Late Permian plume-related magmatism and tectonothermal events in the Kontum Massif, central Vietnam

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The Kontum Massif is situated in the southern part of Trans Vietnam Orogenic Belt (TVOB), central Vietnam, and contains various types of magmatic and metamorphic rocks, the latter including both ultrahigh-pressure and ultrahigh-temperature units. While geochronological data indicate the existence of two main tectonothermal events at 480–420 Ma and 270–240 Ma, the most intense metamorphic and magmatic activity occurred between the Late Permian and Early Triassic due to continental collision between the South China and Indochina cratons. In this study, U–Pb LA–ICP–MS geochronological analyses of zircon obtained from two samples of metagabbro and one sample of charnockite from the massif yielded a magmatic age range of 260–250 Ma for all three samples and an inherited age of ~ 1400 Ma for the charnockite. These magmatic ages overlap with those documented for peak metamorphism in the Kontum Massif. When combined with Nd isotopic data for granitic rocks and pelitic gneisses from the region, these data suggest that the massif may have been derived from reworked continental crust. Geochemical characteristics of metagabbros from the massif reveal that the parental basaltic magma can be correlated with the Song Da igneous suite situated in the northern part of the TVOB, and was assimilated by crustal materials. The Song Da igneous suite is a member of the Emeishan large igneous province and resulted from Late Permian mantle plume activity. We conclude that the plume-related magma intruded into the deeper part of Kontum Massif and induced ultrahigh-temperature metamorphism of the lower crust by acting as a heat source.

Keywords: Metagabbro, Mantle plume, U–Pb zircon dating, Late Permian, Kontum Massif

INTRODUCTION

The collision and accretion of micro-continents plays an important role in large-scale continental growth throughout geological time. Ultrahigh-pressure (UHP) and/or ultrahigh-temperature (UHT) metamorphic rocks, together with syn- to post-collisional igneous rocks, are locally exposed in several collision zones in Asia (Okay et al., 1989; Ree et al., 1996; Zhang et al., 1996; Osanai et al., 2004; Oh et al., 2005; Osanai et al., 2008; Nakano et al., 2008, 2010). Late Permian to Early Triassic continental growth in Asia can be accounted for by collage tectonics, exemplified by events such as the collisions between the South

China and Indochina cratons, and the North China and South China cratons (Metcalf, 1999; Ishiwatari and Tsujimori, 2003). At around this time, the plume-related Emeishan flood basalts were erupted over a large region of southwest China, forming a large igneous province (the Emeishan LIP) (Chung and Jahn, 1995; Xu et al., 2001; Xiao et al., 2004; Ali et al., 2005).

Various metamorphic and igneous rocks are exposed over large regions of north and central Vietnam, with the former, including UHP and UHT lithologies (Figs. 1a and 1b). Both of these metamorphic rock types experienced a similar clockwise *P–T* evolution during the Late Permian and Early Triassic periods (270–240 Ma: Osanai et al., 2004; Nakano et al., 2004, 2007a, 2007b, 2008; Osanai et al., 2008; Nakano et al., 2009, 2010). This led Osanai et al. (2008) to propose the name ‘Trans Vietnam Oro-

Figure 1. (a) The distribution of South China and Indochina cratons within the Trans Vietnam Orogenic Belt (TVOB) (after Osanai et al., 2008). (b) Locations of the Truong Son Belt (TB) and Kontum Massif (KM) in Vietnam, both of which form part of the TVOB. (c) Geological sketch map of the Kontum Massif, central Vietnam (after United Nations, 1990). The Kontum Massif can be divided into three metamorphic terranes: the Kannak, Ngoc Linh, and Kham Duc Complexes. Dashed square shows the location of the study area along the Ba River (Song Ba). Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

genic Belt' (TVOB) for the region containing metamorphic and igneous rocks of this age (Fig. 1), which was interpreted to have formed due to collision between the South China and the Indochina cratons. In addition, the Late Permian plume-related Song Da igneous suite (Fig. 1c), a member of the Emeishan LIP (Hanski et al., 2004), is exposed in the northern part of the TVOB.

The Kontum Massif, central Vietnam, is located in the southern part of the TVOB and is thought to be a core complex of the Indochina craton (e.g., Hutchison, 1989). Geochronological studies have revealed that its metamorphic components experienced a complex history from the Middle Proterozoic to the Phanerozoic (Tran Ngoc Nam et al., 2001; Nakano et al., 2013), although major tectono-

thermal events occurred during the Ordovician-Silurian and the Late Permian-Early Triassic (Carter et al., 2001; Nagy et al., 2001; Tran Ngoc Nam et al., 2001; Maluski et al., 2005; Roger et al., 2007; Lepvrier et al., 2008; Usuki et al., 2009; Nakano et al., 2013) (Fig. 2). According to Nakano et al. (2013), the Ordovician-Silurian thermal event occurred in an active continental margin tectonic setting, whereas the Late Permian-Early Triassic event was associated with UHP/UHT metamorphism and records the formation of deep-seated continental crust within the TVOB collision zone.

