Metamorphism, anatexis, zircon ages and tectonic evolution of the Gongshan block in the northern Indochina continent—An eastern extension of the Lhasa Block

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A B S T R A C T

The Gongshan block near the Eastern Himalayan Syntaxis is a fault-bounded block at the northern tip of the triangle-shaped Indochina continent (NIC). Exposed in this block are late Paleozoic (Carboniferous to Permian) strata and a north–south belt of intermediate to felsic batholiths (i.e., Gaoligongshan magmatic belt). The contact between the Gaoligongshan batholiths and Carboniferous/Permian strata is characterized by a series of high-grade metamorphic gneisses with leucosome granite veins (i.e., the so-called “Gaoligong Group”). U-Pb SHRIMP and LA-ICP-MS dating of zircons indicate that these gneisses are actually metamorphosed Paleogene sediments containing inherited Archean to Cretaceous detrital zircons (from 2690 to 64 Ma) and have undergone medium- to high-pressure granulite-facies metamorphism at ~22 Ma. Leucosome and S-type granite of 22–53 Ma by anatexis are ubiquitous within high-grade metamorphic rocks in the southern part of the Gongshan block. An Early Paleozoic gneissic granite and granite intrusions of Jurassic, Cretaceous and Oligocene-Miocene ages are also recognized in NIC blocks. These ages suggest that the NIC differs distinctly from the Indian continent, the Greater and Lesser Himalaya zones, and the Yangtze Craton, but resembles the Lhasa Block in terms of Paleozoic to Mesozoic magmatism and detrital zircon ages. This offers an entirely new perspective on the tectonic evolution of the Gongshan block in particular and of the history of the Lhasa Block in the context of the India-Asia continental collision in general. Furthermore, the high-grade metamorphism in the NIC indicates a strong crustal thickening (vs. strike-slip shearing) event during much of the Eocene to the Oligocene (~53–22 Ma) that has brought the Paleogene sediments to depths of greater than 25 km. Continuous northward convergence/compression of the Indian Plate at the Eastern Himalayan Syntaxis may have led to the clockwise rotation, southeastward extrusion and extension of the southeastern part of the Indochina continent.

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1. Introduction

From the Eastern Himalayan Syntaxis to the southeast is a triangular region bordered by the Ailaoshan–Red River left-lateral strike-slip fault to the east, by the Sagaing right-lateral fault to the west, and by the Puqu fault, the southeast branch of the Jiali fault zone (Lee et al., 2003), at the northern tip. This region has been defined as “Indochina continent” (e.g. Tapponnier et al., 1986; Replumaz and Tapponnier, 2003) and has been interpreted as a zone of tectonic escape resulting from the India-Asian continental collision and continued convergence in the Cenozoic (Tapponnier et al., 1986; Peltzer and Tapponnier, 1988; Holt et al., 1991). Associated with the escaping are many geological features in the region, including a clockwise flow of materials at the northeastern edge of India. Both the geology and recent tectonic histories recorded in the Indochina continent, therefore, are critical towards a genuine understanding of the deformation processes of the Tibetan Plateau and its peripheral regions in response to the India-Asia continental collision.

Previous studies in this region have mainly focused on the initiation, histories and kinematics of the complex strike-slip fault systems (e.g., Tapponnier et al, 1990; Wang and Burchfiel, 1997; Ji et al., 2000a; Socquet and Pubellier, 2005; Searle, 2006). However, the nature and history of crustal materials of the northern Indochina continent (NIC) as well as its relationships with the rest of the continent and with the adjacent tectonic terranes (i.e., the Yangtze Craton to the east, the Indian continent and Himalayan-Tibetan orogenic belt to the west) remain unclear. Furthermore, the nature and magnitude of the displacement associated with the tectonic escaping (e.g., rotational thickening vs. lateral extrusion) are still in debate (England and Molnar, 1990, 1997, 2005; Tapponnier et al, 1990, 2001; Houseman and England, 1993; Burchfiel and Wang, 2003).

In this paper, we present new data on representative metamorphic and magmatic rocks from the Gongshan block in the NIC. These...
include granulite-facies metapelites from the Gaoligong Group and granitoid samples in the southern Gongshan block. The data include cathodoluminescence (CL) imaging, sensitive high-resolution ion microprobe (SHRIMP II) and laser ablation (LA) ICP-MS analyses to determine the ages of detrital, magmatic and metamorphic zircons. We use these data to deduce the provenance of protolith sediments and crustal affinity with the Himalaya and Lhasa Terranes in southern Tibet, and then discuss the tectonic evolution of the NIC in response to the India-Asia continental collision.

2. Geological background

2.1. Tectonic units of the NIC

The NIC, which is southeast of the Eastern Himalayan Syntaxis, is tectonically active with three major rivers (Jinshajiang, Lanchangjiang, and Nujiang) running in a narrow region. The crust here is strongly shortened with varying degrees of deformation as a result of the bulldozer-like northeastward compression of the eastern Indian continent. The NIC has been divided into four sub-blocks: the Gongshan (GB), Baoshan (BB), Tengchong (TB) and Lanping-Simao (LB) blocks (Fig. 1b) (e.g., Zhong, 1998; Wang et al., 2006). The first three blocks are thought to have the same crustal architecture and basement on the basis of similar Paleozoic strata and high-grade metamorphism (YBGMR, 1990; Zhong, 1998). All these four blocks are bounded by Cenozoic faults with complex histories of ductile and brittle deformation.

