First SHRIMP U–Pb zircon dating of granulites from the Kontum massif (Vietnam) and tectonothermal implications

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Abstract

The Kontum massif in Central Vietnam represents the largest continuous exposure of crystalline basement of the Indochina craton. The central Kontum massif is chiefly made of orthopyroxene granulites (enderbite, charnockite) and associated rocks of the Kannack complex. Mineral assemblages and geothermobarometric studies have shown that the Kannack complex has severely metamorphosed under granulite facies corresponding to P–T conditions of 800–850°C and 8 ± 1 kbars. Twenty-three SHRIMP II U–Pb analyses of eighteen zircon grains separated from a granulite sample of the Kannack complex yield ca 254 Ma, and one analysis gives ca 1400 Ma concordant age for a zoned zircon core. This result shows that granulites of the Kannack complex in the Kontum massif have formed from a high-grade granulite facies tectonothermal event of Indosinian age (Triassic). The cooling history and subsequent exhumation of the Kannack complex during Indosinian times ranged from ~850°C at ca 254 Ma to ~300°C at 242 Ma, with an average cooling rate of ~45°C/Ma. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Granulites are recognized as a potential source of important information toward understanding deep crustal compositions and processes, and early tectonothermal events. The Kontum massif (Central Vietnam) is composed of such granulites. Orthopyroxene granulites (charnockites, enderbite) and associated rocks, which are similar to those of Eastern Ghats (India) and East Antarctica, form the central part of the Kontum massif (Fig. 1). They are grouped into the gneiss complexes under local names (Figs. 1 and 2; Department of Geology and Minerals of Vietnam — DGMVN, 1989, 1995). As it was once held that granulites were only formed in Archean and Early Proterozoic times, the granulites of the Kontum massif were thought to be of Archean age by previous workers (e.g., Tran Quoc Hai, 1986; DGMVN, 1989, 1995). The Archean ages of these granulites have been suggested based on the common occurrence of charnockitic rocks (Tran Quoc Hai, 1986; Hutchison, 1989; DGMVN, 1989, 1995). However, the Archean ages are hardly accepted because no available geochronological data have yet been documented for these granulites.

Recent advanced Ar–Ar and K–Ar geochronological studies have revealed a wide occurrence of three tectono-thermal episodes in Indochina. They are the Triassic Indosinian, Late Jurassic–Early Cretaceous in the Truong Son belt north of the Kontum massif (e.g., Maluski et al., 1995, 1997; Rangin et al., 1995; Lepvrier et al., 1997; Nam, 1998), and Tertiary in the Bu Khang gneiss dome north of the Truong Son belt (e.g., Jolivet et al., 1999) and in the Red River shear zone (e.g., Nam, 1998; Wang et al., 1998). Pre-Indosinian tectonomagmatic events have been poorly documented by geochronological data in this region, and geochronological data of the Kontum massif remain scarce. Since granulites were formed at high temperature conditions under deep crustal levels, U–Pb zircon dating of such granulites could provide valuable evidence for high-temperature stages of the tectonothermal evolution of the Kontum massif that may be difficult to obtain by Ar–Ar or K–Ar techniques. This present study was undertaken in an attempt to determine the timing of tectonomagmatic events recorded in zoned zircons from a main granulite complex in the central
Kontum massif. This is the first SHRIMP U–Pb zircon data documented for the complex, which was previously thought to be the oldest unit (Archean in ages) in Indochina (e.g., Tran Quoc Hai, 1986; Hutchison, 1989; DGMVN, 1989, 1995).

2. Geological setting

The Kontum massif represents the largest continuous exposure of crystalline basement of the Indochina craton, which was once regarded as the stable continental core of South-East Asia (Hutchison, 1989). The Kontum massif is mainly composed of high-grade metamorphic rocks which were thought to be Precambrian in ages by previous workers (e.g., Tran Quoc Hai, 1986; Hutchison, 1989; DGMVN, 1989, 1995). Paleozoic sedimentary rocks are mostly absent there. The massif is partly covered by Mesozoic volcano-sedimentary formations and Neogene–Quaternary basalts, and is intruded by Paleo-Mesozoic granodiorite bodies (Figs. 1 and 2; DGMVN, 1989, 1995; Nam, 1998).