Elucidating the petrogenetic processes by which such extreme metamorphic and magmatic processes occur in collision zones provides valuable information regarding

Figure 2. Summary of previously reported ages for metamorphic and intrusive igneous rocks from the Kontum Massif. (A) zircon U-Pb isotopic age. (B) monazite Th-U-Pb chemical age. Data sources comprise Carter et al. (2001), Nagy et al. (2001), Tran Ngoc Nam et al. (2001), Owada et al. (2006), Roger et al. (2007), Usuki et al. (2009), and Nakano et al. (2013). Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

the evolution of deep-seated continental crust (e.g., Condie, 1997). The Kontum Massif has a prolonged geological history and contains Late Permian UHT metamorphic rocks and syn-kinematic metamorphosed gabbro; hereafter, termed metagabbro (Nakano et al., 2004; Osanai et al., 2004; Owada et al., 2006, 2007; Nakano et al., 2007a). The mechanisms by which deep-seated continental crust formed within the TVOB collision zone are still unclear, although investigating the petrogenetic relationships between UHT metamorphism and the emplacement of extremely hot magmas could provide important insight into this issue (Osanai et al., 2008). As such, we have performed geochronological and geochemical investigations of metagabbros and related granitic intrusions from the Kontum Massif in order to 1) unravel its complex tectono-thermal history, 2) constrain the age of mantle-derived magmatism with respect to UHT metamorphism and investigate potential petrogenetic links between the two, and 3) elucidate the magmatic processes involved with the formation of metagabbro in the region by comparing its geochemical features to those of the plume-related Song Da igneous suite from the northern part of the TVOB.

GENERAL GEOLOGY OF THE KONTUM MASSIF

The Kontum Massif is comprised of three distinct tectonostratigraphic terranes: the northwestern Kham Duc Complex, the central Ngoc Linh Complex, and the south-eastern Kannak Complex (Tran Quoc Hai, 1986) (Fig. 1c).

The Kham Duc Complex is composed of low- to medium-temperature and relatively high-pressure kyanite-bearing metamorphic rocks (Nakano et al., 2007a, 2007b), whereas the Ngoc Linh and Kannak Complexes contain high-temperature (HT) to UHT granulite that reached peak metamorphic P - T conditions of 1.2 GPa and 1050 °C (Nakano et al., 2004; Osanai et al., 2004, 2008). Some of the UHT mafic granulites from the Ngoc Linh Complex record petrological evidence of an earlier eclogite-facies metamorphism (Nakano et al., 2004), and low-grade metamorphic rocks that may belong to the Kham Duc Complex are exposed in the southern part of the Kannak Complex (Fig. 1). Parts of these complexes are suggested to have experienced extreme metamorphism in a deep-crustal environment due to continental collision (Osanai et al., 2004; Nakano et al., 2004, 2007a, 2007b; Osanai et al., 2008).

Intrusive igneous rocks exposed in the Kannak Complex occur as stocks and lenses within granulite-facies metamorphic lithologies. Magmatic rocks of granitic composition are divided into two types: garnet-bearing granite and orthopyroxene-bearing granite (charnockite). The garnet-bearing granite locally shows a migmatitic structure with pelitic gneisses occurring as paleosome layers. Metagabbro occurs as stocks, lenses, or enclaves in the granitic rocks (Fig. 3a), and has dark, millimeter-scale, and fine-grained chilled margins along contacts with the host granitic rocks (Fig. 3a). These relationships show that the granitic rocks and metagabbros were intruded coevally (Owada et al., 2006, 2007).

PETROGRAPHY OF CHARNOCKITE AND METAGABBRO

Charnockite in the Kannak Complex is composed mainly of plagioclase, quartz, K-feldspar, orthopyroxene, and biotite, alongside small amounts of hornblende and clinopyroxene. Apatite, zircon, and opaque minerals occur as accessory phases. Felsic minerals are commonly larger than 5 mm in size, although mafic minerals orthopyroxene and biotite are 2-5 mm (Fig. 3b). Biotite flakes locally surround orthopyroxene grains.

Metagabbro in the Kannak Complex consists mainly of orthopyroxene, clinopyroxene, and plagioclase, with trace amounts of hornblende and biotite. Most examples exhibit a granoblastic texture (Figs. 3c and 3d). Apatite, opaque minerals, and zircon occur as accessory phases. Orthopyroxene locally includes euhedral to subhedral plagioclase (Fig. 3c), and plagioclase grains in the matrix locally include rounded quartz grains (Fig. 3d). Rare biotite grains define a weak foliation. Some of the metagabbros include large plagioclase grains mantled by aggregations of fine-grained mafic minerals (mainly pyroxenes).