2.1.1. Tengchong block (TB)

The Tengchong block (Fig. 1b) is the northern continuation of the Mogok metamorphic belt of Myanmar (Mitchell, 1989; Bertrand et al., 1999, 2001). In Myanmar, it is bounded by the dextral Sagaing fault to

Fig. 1. (a) Tectonic framework of the Southeast Asia subcontinent (modified from Tapponnier et al., 2001; Socquet and Pubellier, 2005). (b) Simplified geological map of the northern Indochina continent (NIC) showing its tectonic units (modified after YBGMR, 1990; Pana and Ding, 2004). (c) Geological map of the study area with sample locations. All units except granite are amphibolite to granulite facies metamorphic rocks.
the west and by the Gaoligong shear zone to the east. It has been considered as part of Gondwana during the late Paleozoic and was accreted to Eurasia in the late Mesozoic (Wang, 1983; Morley et al., 2001). The block is mainly composed of high-grade metamorphic complexes, low- to medium-grade metamorphosed Paleozoic strata, Mesozoic–Tertiary granites and Tertiary–Quaternary volcanic–sedimentary sequences (YBCMR, 1990). Medium to high-pressure mafic granulite has been reported in the China–Myanmar border (see Fig. 1b for locality; Ji et al., 2000a,b) with an assemblage of garnet + clinopyroxene + plagioclase + amphibole + quartz and metamorphic conditions of P = 8–10 kbar and T = 750–860 °C. Amphibole and plagioclase Ar–Ar dating gives plateau ages of 23–24 Ma. The Paleozoic strata are mainly composed of weakly metamorphosed sandstones, shale/slate and limestone with cold-water fossil species (Wang, 1983).

2.1.2. Baoshan block (BB)

The Baoshan block (Fig. 1b) in the south is wedge-shaped and bounded by the Gaoligong shear zone to the west and by the Chongshan shear zone to the east (e.g., Zhang et al., 2010). Rock types in the block, as described in YBCMR (1990), include a high-grade metamorphic complex (Gaoligong Group?); low- to medium-grade metamorphosed Paleozoic strata, Mesozoic–Tertiary granites and Tertiary–Quaternary sedimentaries, similar to the Tengchong block. A comparison of sedimentary facies and fossils in the Carboniferous and Permian strata has led to the suggestion that the Tengchong and Baoshan blocks both may in fact be a fragment from Gondwana (Wang, 1983). Zhong (1998) suggested that the block was amalgamated with the Yungze Craton along the Changning–Mengsul suture zone in Late Paleozoic time.

2.1.3. Lanping-Simao block (LB)

The Lanping-Simao block (or fold belt) is bounded by Ailaoshan shear zone to the east and by Chongshan shear zone to the west. The block shows outcrops of Proterozoic basement and has Paleozoic marine strata that might be similar to those of the Yangtze Block (Wang et al., 2006). The late Paleozoic strata are mostly thick basaltic sandstones, shale/slate and limestone with cold-water fossil species. Triassic granites with zircon U-Pb ages of 200–259 Ma and Early Paleozoic granitic gneiss (490-Ma S-type granite) have also been reported from both Gongshan and Baoshan blocks (YBCMR, 1990; Peng et al., 2006; Song et al., 2007) (Fig. 1b).

The right-slip Gaoligong shear zone is marked by a series of mylonite zones located between the Gongshan and Tengchong Blocks in the north and between the Baoshan and Tengchong Blocks in the south (Fig. 1b). This shear zone, together with the right-slip Sagaing fault (Fig. 1a) to its southwest, has been considered to be a conjugate shear system to the left-slip Aila Shan shear zone (Wang and Burchfiel, 1997; Ji et al., 2000a; Yin and Harrison, 2000; Socquet and Pubellier, 2005). However, the dextral Sagaing fault, i.e., the west boundary of the Indochina continent, was not active prior to 15 Ma (Morley et al., 2001; Replumaz and Tappornier, 2003). The total displacement of ~700 km (Replumaz and Tappornier, 2003) along the Sagaing fault, if correct, would suggest that the extrusion (i.e., the escape) of the Indochina continent has been rather rapid in the past 15 million years.

