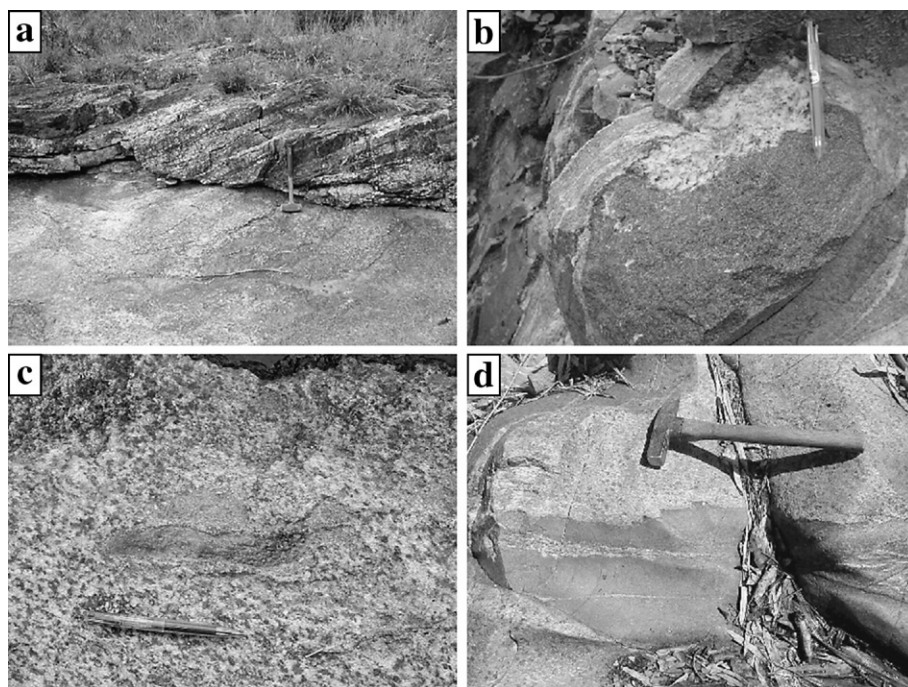


Fig. 3. Occurrence of the granitic rocks occurring along the Dac To Khan shear zone. a: the granite cutting the pervasive metamorphic banding. b: the leucocratic granite associated with the garnet-bearing mafic granulite. c: the granite including the pelitic gneisses showing migmatite structure. d: field relationship between the granite and the fine-grained gabbro.

4.2. Results

In spite of their similar SiO_2 contents, both Grt granite and Opx granite show different geochemical signatures (Table 1).

Grt granite has high alumina-saturation index (ASI) values ($\text{ASI} > 1.1$; S-type), whereas the ASI values of Opx granite are less than 1.1 (I-type) (Fig. 5). Opx granite is characterized by high Sr ($\sim$ ca. 500 ppm) and low Y (7–20 ppm) concentrations