Figure 3. Field occurrence and photomicrographs of metagabbro and charnockite from the Song Ba area of the Kannak Complex. (a) Metagabbro is included as enclaves in charnockite and has fine-grained, dark-colored chilled margins (arrow) along its contact with the host, indicating that both lithologies intruded into the crust coevally. (b) Charnockite (sample 00041905B) is composed mainly of quartz, K-feldspar, and plagioclase, with small amounts of orthopyroxene and biotite. (c) Metagabbro (sample 00042001C1) consists mainly of two pyroxenes and plagioclase, with minor amounts of biotite, and shows a granoblastic texture. The studied sample locally contains large orthopyroxene grains that include euhedral to subhedral plagioclase. (d) Metagabbro (sample 00041903B) has a mineral assemblage similar to sample 00042001C1, though locally contains quartz. All scale bars are 1 mm in length. Opx, orthopyroxene; Cpx, clinopyroxene; Bt, biotite; Pl, plagioclase; Qz, quartz; Kfs, K-feldspar. Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

This texture is similar to that commonly observed during magma mingling (Hibbard, 1995). Overall, these mineral assemblages and textural relations imply that both rock types underwent granulite-facies metamorphism following their emplacement.

U-Pb DATING OF ZIRCON

U-Pb dating of zircon obtained from two samples of metagabbro and a charnockite was performed on a laser-ablation (LA) inductively coupled plasma mass spectrometer (ICP-MS) housed at the Graduate School of Integrated Sciences for Global Society, Kyushu University. The analytical procedure utilized has been described in detail by Adachi et al. (2012) and Nakano et al. (2014). Separated zircons were mounted in epoxy resin and polished. Internal textures and mineral inclusions were observed using a scanning electron microscope (JEOL JED2140 JSM-5301S) equipped with a cathodolumines-

cence imaging system at Kyushu University. For U-Pb geochronology, concentrations of the isotopes ^{202}Hg , ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , and ^{238}U were monitored during all analyses, with ablations performed using laser diameters of 30 to 40 μm . No reliable concentrations of ^{204}Pb were obtained from any analyzed grains. Integrated isotopic ratios were corrected against the Temora zircon standard, which has a $^{206}\text{Pb}/^{238}\text{U}$ age of 417 Ma (Black et al., 2003), and the NIST SRM-611 glass standard was used to calculate Th/U ratios. All zircon data reductions and calculations were processed with GLITTER (Griffin et al., 2008) using the analytical and calculation protocols for time-resolved analysis described by Jackson et al. (2004). The software Isoplot/Ex 3.7 (Ludwig, 2008) was used to construct all concordia diagrams and perform all age determinations. During the analyses conducted in this study, a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 1102 ± 9 Ma was obtained for standard FC-1 (95% confidence interval, $N = 10$), which is con-

Figure 4. Representative cathodoluminescence images of zircon grains from dated samples. Circles indicate the locations of analytical spots, which are labeled with analysis numbers. Each image also shows individual $^{206}\text{Pb}/^{238}\text{U}$ ages (Ma) with 2σ errors, Th/U ratios, and a 30- μm scale bar. Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

sistent with its reported age of 1100 Ma (Paces and Miller, 1993). Cathodoluminescence images showing the internal structures of zircon grains, and the ages and Th/U ratios for analyzed samples are shown in Figure 4. All results are presented in Supplemental Table S1 (available online from <http://doi.org/10.2465/jmps.151019b>) and concordia diagrams are shown in Figure 5.

Zircon grains analyzed from metagabbro samples exhibit elongated shapes with oscillatory internal zoning and have Th/U ratios >0.1 , indicative of a magmatic origin. By contrast, zircon grains analyzed from the charnockite sample show rounded shapes and have clear rims with inherited cores (Fig. 4). The Th/U ratios of these grains are mostly >0.1 , regardless of analyzed positions, although some core domains have ratios <0.1 (Table S1 and Fig. 4).

Metagabbro (sample 00041903B). This sample occurred in the field as an enclave together within charnockite. The zircon grains in this sample do not have inherited cores and show clear igneous zoning (Fig. 4). The majority of analyses produced concordant data, although the small number of discordant data produced ages that were slightly younger than for the former (Fig. 5a), suggesting that some degree of Pb-loss occurred following metagabbro emplacement. Data that were discordant by more than 5% were omitted from calculations, which produced a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 250 ± 4 Ma (Fig. 5a).