High-grade gneiss rocks of the Kontum massif (Vietnam) are grouped into different units under local names, including the Kannack complex and associated intrusive complexes, the Ngoc Linh complex, the Kham Duc and Poko formations (DGMVN, 1989, 1995). The Kannack complex occupies the central and southern Kontum massif (Fig. 1). It is subdivided into three parts: (1) lower, (2) middle and (3) upper (Fig. 2). The lower part is composed of two-pyroxene and hypersthene-garnet-bearing granulites in close connection with autochthonous plutons of orthopyroxene-bearing granites (charnockites and enderbites), and cordierite–sillimanite-bearing gneisses (khondalites). The thickness of the lower part is estimated to be 700–1000 m. The middle part is mainly composed of plagioclase–biotite–hypersthene gneiss, two-pyroxene plagioclase gneiss, biotite–sillimanite–cordierite gneiss and migmatite rocks, with an estimated thickness of 500–900 m. The upper part is chiefly made of garnet–cordierite–sillimanite–biotite gneiss, cordierite–sillimanite schist, and quartzite. Several calciphyre and marble intercalations are found among the gneiss and schist. The upper part is estimated to be 700 m thick.

Autochthonous plutons of gabbrogranulite, enderbites and charnockites, and biotite–garnet–cordierite granite are distinctly placed into the Konkbang, Songba and Pleimanko complexes, respectively (Fig. 2). Plutonic bodies show massive, granitic texture in the center and gradually change to strongly foliated rocks along the peripheries. Foliation of these rocks is commonly parallel to those of host gneisses. The boundary between plutonic bodies and host gneisses or migmaites is often unclear because of the gradual change. Several small lenses of host gneisses (two-pyroxene and hypersthene granulites) ranging from 1–2 cm to 2–3 m in thickness are found within the enderbite–charnockite bodies.

Mineral assemblages of the Kannack complex include: (i) plagioclase (Pl) + clinopyroxene (Cpx) + orthopyroxene (Opx) + quartz (Q), (ii) Pl + hypersthene (Hyp) + garnet (Gt) + Q, and (iii) Pl + Hyp + K-feldspar (Kfs) + Q in the lower part; (iv) Q + Pl + Kfs + sillimanite (Sil) + Gt + Bi ± cordierite (Cord), (v) Q + Pl + Kfs + Cord + Hyp + Sil + Gt, and (vi) Q + Pl + Kfs + spinel + Hyp + Cord + Gt in the middle part; (vii) calcite + diopside, (viii) calcite + oligoclase + garnet ± dolomite, and (ix) plagioclase + diopside + quartz in the upper part. These assemblages are typical of granulite facies metamorphism. Geothermobarometric studies of the complex have yielded P–T conditions of 800–850°C (by garnet–cordierite and...
two-pyroxene geothermometry), and 8 ± 1 kbars (by garnet–orthopyroxene–plagioclase–quartz geobarometry) (DGMVN, 1989). Some additional calibrations using garnet–biotite and garnet–hornblende geothermometry give estimations of 700–750°C, regarded as indicating the conditions of a later retrograde stage of metamorphism. The above mineral assemblages and geothermobarometric results therefore indicate peak metamorphism P–T conditions for the Kannack complex to be 800–850°C and 8 ± 1 kbars. The Kannack complex and associated intrusive complexes were previously proposed to be Archean in age on the basis of petrological correlation with classic Archean granulites in other parts of the world (Phan Truong Thi, 1985; Tran Quoc Hai, 1986; DGMVN, 1989, 1995). However, the proposed Archean age is hardly accepted without available geochronological data. Few geochronological data have been reported for the complex, including a K–Ar age of 242 Ma obtained on a biotite separate (Nam, 1998), and a K–Ar age range of 1650–1810 Ma, which was from 'a personal communication' source but often cited by previous workers (e.g., Phan Truong Thi, 1985; Tran Quoc Hai, 1986; Hutchison, 1989).