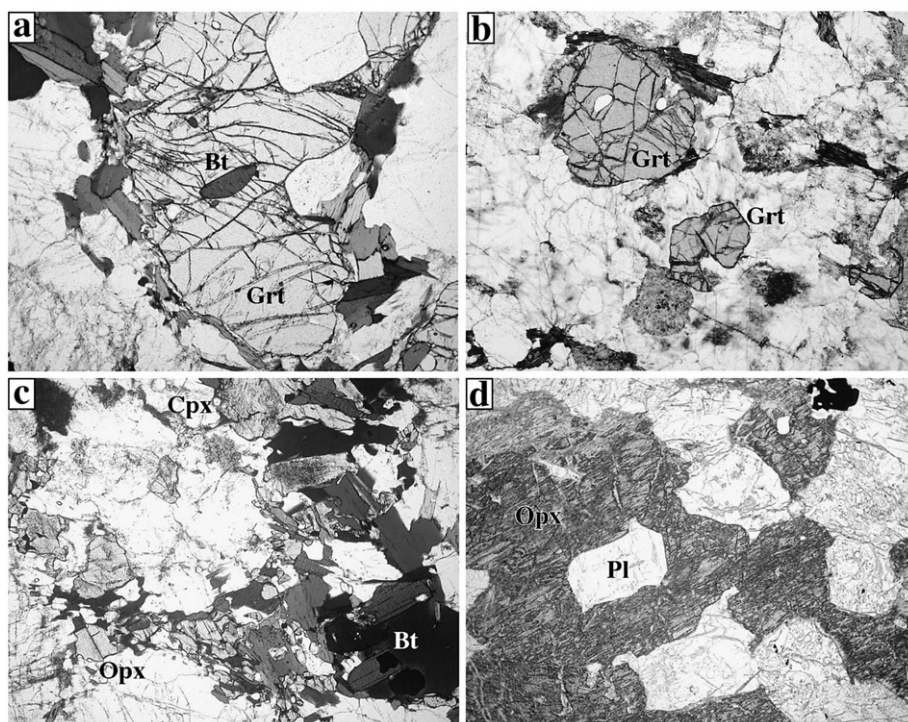


Fig. 4. Photomicrographs of granitic rocks (plane-polarized light). Base of photos are 4 mm. a: Grt granite including anhedral Grt. Note that anhedral Grt includes Bt inclusions. b: Grt granite consisting of euhedral Grt, Bt and felsic minerals. c: Opx granite including Opx, Cpx and Bt. This section also contains a small amount of Hbl. d: Opx granite consisting of subhedral to euhedral Opx and felsic minerals. Note that euhedral Pl is included in Opx as a poikilitic inclusion.

Table 1
Whole rock analyses for igneous and metamorphic rocks from the Kannak Complex

Sample	00042001A	00041907A	00041907D	00041904A	00041907F	00041907B	00041910B2	00041911	00041905B	00041903A	00042001C2	00041909A	00042001E
XRF	Grt granite	Grt granite	Grt granite	Grt granite	Grt granite	Grt granite	Opx granite	Opx granite	Opx granite	Opx granite	Grt–Opx gn	Grt Bt gn	Grt Bt gn
<i>(wt.%)</i>													
SiO ₂	57.72	62.92	64.02	69.49	69.60	72.66	56.35	64.43	72.31	73.64	53.08	56.30	57.98
TiO ₂	1.49	0.57	1.01	0.18	0.34	0.08	1.12	0.74	0.69	0.43	1.79	1.45	1.52
Al ₂ O ₃	18.24	16.96	16.43	15.37	14.81	14.18	16.76	15.83	13.03	13.82	17.44	18.39	17.44
Fe ₂ O ₃	7.81	6.74	5.64	2.85	4.55	2.71	7.94	5.16	3.16	2.99	11.06	8.45	8.73
MnO	0.08	0.10	0.09	0.07	0.07	0.04	0.12	0.07	0.03	0.05	0.18	0.10	0.12
MgO	2.19	2.45	1.61	0.86	1.37	0.84	4.07	2.29	0.58	0.95	3.71	2.36	2.60
CaO	5.62	4.06	3.15	2.13	3.44	1.76	6.55	5.05	1.91	3.92	7.67	6.27	5.84
Na ₂ O	2.54	2.82	3.13	2.50	3.13	2.06	3.51	3.34	2.49	2.96	0.93	2.94	1.88
K ₂ O	1.37	1.28	2.67	4.82	1.13	4.16	2.02	1.22	4.25	1.23	1.31	1.13	1.32
P ₂ O ₅	0.40	0.03	0.03	0.04	0.03	0.02	0.17	0.10	0.06	0.01	0.37	0.34	0.26
LOI	1.30	0.96	0.77	0.59	1.26	0.70	0.37	1.23	0.83	0.98	0.97	1.91	0.49
Total	98.77	98.89	98.55	98.91	99.73	99.21	98.99	99.47	99.32	100.98	98.52	99.64	98.18
ASI	1.15	1.27	1.19	1.16	1.17	1.28	0.84	0.99	1.07	1.04	1.03	1.05	1.15
<i>(ppm)</i>													
Ba	419	161	284	732	129	872	522	357	816	140	409	445	411
Cr	<5	8	7	6	9	<5	56	28	<5	11	<5	<5	8
Ni	<5	8	<5	11	16	11	13	12	7	12	6	<5	12
Rb	81	59	95	188	51	128	55	35	146	40	115	63	90
Sr	264	174	195	161	185	204	508	382	218	211	196	259	232
V	129	100	82	30	48	21	165	108	49	43	163	142	143
Zn	95	60	58	33	40	23	106	68	34	49	113	128	101
Zr	306	296	184	135	155	165	159	93	256	256	401	318	310
<i>ICP-MS</i>													
La	45.6	56.8	106	36.5	50.1	23.3	23.5	15.3	17.7	16.2	33.2	77.5	78.9
Ce	102	114	230	84.4	98.9	38.0	56.7	29.8	33.4	29.8	72.9	168	174
Pr	11.6	11.9	25.5	9.8	10.3	3.5	7.0	3.2	3.6	2.9	8.1	18.5	19.3
Nd	47.4	44.6	97.3	39.4	37.4	11.9	29.7	13.0	14.6	10.2	32.9	71.0	75.1
Sm	8.8	7.5	15.2	7.8	6.1	2.1	6.0	2.4	2.8	1.6	6.3	12.1	12.4
Eu	1.66	1.55	1.34	1.37	1.10	1.70	1.47	1.14	1.29	0.94	1.19	1.74	1.55
Gd	7.5	7.6	10.2	5.5	5.6	3.0	5.2	2.0	2.5	1.2	7.3	9.0	9.0
Tb	1.1	1.4	1.3	0.8	1.1	0.7	0.8	0.3	0.4	0.2	1.4	1.1	1.1
Dy	4.9	8.4	6.1	5.1	7.2	4.4	3.7	1.2	1.8	1.2	8.9	4.8	4.9
Ho	0.9	1.7	1.1	1.1	1.7	1.0	0.7	0.2	0.4	0.3	2.0	0.8	0.8
Er	2.1	4.4	2.7	3.4	5.0	2.7	2.0	0.6	1.0	1.1	5.9	2.0	2.0
Tm	0.27	0.61	0.37	0.52	0.80	0.42	0.27	0.08	0.14	0.20	0.93	0.24	0.25
Yb	1.5	3.5	2.1	3.0	5.0	2.7	1.6	0.5	0.9	1.5	5.5	1.3	1.5
Lu	0.21	0.54	0.30	0.44	0.78	0.43	0.24	0.08	0.15	0.27	0.85	0.18	0.20
Y	25	46	31	33	47	28	20	7	10	8	55	22	23
Hf	10	8	6	4	5	5	4	2	9	7	11	9	10
Nb	15	5	9	4	3	2	9	8	11	4	16	17	17
Ta	0.93	0.16	0.63	0.08	0.12	<0.01	0.36	0.35	0.70	0.15	1.19	1.09	1.49
Pb	11	18	25	16	15	24	8	11	10	12	<5	6	11
(La/Yb) _N	22.4	11.7	36.5	8.8	7.2	6.3	10.2	21.0	14.1	7.8	4.4	43.0	39.0
Yb _N	8.6	20.4	12.3	17.5	29.2	15.7	9.7	3.1	5.3	8.7	32.1	7.6	8.5