Metagabbro (sample 00042001C1). Akin to metagabbro sample 00041903B, sample 00042001C1 occurred in the field as an enclave, although was included within garnet-bearing granite instead of charnockite. Zircon

Figure 5. Concordia diagrams showing the results of LA-ICP-MS U-Pb dating of zircon from Kannak Complex metagabbro and charnockite. (a) Weighted-average mean $^{206}\text{Pb}/^{238}\text{U}$ age for metagabbro sample 00041903B. (b) Concordia age for metagabbro sample 00042001C1. (c) Concordant data for metagabbro sample 00042001C1. (d) Concordia age for charnockite sample 00041905B. (e) Concordant data for charnockite sample 00041905B. Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

grains in this sample have elongate shapes and show clear zoning patterns that are similar to those from sample 00041903B; however, some contained inherited cores that produced discordant isotopic data (Figs. 5b and 5c). A concordia age of 263 ± 2 Ma (Fig. 5b) was obtained from zoned zircon cores after these discordant data were omitted. This age is consistent with that of 264 ± 4 Ma for garnet-bearing granite from the same locality, which was obtained by Owada et al. (2006) via electron probe micro-analyzer (EPMA) Th-U-Pb dating of monazite.

Charnockite (sample 00041905B). This sample contains rounded zircon grains that have inherited cores and thin rims. All rim analyses showed concordant ages and yielded a concordia age of 249 ± 4 Ma (Fig. 5d), which is consistent with that of metagabbro sample 00041903B, but younger than that of metagabbro sample 00042001C1. The data obtained from inherited cores in this sample were discordant (Fig. 5e) and defined a discordia line that has an upper intercept age of 1412 ± 18 Ma and a lower intercept age of ~ 440 Ma (Silurian).

The U-Pb zircon dating performed for these samples indicates that magmatic activity in the Kontum Massif occurred during the Late Permian, which is very similar to the timing of mafic igneous activity documented in the Song Da area (260–250 Ma; Usuki et al., 2015) situated 300 km north of the Kontum Massif.

MAJOR AND TRACE ELEMENT GEOCHEMISTRY

Major-element abundances in the Kontum Massif metagabbro samples were determined via X-ray fluorescence (XRF) using a RIX-3000 housed at the Center for Instrumental Analyses, Yamaguchi University. The analytical procedure utilized has been described in detail by Yamasaki et al. (1999). Trace element and rare earth element (REE) contents were analyzed using an ICP-MS at Actlabs Ltd., Canada. All data are given in Table 1.

SiO₂ contents of all samples range from 45 to 53 wt%. Most data lie within the non-alkaline field on a total alkali-silica (TAS) diagram, but are scattered with respect to increasing SiO₂ (Fig. 6a). Because high-field-strength elements are believed to be immobile during metamorphism (Winchester and Floyd, 1977), a plot of Zr/TiO₂ against Nb/Y is widely used as an immobile element proxy for the TAS diagram. A Nb/Y-Zr/TiO₂ diagram is shown in Figure 6b, where it can be seen that the Kontum Massif metagabbros lie within the subalkaline basalt field. A Mg# versus Ti/Y diagram, where Mg# = MgO/(FeO + MgO), shows that the metagabbros have Ti/Y ratios less than 500 (Fig. 6c). The chemical compositions of mafic rocks from the Song Da igneous suite are also

Table 1. Whole-rock chemical analyses of metagabbro samples

Sp. No.	000 41907 E	000 42001 B	000 41903 B	000 41910 B1	000 42001 C1	000 41906 A	000 41907 C
wt%							
SiO ₂	49.51	48.36	45.25	50.05	51.90	49.69	45.26
TiO ₂	1.42	1.46	1.94	1.49	1.07	1.41	1.48
Al ₂ O ₃	13.62	15.51	19.19	17.84	14.34	13.52	16.37
Fe ₂ O ₃	16.96	12.72	12.21	10.34	14.29	16.03	18.54
MnO	0.26	0.19	0.17	0.13	0.21	0.24	0.25
MgO	6.68	8.26	5.36	5.27	7.58	6.71	7.09
CaO	9.79	13.17	11.12	8.13	10.33	10.32	6.44
Na ₂ O	0.37	0.59	1.64	3.60	0.45	2.02	0.64
K ₂ O	0.86	0.55	1.17	2.03	0.16	0.51	1.91
P ₂ O ₅	0.07	0.09	0.42	0.18	0.08	0.07	0.05
Total	99.55	100.90	98.47	99.06	100.40	100.52	98.03
ppm							
V	412	247	165	183	300	299	354
Cr	87	235	<20	60	164	82	91
Co	53	48	22	24	52	42	58
Ni	73	63	<20	23	58	51	57
Cu	50	34	17	30	27	35	72
Zn	115	93	96	71	102	112	217
Ga	16	16	20	21	16	15	22
Rb	55	15	73	43	11	12	149
Sr	69	158	372	398	110	50	45
Y	36	23	42	30	18	24	30
Zr	74	81	291	146	51	84	81
Nb	3	9	14	12	6	7	4
Ba	88	31	395	376	40	49	448
La	4.22	6.81	28.0	34.0	7.27	7.95	5.77
Ce	12.1	17.0	73.9	86.5	17.9	18.6	13.6
Pr	1.78	2.21	9.64	10.7	2.22	2.40	1.67
Nd	9.43	10.4	42.6	44.9	10.1	11.0	7.52
Sm	3.33	2.99	9.23	9.24	2.50	3.07	2.16
Eu	1.04	1.18	1.94	1.93	0.919	1.07	0.885
Gd	4.73	3.63	8.86	7.92	2.95	3.65	2.88
Tb	0.945	0.687	1.39	1.14	0.520	0.669	0.595
Dy	5.82	3.87	7.56	5.58	2.98	4.18	4.23
Ho	1.30	0.829	1.54	1.06	0.670	0.921	1.07
Er	3.89	2.37	4.36	2.87	1.87	2.68	3.37
Tm	0.594	0.364	0.658	0.409	0.293	0.413	0.568
Yb	3.71	2.08	3.81	2.36	1.75	2.49	3.66
Lu	0.578	0.316	0.578	0.350	0.272	0.397	0.610
Hf	2.23	2.27	7.20	3.73	1.47	2.36	2.51
Ta	0.072	0.449	0.755	0.554	0.270	0.399	0.441
Pb	<5	7	<5	<5	<5	<5	5
Th	0.43	0.65	1.1	0.52	0.45	0.68	0.52
U	0.37	0.20	0.64	0.21	0.090	0.40	0.76