Other metamorphic formations, which were thought to be Precambrian (e.g., DGMVN, 1989, 1995), are widely distributed in the northern Kontum massif (Fig. 1). They are composed of biotite–sillimanite gneiss, amphibolite, biotite schist, migmatite rocks and lenses of marble. This rock assemblage suggests amphibolite facies metamorphism. Some Rb–Sr ages of 1400–1600 Ma have been reported for these formations (Phan Truong Thi, 1985).
The Poko formation south-east of Kontum town (see location in Fig. 1) contains some characteristic algal stromatolites, suggesting an Upper Proterozoic age (DGMVN, 1989). Precambrian rocks are strongly foliated (DGMVN, 1989). The foliation is folded to form gentle folds with commonly North–South trending axes.

Mesozoic volcano-sedimentary formations are composed of andesite, rhyolite and tuffs, and conglomerates, sandstone and siliceous shale of Late Triassic–Early Jurassic and Cretaceous ages. Neogene–Quaternary basalt is mainly of tholeiitic and sub-alkaline olivine compositions, ranging from 16 to 0.2 Ma in age (DGMVN, 1989, 1995; Hoang and Flower, 1998; Lee et al., 1998).

3. Sample and mineral descriptions

Zircons analyzed in this study were separated from a granulite sample (KT13108 in Fig. 2) collected from the middle part of the Kannack complex in the central Kontum massif, Vietnam (Fig. 2). The sample is coarse grained and has a gneissic texture. Mineral constituents of the sample are quartz (~25–30%), plagioclase (~25–35%), K-feldspar (~10–15%), garnet (~10%), sillimanite (~7–10%), biotite (~5–10%), and cordierite. Apatite and zircon are common accessory minerals in the sample.

Zircons were concentrated by crushing, sieving, and mineral separation with an isodynamic separator and heavy-liquid, and hand-picking using a binocular microscope. Zircons occur as an individual crystal with an euhedral shape, and range from 0.2 to 0.5 mm in size (Fig. 3). The perfectly euhedral shape suggests that zircons have finally grown in an environment that supposes presence of liquid melt (i.e., likely magmatic zircon). Fig. 4 shows representative EMPA backscatter images of zircon grains, in which three types of zoning patterns can be seen: (a) perfectly homogeneous from central to outer part, (b) large homogeneous core and a narrow rim, and (c) oscillatory zoning. Among eighteen grains analyzed in this study, twelve grains (67% of zircon population) have type (a), five grains (27% of zircon population) display type (b) and one grain does display type (c). Types (b) and (c) suggest likely overgrowths of zircon, whereas the type (a) indicates one-stage growth. SHRIMP U–Pb analyses have been performed on both cores and rims of overgrowth zircons.

4. Analytical methods and results

Analyzed zircon grains were mounted in epoxy-resin disk with several grains of the standard zircon SL13 and QGN. SL13 is the well-known Sri Lanka 572 Ma megacryst extensively used by the Australian National University SHRIMP group as a U/Pb and abundance calibration standard (Roddick and van Breemen, 1994; Claoué-Long et al., 1995; Williams, 1998), and QGN is a new multicrystal zircon standard from Quartz–Gabbro–Norite–Gneiss (QGN) from Cape Donnington, Eyre Peninsula, South Australia whose TIMS U/Pb age is 1850 ± 2 Ma (2σ) (C.M. Fanning, personal communication, 1997). Zircon grains were polished to provide a flat surface for sputtering of secondary ions until they were exposed through their mid-sections. After polishing (by using 0.25 μm diamond paste), they were coated by thin gold plate to prevent charging of the sample surface by the primary ion beam.