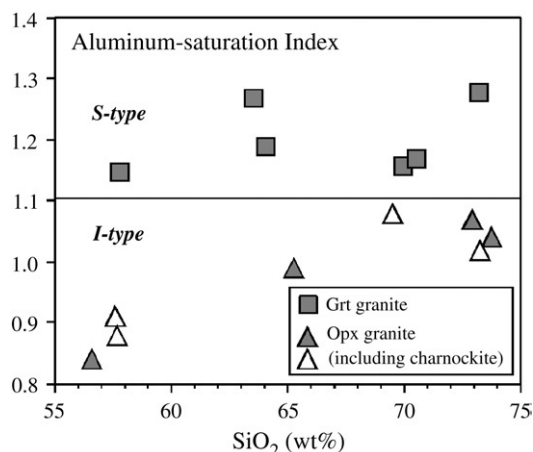


Fig. 5. SiO_2 (wt.%) — ASI diagram for the granitic rocks from the Kannak Complex. Data of Opx granite used in this diagram are from this study, Nagy et al. (2001) and Lan et al. (2003).

as compared with Grt granite ($\text{Sr} < 270$ ppm, $\text{Y} = 25\text{--}47$ ppm) (Table 1). Fig. 6 shows Sr/Y vs. Y (ppm) diagram with a compositional field of adakite and Archean high-Al TTG and Island arc ADR. The chemical compositions of Opx granite are plotted within the adakite and Archean high-Al TTG field. Chondrite-normalized REE patterns for Grt granite show LREE-enrichment with positive or negative Eu anomaly (Fig. 7a). With the exception for one sample, the normalized patterns of Opx granite indicate not only LREE-enrichment but also HREE-depletion (Fig. 7b). Chondrite-normalized (La/Yb_N and Yb_N values of Opx granite are >7 and <10 , respectively (Table 1). These values are plotted within the Archean TTG field in the (La/Yb_N) vs. Yb_N diagram designated by Martin (1986).