plotted, indicating that the compositions of the Kontum Massif metagabbros considered herein overlap with those of the low-Ti series of the Song Da igneous suite.

Chondrite-normalized REE patterns and primitive mantle-normalized trace element patterns for the Kontum Massif metagabbros are shown in Figure 7. These units mostly show flat REE patterns; however, two samples show elevated light REE/heavy REE (LREE/HREE) ratios with slightly negative Eu anomalies (Fig. 7a). All samples show a negative P anomaly (Fig. 7b). In addition, the two high-LREE/HREE samples shown in Figure 7a possess negative Nb, Ta, and Ti anomalies with Nb, Ta, and Ti negative anomalies; however, all other sam-

Figure 6. Discrimination diagrams for metagabbro from the Kontum Massif. (a) Total alkali-SiO₂ wt% diagram, with the line separating alkaline and non-alkaline fields drawn after Miyashiro (1978). (b) Zr/TiO₂-Nb/Y diagram (after Winchester and Floyd, 1977). (c) Mg#-Ti/Y diagram for metagabbro from the Kontum Massif and mafic rocks from the Song Da igneous suite. Chemical compositions of the Song Da igneous suite are taken from Hanski et al. (2004), Wang et al. (2007), and Tran Viet Anh et al. (2011). Data for metagabbros from the Song Ba area lie within the compositional range of low-Ti mafic rocks from the Song Da igneous suite. Mg#: 100*MgO/(FeO* + MgO) mole ratio. Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

ples show fairly flat patterns, except for the concentrations of large ion lithophile elements (Fig. 7b).

Sr-Nd ISOTOPIC ANALYSIS

Strontium (Sr) and neodymium (Nd) 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) at Niigata University.

Measured ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ were normalized to $^{86}\text{Sr}/^{88}\text{Sr}$ and $^{146}\text{Nd}/^{144}\text{Nd}$ values of 0.1194 and 0.7219, respectively. These normalized $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were corrected using the NIST-987 standard $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.710241 and the JNdi-1 (Nd isotopic reference material of the Geological Survey of Japan) standard $^{143}\text{Nd}/^{144}\text{Nd}$ value of 0.512106, which has been verified using the international standard La Jolla $^{143}\text{Nd}/^{144}\text{Nd}$ value of 0.511849 (Tanaka et al., 2000). Concentrations of Rb, Sr, Sm, and Nd were measured via ICP-MS. Analytical errors associated with both $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{147}\text{Sm}/^{144}\text{Nd}$ measurements were 1% (1 σ). The initial Sr and Nd isotope ratios (Sr_i and Nd_i) were calculated using the decay constants: $\lambda^{87}\text{Rb} = 1.42 \times 10^{-11}/\text{y}$ (Steiger and Jäger, 1977) and $\lambda^{147}\text{Sm} = 6.54 \times 10^{-12}/\text{y}$ (Lugmair and Marti, 1978).

All Rb-Sr and Sm-Nd isotopic data are given in Table 2. Sample Sr_i and Nd_i values were calculated for an age of 260 Ma. Epsilon Sr and Nd values were calculated using the following CHUR data: $^{87}\text{Rb}/^{86}\text{Sr} = 0.0827$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7045$, $^{147}\text{Sm}/^{144}\text{Nd} = 0.1966$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$. Figure 8 shows a ϵSr and ϵNd diagram corrected for the time-integrated effects of a 260 Ma age, $\epsilon\text{Sr}(t)$ and $\epsilon\text{Nd}(t)$, respectively, for metagabbro and previously reported isotopic compositions of granitic and metamorphic rocks from the Kontum Massif. Figure 8 also plots isotopic data for high-Ti and low-Ti mafic rocks from the Song Da igneous suite. Although the metagabbro appears to be heterogeneous with respect to Sr and Nd isotopic signatures, its $\epsilon\text{Nd}(t)$ values range from +4 to -9 and resemble those of mafic rocks from the Song Da igneous suite (Fig. 8).