The samples were evacuated in the sample lock overnight and introduced into the sample stage in the ion source chamber. A 3-nA mass-filtered O⁻ primary beam was focused to sputter a 30-μm-diameter area with positive ions extracted. Before the actual analysis, the sample surface was rastered for 3 min in order to clean up the surface of the grain and eliminatory possible contaminants. The magnet was cyclically peak-stepped through a series of mass numbers ranging from mass 196 for ⁹⁰Zr⁶⁰⁰O⁻ to mass 254 for ²³⁸U¹⁶O⁺, including the background at mass number 204.1, and Pb isotopic mass numbers at 204, 206, 207, and 208, and the atomic U peak at the number 238 and Th¹⁶O peak at number 248. The ²⁰⁶Pb/²³⁸U ratios in the samples were calibrated using an empirical relationship (Claoué-Long et al., 1995) as follows:

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\frac{²⁰⁶Pb}{²³⁸U} \approx A \times \frac{²⁰⁶Pb}{²³⁸U} \times \frac{²³⁸U¹⁶O}{²³⁸U} \times \frac{²³⁸U}{²³⁸U} = \frac{²³⁸U¹⁶O}{²³⁸U} \times \frac{²³⁸U}{²³⁸U} \approx \frac{²³⁸U}{²³⁸U} \times \frac{²³⁸U}{²³⁸U} = \frac{²³⁸U}{²³⁸U} \times \frac{²³⁸U}{²³⁸U} = \frac{²³⁸U}{²³⁸U}
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where \( A \), \( \frac{²⁰⁶Pb}{²³⁸U} \) and \( \frac{²³⁸U¹⁶O}{²³⁸U} \) are constants, observed secondary ²⁰⁶Pb and ²³⁸U, and ²³⁸U¹⁶O and ²³⁸U ratios, respectively. The constant A was obtained by repeated measurements of standard zircons.

Subtraction of common Pb from measured Pb is required to estimate the accurate age. In this study, measured ²⁰⁶Pb/²³⁸U ratio in each grain was used for the correction of common Pb (Compston et al., 1984). This method is effective for low Th/U samples such as zircon. Although ²⁰⁶Pb/²⁰⁶Pb was measured to confirm the presence of common Pb, the correction of common Pb using ²⁰⁶Pb/²³⁸U causes a large analytical uncertainty because of minor ²⁰⁶Pb abundance. Use of measured ²⁰⁷Pb/²⁰⁶Pb for the correction of common Pb is also possible, but radiogenic ²⁰⁷Pb/²⁰⁶Pb in sample must be assumed. An advantage of the use of ²⁰⁷Pb/²⁰⁶Pb correction is that measured ²⁰⁷Pb/²⁰⁶Pb can be used to calculate the radiogenic ²⁰⁷Pb/²⁰⁶Pb. Experimental details are given elsewhere (Sano et al., 1999a,b).

Table 1 lists zircon data of measured U concentration, ²⁰⁴Pb/²⁰⁶Pb, ²⁰⁷Pb/²⁰⁶Pb, ²⁰⁸Pb/²⁰⁶Pb and ²³⁸U/²⁰⁶Pb ratios, and radiogenic ²³⁸U/²⁰⁶Pb ages for the Kannack complex of the Kontum massif, Vietnam. Fig. 5 shows a Tera–Wasserburg U–Pb zircon concordia diagram for twenty-four analyses listing in Table 1. Most of the zircon grains are concordant within an experimental error. Twenty-three analyses yield an age of 253.7 ± 11.6 Ma. There is only one age of 1404 ± 34 Ma, which is distinct from the others (VTM08.1 in Table 1; Fig. 5).
Fig. 3. Microphotographs of zircon under transmitted light, showing euhedral shape of individual zircon grain (three grains 15, 16 and 17 are not shown). Labeled-grain numbers are the same as those in Table 1. Scale bar is 0.5 mm.
5. Discussion