The initial Sr and Nd isotope (SrI , NdI) ratios of Grt granite and pelitic gneisses corrected to 250 Ma range from 0.7321 to 0.7562 and 0.51163 to 0.51167 (equivalents ϵ_{Nd} values range from -12.4 to -13.3), respectively (Table 2). These high-SrI

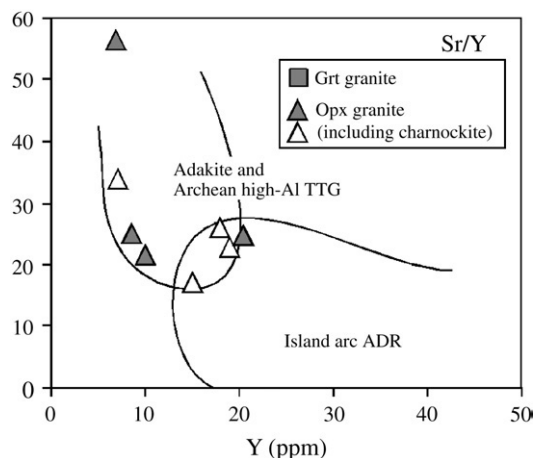


Fig. 6. Y (ppm)–Sr/Y diagram with the compositional fields of adakite and Archean high-Al TTG, and island arc (Defant and Drummond, 1990). Data of Opx granite used in this diagram are the same as Fig. 5.

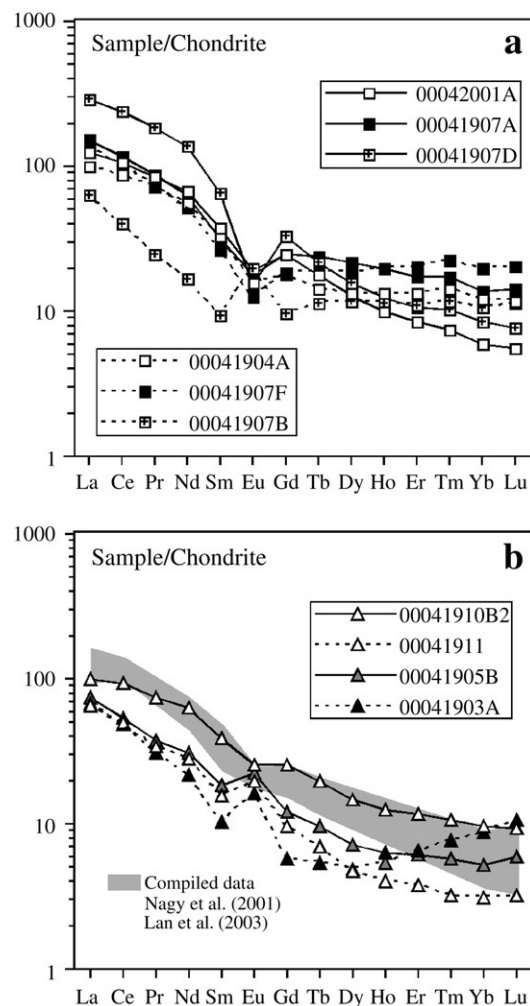


Fig. 7. Chondrite-normalized REE pattern for Grt granite (a) and Opx granite (b), respectively. Normalized values are taken from Sun and McDonough (1989).

and low-NdI ratios suggest that the protolith of Grt granite and pelitic gneisses had a long history in the crust, possibly dating back to the Paleoproterozoic era (Table 2). Fig. 8 shows the ϵ_{NdI} and SrI ratios for Grt granite and the pelitic gneiss as well as the data compiled from Lan et al. (2003), including pelitic gneisses, a mafic granulite, and the charnockites (Opx granite). The isotopic signature of the charnockite (Opx granite) differs from Grt granite; however, it resembles the mafic granulite (Fig. 8).