DISCUSSION

Reworked continental crust in the Kontum Massif

Detailed geochronological and petrological studies of metamorphic and igneous rocks can significantly improve our understanding of the tectonic processes that occur in orogenic belts. The Late Permian-Early Triassic metamorphic rocks in the Kontum Massif, south Viet-

Figure 7. (a) Chondrite-normalized REE diagram and (b) primitive mantle-normalized spider diagram for metagabbro from the Song Ba area. Normalized values are quoted from Sun and McDonough (1989). Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

Table 2. Results of Sr and Nd isotopic analyses for whole-rock samples

Sample No.	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	2σ	SrI 260 Ma	ϵSrI 260 Ma	Nd (ppm)	Sm (ppm)
00041907E	55	69	2.316	0.73606	1	0.72749	330.77	9.43	3.33
00042001B	15	158	0.2650	0.71064	1	0.70966	77.55	10.4	2.99
00041903B	73	372	0.5717	0.71558	1	0.71346	131.55	42.6	9.23
00041910B1	43	398	0.3164	0.71120	1	0.71003	82.81	44.9	9.24
00042001C1	11	110	0.2901	0.73481	1	0.73373	419.41	10.1	2.50
00041906A	12	50	0.6994	0.71703	1	0.71444	145.47	11.0	3.07
00041907C	149	45	9.664	0.77029	1	0.73455	430.99	7.52	2.16
00041911	35 *	382 *	0.265	0.71679	1	0.71581	164.85	13.0 *	2.41 *

* Data are quoted from Owada et al. (2007).

Table 2. (Continued)

$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	2σ	NdI 260 Ma	ϵNdI 260 Ma
0.2135	0.512874	14	0.512511	4.09
0.1738	0.512778	14	0.512482	3.54
0.1311	0.512016	14	0.511793	-9.92
0.1245	0.512134	14	0.511922	-7.40
0.1496	0.512224	14	0.511969	-6.47
0.1687	0.512414	14	0.512127	-3.40
0.1736	0.512523	14	0.512227	-1.44
0.1121	0.512036	14	0.511845	-8.90

nam, correspond well with the metamorphic characteristics of a collision between the Indochina and South China cratons in terms of peak P - T conditions and the time-scales of deformation (Osana et al., 2008).

Tran Ngoc Nam et al. (2001) reported evidence of Middle Proterozoic inherited zircon ages in pelitic gneiss from the Kannak Complex. Moreover, monazite grains in pelitic gneisses from the Kannak and Ngoc Linh Complexes locally include Middle Proterozoic cores (Nakano et al., 2013). These Middle Proterozoic ages are only recorded in detrital grains and so their origin remains un-

Figure 8. $\epsilon\text{Sr}(t)$ - $\epsilon\text{Nd}(t)$ diagram for metagabbro and other rock types from the Kannak Complex. Isotopic data for mafic rocks from the Song Da igneous suite are also shown, which are taken from Lan et al. (2003), Owada et al. (2007), Wang et al. (2007), Tran Viet Anh et al. (2011), and this study. Sr and Nd isotopic data were corrected to an age of 260 Ma. Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

known. In this work, U-Pb analyses obtained from zircon in charnockite lie upon a well-defined discordia line (Fig. 5e), suggesting that the parental rock of the charnockite may have been derived from magmatic activity that occurred at ~ 1400 Ma. Lan et al. (2003) proposed that some mafic granulites from the Kannak Complex possess $\varepsilon\text{Nd}(t)$ values of -8.7 , which is similar to that of the charnockite studied herein. In addition, Nd model ages of Kontum Massif charnockites lie in the range 1500–1900 Ma (Lan et al., 2003). These charnockites have geochemical characteristics of I-type granite and were likely produced via partial melting of a mafic granulite protolith, according to Sr–Nd isotopic signatures and trace-element geochemical modeling performed by Owada et al. (2007). Based on the concordia age of 249 Ma obtained from constituent zircon rims in this work, the charnockite magma is interpreted to have formed via partial melting of metamorphosed mafic rocks during Permian high-grade metamorphism. The lower intercept of Silurian age (~ 440 Ma; Fig. 5e) suggests that the charnockite source rock would have undergone metamorphism at this time.

Given that geochronological data have revealed the occurrence of Silurian magmatism within the Kontum Massif (Fig. 2), the Late Permian tectonothermal event must have overprinted Silurian units, meaning that the Kontum Massif contains reworked crust. The charnockite studied here shows Silurian and Middle Proterozoic intercept ages (Fig. 5e) alongside a $\varepsilon\text{Nd}(t)$ value of -9 (Table 2), indicating that it may have been derived from old continental crust, probably of Middle Proterozoic age.