Zircon is the most commonly used mineral for dating both high-grade metamorphic events and magmatic solidification. The closure temperature of zircon U-Pb system is recently proposed to be greater than 850°C (e.g., Claoué-Long et al., 1995; Lee et al., 1997; Sano et al., 1999a), though it has previously been commonly accepted to be ~750°C (e.g., Mattinson, 1978). Lee et al. (1997) have estimated the closure temperature for U-Th-Pb isotopic system in natural zircon to be greater than 900°C. The peak metamorphic conditions recorded in the studied granulite were estimated to be 800–850°C, and analyzed zircons have perfectly euhedral shapes (Fig. 3), and mostly appear to be homogeneous in zoning pattern (type (a)), suggesting their growth in a melting environment, as mentioned in previous sections. Assuming the closure temperature for zircon U-Pb system is higher than 850°C, ages of 253.7 ± 11.6 Ma obtained from twenty three analyses in this study (Table 1; Fig. 5) are therefore interpreted to be the age of a high-grade metamorphic event that formed granulites of the Kontum massif.

An apparent concordant U-Pb age of ca. 1400 Ma was obtained on the core of oscillatory zoned zircon (Fig. 4c). This old core was surrounded by a younger (250 ± 8 Ma) rim, which is consistent with the ages of other analyzed zircons. The oscillatory zoned zircon could recrystallize during later high-grade metamorphism (Pidgeon, 1992). Radiogenic Pb can be partially lost during recrystallization and other processes, including radiation damage, self-annealing and chemical reaction (e.g., Pidgeon, 1992; Sano et al., 1999a). Therefore, the inherited age of ca. 1400 Ma could be tentatively interpreted as a minimum age for the protolith of the granulites. Furthermore, the inherited age obtained here is generally consistent with previous Rb-Sr ages of 1400–1600 Ma reported for Proterozoic formations of the Kontum massif (Phan Truong Thi, 1985; DGMVN, 1989). There is also a possibility that the old inherited zoned core has formed from an earlier high-grade metamorphism occurring in Middle-Proterozoic times (1400–1600 Ma).

Granulite occurrences have been known for a wide range of ages, including ages as young as 700–500 Ma (e.g., Pan-African, India and Sri Lanka) and 300 Ma (Hercynian...
granulites of Europe), although Archean and Proterozoic ages are most common for granulites (see Harley, 1989; and references therein). This present study strongly indicates an Indosinian age for granulites of the Kontum massif instead of Archean as proposed by previous workers. The Indosinian orogeny (ca. 250–240 Ma) has affected the Indo-China craton and is well documented by recent advanced geochronological data for several metamorphic belts (e.g., Maluski et al., 1995, 1997; Rangin et al., 1995; Lepvrier et al., 1997; Nam, 1998). The granulites in this study could provide the first example of an Indosinian age for granulites worldwide.

From the above discussions, it is inferred that the Kannack complex in the Kontum massif has suffered a tectono-thermal event, that occurred at granulate facies metamorphism conditions of 800–850°C during Indosinian times (254–240 Ma). The cooling history and subsequent exhumation of the Kannack complex that occurred during Indosinian times could be calculated by using present U–Pb 254 Ma zircon ages and the K–Ar 242 Ma biotite age (Nam, 1998). Calculated result shows that the Kannack complex started to cool from ~850°C (peak of metamorphic conditions) at 254 Ma to 300°C (the closure temperature of biotite K–Ar system) at 242 Ma, with an average cooling rate of ~45°C/Ma.

6. Conclusions

1. Granulites of the Kannack complex of the Kontum massif (Vietnam) have been generated during Indosinian
times as shown by the ca. 254 Ma age of most SHRIMP U–Pb zircon analyses.

2. An inherited age of ca. 1400 Ma recorded in an oscillatory zoned zircon core indicates a minimum age for the protolith of studied granulites as being Middle Proterozoic.

3. The cooling history and subsequent exhumation of the Kannack complex (the Kontum massif, Vietnam) occurred during Indosinian times with an average cooling rate of ~45°C/Ma between ~850°C at 254 Ma and 300°C at 242 Ma.

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