5. Discussion

5.1. Petrogenesis of two types of granitic magma

According to isotopic features, the pelitic gneisses and mafic granulites are candidate source rocks for Grt granite and Opx granite, respectively (Fig. 8). Fig. 9 shows the geochemistry of major elements of Grt granite and Opx granite with pelitic gneisses and mafic granulites. These diagrams also represent plots of the results of the melting experiments related to both pelitic and mafic systems (Vielzeuf and Holloway, 1988; Osanai

Table 2
Rb–Sr and Sm–Nd isotopic compositions for igneous and metamorphic rocks from the Kannak Complex

Sample no.	Lithology	Rb ppm	Sr ppm	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ	SrI 250 Ma	Sm ppm	Nd ppm	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	NdI 250 Ma	ϵNdI 250 Ma	T_{DM} Ga
00042001C2	Grt–Opx gneiss	98	166	1.7133	0.73874	(1)	0.73265	6.25	32.9	0.1148	0.511838	(14)	0.511650	–13.0	2.01
00041909A	Grt–Bt gneiss	54	206	0.7604	0.73484	(1)	0.73214	12.1	71.0	0.1030	0.511821	(14)	0.511653	–12.9	1.82
00042001A	Grt granite	72	203	1.0302	0.74758	(1)	0.74391	8.82	47.4	0.1124	0.511819	(14)	0.511635	–13.3	1.99
00041907A	Grt granite	52	143	1.0575	0.76004	(1)	0.75628	7.54	44.4	0.1026	0.511847	(14)	0.511679	–12.4	1.78
00041904A	Grt granite	152	137	3.2277	0.76375	(1)	0.75227	11.3	56.0	0.1217	0.511877	(14)	0.511678	–12.5	2.09

et al., 1997; Springer and Seck, 1997) as a chemical comparison with Grt granite and Opx granite.

The chemical compositions of the Grt granite and pelitic gneisses indicate monotonous trends in variation diagrams (Fig. 9a,b), thereby suggesting that the restite-unmixing model is used to form these trends (White and Chappell, 1977). The pelitic gneisses are characterized by low concentrations of SiO_2 , Na_2O , and K_2O and high concentrations of Fe_2O_3 and CaO as compared to those of Grt granite (Table 1). The chemical compositions of the starting materials and the synthetic melt in the melting experiments are similar to those of the pelitic gneisses in the Kannak Complex and SiO_2 -rich Grt granite, respectively (Fig. 9a,b). The major element chemistry suggests that Grt granite can be produced by partially melting pelitic gneisses.

Opx granite possesses high Sr and $(\text{La}/\text{Yb})_N$ values. Major element compositions of Opx granite together with mafic granulites show smooth trends in the variation diagrams (Fig. 9c,d). Fig. 9c,d also represent the plots of the melting experiment results for the mafic system. The starting material is included within the compositional range of the mafic granulites. The synthetic melt compositions coexisting with both Grt-bearing and Grt-free phases are plotted on the variation trends of Opx granite (Fig. 9c,d). These geochemical features combined

with isotopic signatures suggest that Opx granite can be derived from mafic granulites.

In order to test the petrogenesis of Grt granite and Opx granite, we examine geochemical modeling, which focuses on the partial melting of pelitic gneisses and mafic granulites. The formulation for residual phases and melting conditions used in this modeling refers to the experimental results of Vielzeuf and Holloway (1988) and Osanai et al. (1997) with regard to the pelitic system and those of Springer and Seck (1997) related to the mafic system. The values of the partition coefficient, proportion of residual phases, and inferred source compositions of Grt granite and Opx granite are shown in Table 3. The melt compositions derived from both pelitic gneisses and mafic granulites were calculated by a simple batch melting equation. The inferred melt compositions are represented on the Rb (ppm) vs. Sr (ppm) diagrams (Figs. 10 and 11).