Timing of mantle-derived magma emplacement

U-Pb sensitive high-resolution ion microprobe dating of zircon from metamorphic rocks of the Kannak Complex has yielded ages of 260–250 Ma (Carter et al., 2001; Tran Ngoc Nam et al., 2001), which are thought to date peak metamorphism (Osanai et al., 2008). Owada et al. (2006) performed EPMA Th–U–Pb monazite dating of garnet-bearing granite, and garnet- and orthopyroxene-bearing gneiss, and concluded that the timing of formation of crustal-derived granite overlapped with the age of peak metamorphism; thus, crystallization of garnet-bearing granite in the Kontum Massif is assumed to have been simultaneous with peak metamorphism.

Figure 2 indicates that most of the igneous activity documented from the Kontum Massif occurred between the Late Permian and Early Triassic. According to Osanai et al. (2004, 2008) and Nakano et al. (2013), collision between the South China and Indochina cratons caused regional metamorphism during this same time period. The Late Permian–Early Triassic igneous lithologies in

the Kontum Massif would therefore represent syn- to post-collisional magmatism.

Owada et al. (2006, 2007) and Osanai et al. (2008) also inferred that a significantly high geothermal gradient was required to produce the HT/UHT metamorphism documented in the Ngoc Linh and Kannak Complexes. Metagabbro lenses within host gneisses show magmatic ages of 260–250 Ma, which are similar to metamorphic ages recorded for HT and UHT rocks from the Ngoc Linh and Kannak Complexes. Considering the field relationships and newly determined zircon U–Pb ages for the metagabbro described herein, we interpret that mantle-derived magma played an important role as a heat source to drive HT/UHT metamorphism.

Magmatic process of metagabbro formation

U–Pb dating of zircon from metagabbro confirms that magmatic activity occurred in the Kontum Massif during the Late Permian (260–250 Ma). At this time, a major LIP component, the Song Da igneous suite, is thought to have formed in the northern part of the TVOB (Fig. 1; Hanski et al., 2004; Wang et al., 2007; Tran Viet Anh, 2011; Usuki et al., 2015). Moreover, as the Nd isotopic compositions of the Kontum Massif metagabbros resemble those of the Song Da mafic rocks (Fig. 8), it appears likely that magmatism in both regions was connected.

Zircon U–Pb dating, Nd isotopic compositions, and LREE/HREE ratios of metagabbro all unravel the relationships between it and the Song Da mafic magmatism. Figure 9a shows chondrite-normalized La/Yb ratios and $\varepsilon\text{Nd}(t)$ values for both suites. The most depleted $\varepsilon\text{Nd}(t)$ sample of the Kontum Massif metagabbros has a high value of $+4$, which is similar to those for the Song Da mafic rocks (Fig. 9a). Such depleted $\varepsilon\text{Nd}(t)$ mafic rocks from the Song Da igneous suite were derived from a mantle plume and correspond with the southern extension of the Emeishan LIP (Hanski et al., 2004; Wang et al., 2007; Hanski et al., 2010; He et al., 2010; Tran Viet Anh et al., 2011; Vladimirov et al., 2012; Usuki et al., 2015). Conversely, enriched $\varepsilon\text{Nd}(t)$ mafic rocks from the Emeishan LIP, including those at Song Da, are thought to have formed from interaction between depleted mafic magma and enriched lithosphere, the latter including crustal rocks (Chung and Jahn, 1995; Wang et al., 2007; Hanski et al., 2010; Tran Viet Anh et al., 2011; Shellnutt, 2014). The enriched $\varepsilon\text{Nd}(t)$ rocks possess high-LREE/HREE ratios (Chung and Jahn, 1995), and values for the Kontum Massif metagabbros overlap with those of the Song Da mafic units (Fig. 9a).

Figure 9b shows a $\varepsilon\text{Nd}(t)$ –Nb/La ratio diagram that plots values for the Kontum Massif metagabbro and units

Figure 9. Binary plots related to magma-crust interaction for metagabbro and Late Permian Song Da mafic rocks. (a) Chondrite-normalized La/Yb- $\epsilon\text{Nd}(t)$ diagram. (b) $\epsilon\text{Nd}(t)$ -Nb/La diagram (after Peate, 1997). Primitive mantle and upper crust values are after McDonough and Sun (1995) and Rudnick and Gao (2003). Data for the Song Da mafic rocks are from Hanski et al. (2004), Wang et al. (2007), and Tran Viet Anh et al. (2011). Nd isotopic data were corrected to an age of 260 Ma. Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