Fig. 10 plots the composition of the Grt granite and pelitic gneisses with the results of the estimated melt compositions (Models 1 and 2). The models were calculated based on differing residual mineral assemblages. Models 1 and 2 indicate the inferred melt compositions coexisting with Grt-bearing or Grt-free residues, respectively. The chemical compositions of Grt granite are closely plotted on Model 1. The Rb and Sr contents of the SiO_2 -rich Grt granite (00041904A, $\text{SiO}_2=69.49$ wt.%) are identical to those of the 40% degree of melting in Model 1. On the other hand, the other Grt granites are situated between the SiO_2 -rich Grt granite and pelitic gneisses. Consequently, the chemical compositions of Grt granite can be replicated by the partial melting of pelitic gneisses leaving Grt as a residual phase.

Fig. 11 plots the composition of the Opx granite and mafic granulites and shows the geochemical modeling for the petrogenesis of Opx granite. In Model 1, partial melting takes place in the mafic granulite leaving Grt-bearing residues under the pressure condition of 1.0 GPa. On the other hand, Model 2 is proposed by low-pressure melting (0.5 GPa) involving large amounts of Pl without Grt as residual phases. The chemical compositions of Opx granite are plotted around a 30% degree of melting on Model 1; however, they do not fit on Model 2. Fig. 11 also shows the fractional crystallization trends for Pl, Hbl, Cpx, and Opx using the Rayleigh fractionation model. The chemical compositions of Opx granite are located mainly on both the Pl fractionation and accumulation trends. These trends are supported by the petrographical signature, where euhedral plagioclase is included in orthopyroxene, thereby suggesting plagioclase accumulation. Therefore, geochemical modeling reveals that Opx granite can be produced by the partial melting

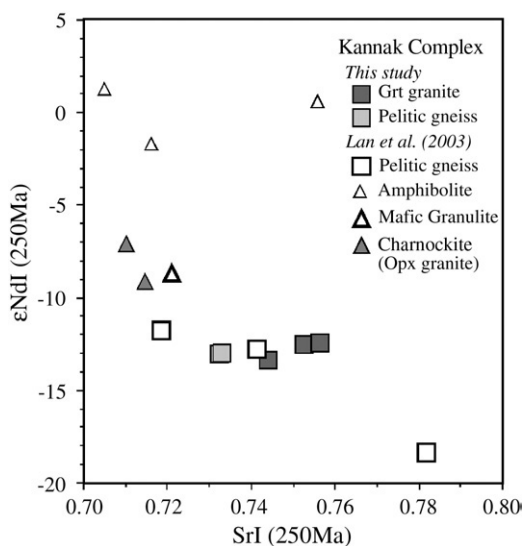


Fig. 8. Initial epsilon Nd–Sr isotopic ratios corrected to 250 Ma for the igneous and metamorphic rocks from the Kontum massif.