Figure 10. (a) Mg#-SrI(t) and (b) Mg#-NdI(t) diagrams with mixing lines. Ticks with numbers on the mixing lines indicate mixing proportions. End members for the source and contaminant are represented by a typical Song Da mafic rock (Wang et al., 2007) and pelitic gneiss (Lan et al., 2003), respectively. Fractional crystallization (FC) trend is shown by an arrow. Data for each end member are as follows: Sr = 102 ppm, Nd = 4.4 ppm, SrI = 0.7041, NdI = 0.51270, FeO^(total) = 10.2 wt%, and MgO = 16.1 (source), and Sr = 237 ppm, Nd = 44.7 ppm, SrI = 0.7814, NdI = 0.51137, FeO^(total) = 2.5 wt%, and MgO = 1.0 (contaminant). Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

of the Song Da igneous suite in order to evaluate the extent of crustal assimilation. The metagabbros lie between the Nb/La values of primitive mantle and upper crust, and show a weak, positive correlation. Two samples (00041903B and 00041910B1) with high-LREE/HREE ratios and negative Ta, Nb, and Ti anomalies (Fig. 7) possess $\epsilon\text{Nd}(t)$ values of -9.9 and -7.4 , respectively (Table 2), suggesting that these samples were assimilated by significant amounts of crustal materials during magma emplacement.

Some metagabbros (00041907E and 00041907C)

possess high $\epsilon\text{Sr}(t)$ values (330 and 430), $\epsilon\text{Nd}(t)$ values of 4.1 and -1.4 (Table 2), and low Sr contents of 45–69 ppm (Table 2). These metagabbros would have been easily affected by the Sr isotopic ratios of crustal materials, as the host gneisses in the Kannak Complex have high Sr contents (>200 ppm) and SrI ratios from 0.7258 to 0.7867 (Lan et al., 2003; Owada et al., 2007). Therefore, we conclude that most of metagabbros analyzed in this study have been isotopically modified by the host gneisses to some degree. The metagabbros possess evolved compositions with Mg# from 40 to 60 (Fig. 10). In this

Figure 11. Schematic tectonic model for the evolution of the TVOB. (a) Continent-continent collision at ~ 270 Ma and (b) Late Permian plume-related magmatism at 260–250 Ma. The metagabbro described in this work formed in conjunction with the Song Da igneous suite as a result of plume-related magmatism. See text for discussion. Color version is available online from <http://doi.org/10.2465/jmps.151019b>.

figure, mixing lines plotted between a source (the most depleted Song Da mafic rock) and a contaminant (the most enriched host gneiss) indicate that the Sr and Nd isotopic values of the Kontum Massif metagabbros can be produced by crustal assimilation of less than 20% of the host gneiss (Figs. 10a and 10b). The zircon U–Pb ages and geochemical signatures obtained in this work therefore suggest that the metagabbro would have been originally derived from plume-related Song Da-type mafic magma, and was subsequently affected by crustal assimilation and fractional crystallization.

The Song Da igneous suite formed in the marginal part of the Emeishan plume (Hanski et al., 2010; He et al., 2010). The geochemistry and melting depth of the Emeishan LIP mafic magmas suggest that the lithospheric lid of the Emeishan plume was thicker at its periphery than at its head (fig. 12 in He et al., 2010). As such, a schematic model of Late Permian magmatism in the Kontum Massif can be constructed (Fig. 11). At ~ 270 Ma, the Indochina craton was subducted beneath the South China craton (Osanai et al., 2008) whereby its crust was metamorphosed at high P – T conditions (Fig. 11a). The Emeishan plume ascended through the asthenospheric mantle and formed the Emeishan LIP at 260–250 Ma. The plume–lithosphere boundary was likely inclined away from the plume center towards its margins (Fig. 11b). The base of thickened crust beneath the Kontum Massif was situated close to the plume–lithosphere boundary (Fig. 11b). As a result, plume-related magma intruded into the deeper part of the massif and induced HT/UHT metamorphism and crustal melting during the Late Permian (260–250 Ma).

CONCLUDING REMARKS

- 1) Zircon U–Pb dating of charnockite from the Kannak Complex has revealed that its magma source may

have formed as early as ~ 1400 Ma, and it has since experienced two distinct high-grade metamorphic events during the Ordovician–Silurian and Permian periods. Furthermore, ϵ Nd values of pelitic gneisses and granitic rocks in the region suggest that the Kontum Massif could have formed from reworked continental crust.

- 2) Zircon U–Pb dating of metagabbro produced magmatic ages of 260–250 Ma that are identical to those reported for peak metamorphic periods in the Kontum Massif. Mantle-derived magma is interpreted to have played an important role as a heat source for HT/UHT metamorphism and partial melting of the massif crust.
- 3) The geochemical and geochronological signatures of Kontum Massif metagabbros are almost identical to those of plume-related basalts in the Song Da igneous suite, which were originally derived from the Emeishan mantle plume and were affected by crustal assimilation. Plume-related magmas intruded into the Kontum Massif lower crust were associated with HT/UHT metamorphism and crustal anatexis, and experienced various amounts of crustal assimilation during the Late Permian (260–250 Ma).

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SUPPLEMENTARY MATERIAL

Supplementary Table S1 and color version of all Figures are available online from <http://doi.org/10.2465/jmps.151019b>.

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