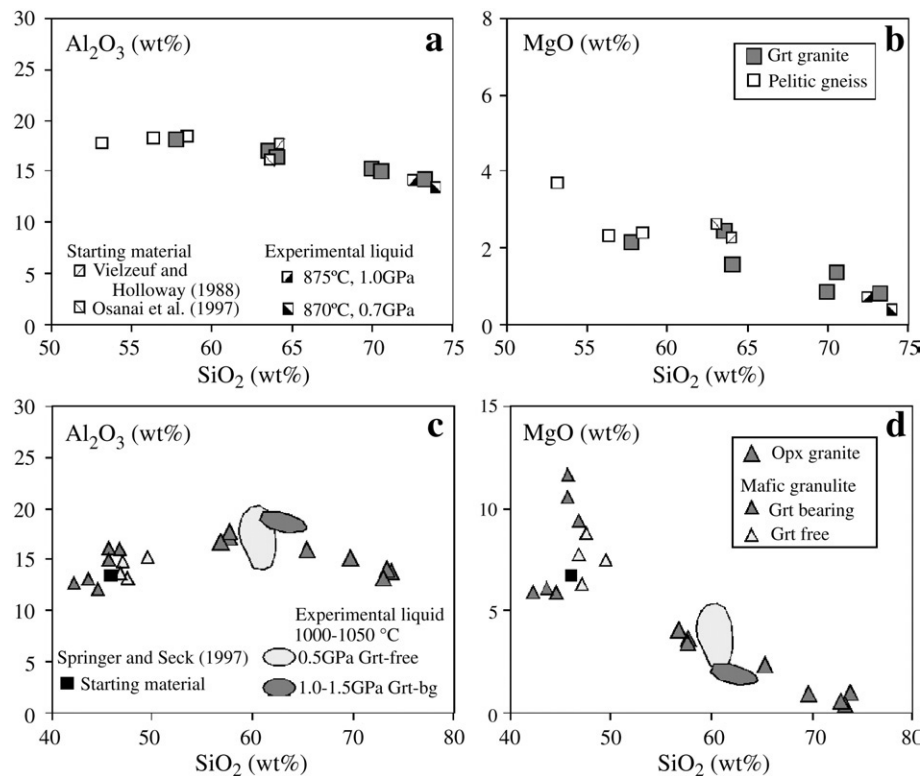


Fig. 9. Major element geochemistry of granitic rocks from the Kannak Complex with pelitic gneisses and mafic granulites from the Kannak and Ngoc Linh Complexes. Chemical compositions both starting materials and melts of high-pressure melting experiment in pelitic and mafic systems are also shown. Chemical compositions of mafic granulites are from Lan et al. (2003) and Nakano et al. (2004). Chemical compositions of Opx granite are the same as Fig. 5. Data of experimental studies are taken from Vielzeuf and Holloway (1988) and Osanai et al. (1997) with regard to the pelitic system (a and b) and those of Springer and Seck (1997) related to the mafic system (c and d).

of a source that is similar in composition to the mafic granulite under the garnet-stable pressure condition.

5.2. Crustal evolution of the Kontum massif

The Kontum massif was reworked by continental collision between the Indochina and South China cratons during the Late Permian (Osanai et al., 2004). Analyzed metamorphic P – T – t paths reveal that the UHT metamorphism in the Kontum massif has undergone high-pressure eclogite-facies metamorphism (M0-stage: >2.5 GPa, 950 °–1000 °C) prior to peak metamorphic

conditions (M1-stage: 1.1–1.2 GPa, 1000 °–1050 °C) (Osanai et al., 2004; Nakano et al., 2004). After the M1-stage, near isothermal decompression occurred continuously in the UHT condition (>900 °C), and pressure and temperature decreased (M2-stage) (Osanai et al., 2004).

Zircon U–Pb Sensitive High Resolution Ion Microprobe (SHRIMP) dating of granulite facies metamorphic rocks, including the UHT metamorphic rocks from the Kontum massif, has revealed ages ranging from 250–260 Ma (Nagy et al., 2001; Tran Ngoc Nam et al., 2001; Carter et al., 2001; Nakano et al., 2005). A preliminary monazite CHIME date for UHT metamorphism indicates an age of

Table 3
Partitioning coefficient, mineral proportion of residual phases, and inferred source compositions using geochemical modeling in this study

	Pl ¹	Cpx ²	Opx ³	Hbl ³	Grt ³	Crd ⁴	Qtz ⁵
Rb	0.11	0.02	0	0.04	0.01	0.08	1.0E−06
Sr	15.63	0.08	0.01	0.2	0.02	0.12	1.0E−06
Pelitic system					Source composition		
Model 1	Pl:Grt:Qtz=0.15:0.60:0.25				Rb	63 ppm	
Model 2	Pl:Crd:Opx:Qtz=0.50:0.05:0.25:0.20				Sr	259 ppm	
Mafic system					Source composition		
Model 1	Cpx:Opx:Grt:Hbl=0.50:0.30:0.10:0.10				Rb	12 ppm	
Model 2	Pl:Cpx:Opx:Hbl=0.35:0.40:0.20:0.05				Sr	115 ppm	

Samples 00041909A and KT923 (Lan et al., 2003) represent the source compositions of Grt granite and Opx granite, respectively. 1: Nash and Crecraft (1985), 2: Irving and Frey (1978), 3: Arth (1976), 4: Bea et al. (1994), 5: Tatsumi (2001).

248±16 Ma (Osanai et al., 2001, 2004). Considering the closure temperature of monazite and zircon in the U–Pb system, the UHT metamorphism and succeeding decompression retrograde metamorphism occurred during 250–260 Ma (Osanai et al., 2004). A monazite CHIME age for Grt granite and a zircon U–Pb SHRIMP age for Opx granite give ages of ca. 250–260 Ma (Osanai et al., 2001; Carter et al., 2001; Osanai et al., 2004), suggesting that Grt granite and Opx granite magma were formed during the period from the peak metamorphic stage to the decompression stage.

In Fig. 3d, fine-grained gabbro intruded simultaneously into Grt granite. According to field occurrence, the time of intrusion of fine-grained gabbro as well as Grt granite and Opx granite is considered to be ca. 250–260 Ma. Granitic rocks and basaltic enclaves (MMEs) are common associations for post-collisional magmatism (Bonin, 2004). Therefore, Grt granite, Opx granite, and fine-grained gabbro correspond to the post-collisional magmatism during exhumation of the Kontum massif. In this case, the mantle-derived fine-grained gabbro may play an important role as a heat source for UHT metamorphism and the partial melting of crust. A similar scenario was proposed by Rajesh (2004) in southern India during a Pan-African event, in which extension and uplift after lithospheric thickening provides an important tectonic environment for crustal melting.

Such a high-temperature condition can be provided by the underplated basaltic magma, as mentioned above. Plume-related basaltic magma is reported from the Song Da area (Hanski et al., 2003) in north Vietnam and at the Emeishan province in south China (Chung and Jahn, 1995) during the Late Permian to Triassic. These two basaltic provinces are situated close to each other on the northern extension of the collision zone between the South China and Indochina cratons (Fig. 1). Therefore, an upwelling mantle plume can explain the heat source for formation of the fine-grained gabbro.

Based on petrological constraints described above, we assume that the formation process of the Kontum massif involving Grt granite and Opx granite is as follows: (1) continent–continent

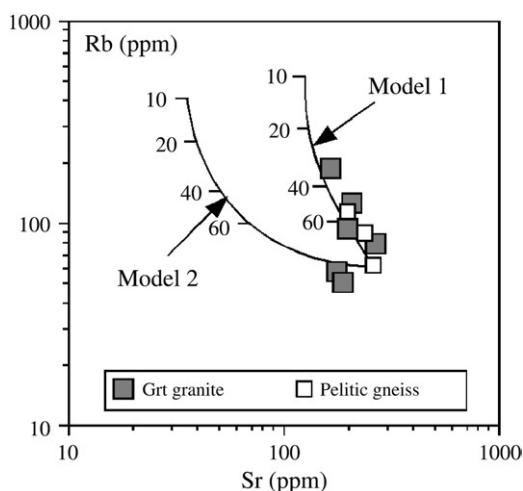


Fig. 10. Sr (ppm)–Rb (ppm) diagram for Grt granite and pelitic gneisses. Models 1 and 2 indicate estimated chemical trends calculated by batch melting using the pelitic gneiss (sample 00041909A) as a source material. Numbers (10, 20...40) on the calculation curves correspond to degree of melting. Proportion of the residual phases for Models 1 and 2 are shown in Table 3.

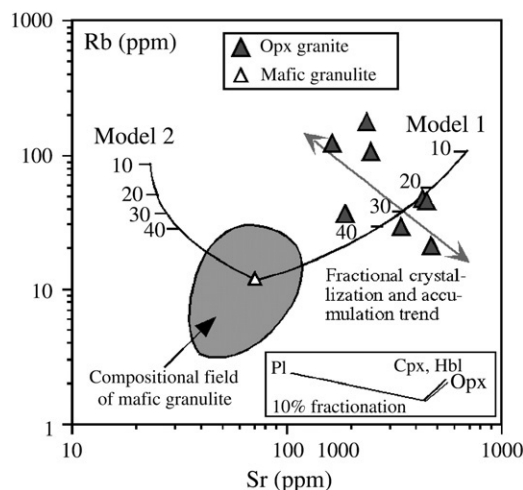


Fig. 11. Sr (ppm)–Rb (ppm) diagram for Opx granite and mafic granulites. Models 1 and 2 indicate estimated chemical trends calculated by batch melting using the mafic granulite (sample KT923; Lan et al., 2003) as a source material. Numbers (10, 20...40) on the calculation curves correspond to degree of melting. Proportion of the residual phases for Models 1 and 2 are shown in Table 3. Chemical compositions of Opx granite used in this diagram are the same as Fig. 5.

collision produced a thickened crust, (2) exhumation and underplating basaltic magma was deduced from mantle plume, and (3) UHT metamorphism occurring in the thickened crust of the collision zone, and the formation of Grt granite and Opx granite by the partial melting of the pelitic gneisses and garnet-bearing mafic granulites, respectively.

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