2.2. Metamorphic architecture in the Gongshan block

The Gongshan block exhibits spatial variation in metamorphic grade. In the north segment (north of Cawlalong, see Fig. 1b for location), all the rocks (except for granite intrusions) show amphibolite-facies metamorphism, e.g., marble of Carboniferous limestone, garnet-staurolite-mica schist of mudstone (Fig. 2a), and amphibolite of basaltic layers. The early minerals of garnet, staurolite and biotite as porphyroblasts have been strongly overprinted and foliated by the late muscovite + albite + quartz assemblage that is genetically associated with the strike-slip shearing (Fig. 2b). In the middle segment of the Gongshan block (from Cawlalong to north of Gongshan), sandstone, siltstone, mudstone, limestone and basalts of Carboniferous to Permian age have undergone sub-green schist to green schist-facies metamorphism (Fig. 2c–f). The common metamorphic assemblage of the strongly deformed mylonite consists of fine-grained white mica, calcite and chlorite with rare biotite (Fig. 2h and g). In the southern segment of the Gongshan block (our primary study area), the metamorphic grade increased from lower amphibolite to upper amphibolite and to granulate facies (see below). All these observations reflect the varying depths of erosion in response to differential tectonism in the N–S direction.

3. Petrography and metamorphism of the southern Gongshan block

The southern segment of the Gongshan block (Gongshan-Fugong region, see Fig. 1b for location) includes (1) metamorphosed Carboniferous strata and (2) the Gaoligong Group. Two events of metamorphism can be recognized. The earlier event is pervasive varying, from north to south, in conditions from amphibolite to granulate facies with localized anatexis. The later event is restricted to narrow and strongly deformed shear zones, overprinting the early fabrics and cutting Gaoligongshan granitoid plutons.

3.1. Metamorphism and deformation of the Carboniferous strata

The Carboniferous strata of sandstone, limestone, mudstone and basaltic layers have all undergone varying grade of metamorphism, comparable to the metamorphosed Carboniferous strata in the north.
3.1. Metapelite

Metapelite in the northern part of the southern Gongshan block is coarse-grained with a mineral assemblage of gt + st + ky + bi + mu + pl + q (see Table 1 for mineral Abbreviations) in the northern part of the southern Gongshan block. In the literature, the "Gaoligong Group" is referred to the high-grade metamorphic complex exposed in the NIC blocks (i.e., the Tengchong, Baoshan and Gongshan blocks) (e.g., YBGRM, 1990; Zhong, 1998). This group has long been described as the Precambrian basement of the NIC because of the high-grade metamorphism (Zhai et al., 1990; Zhong, 1998; Wang et al., 2006). In our study area, the Gaoligong Group mainly crops out along both sides of the Gaoligong shear zone in the southern Gongshan block. It consists of high-grade pelitic gneiss, migmatite and abundant garnet-bearing leucogranite pods/veins (see below).

Peltic gneisses from the Gaoligong Group (samples NJ32, NJ54 and NJ56, Fig. 1c) contain a mineral assemblage of gt + sil + ksp + bi + pl + q (+ ilm + tour + zir + mon) (see Table 3a and b). Muscovite is an unstable phase and occurs as relics of the reaction: gt + mu + pl = bi + ksp + Al2SiO5 + H2O. Further to the south, perthite appears in the assemblage along with garnet and sillimanite, but biotite modal content decreases and garnet-bearing leucogranite pods or veins become common within the strata (Fig. 3c), suggesting that anatexis must have taken place in the metapelite under granulite-facies conditions. The late greenschist facies metamorphism (i.e., an assemblage of fine-grained muscovite, albite, chlorite and quartz) was associated with shearing deformation, strongly overprinting the peak assemblages (Fig. 3a and b).

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3.1.2. Calcic sandstone

Calcic sandstone is one of the major rock types of the Carboniferous strata interlayered with metapelite and marble. The rock shows a medium- to fine-grained granular texture with a metamorphic mineral assemblage of diopside + biotite + quartz ± calcite ± amphibole. With increasing metamorphic grade from north to south, amphibole content decreases. A diopside + scapolite assemblage has been observed in some samples in the south (Fig. 3d). Retrograde assemblage of amphibole + epidote (+ chlorite) is present in most samples.

3.1.3. Marble

Marble interlayers can be traced steadily following the strata from north to south. In the northern part of the southern Gongshan block, marbles are mostly pure with coarse-grained calcite and minor diopside. Garnet-clinoxyroxene layers and pods exist within the marble and show a medium-grained granular texture without strong deformation (Fig. 3e). The garnet is CaO rich with high grossular (70.5 mol%), low almandine (28.5 mol%) and extremely low pyrope (0.25 mol%). The clinoxyroxene is diopside with high wollastonite (~49.5–50 mol%), and low ferrosilite (~19.7–21.8 mol%) and enstatite (~28.1–30.8 mol%). In the southern part of the southern Gongshan block, marble is coarse-grained with a granoblastic texture and consists of phlogopite + diopside + calcite + olivine ± quartz (Fig. 3f).

3.1.4. Deformation of the late Paleozoic strata

The style and intensity of deformation also vary from north to south as manifested by the behavior of calcic meta-sandstone layers. In the conjunct region between the middle and southern segments of the Gongshan block, metamorphism is under greenschist and lower-amphibolite facies conditions, deformation of the Carboniferous sandstone/siltstone is characterized by isoclinal folds with high-angle axial planes (Fig. 4a and b). With increasing metamorphic grade towards south, sedimentary layers are replaced by axial schistosity (Fig. 4c and d) before they disappear completely (Fig. 4e) in the southern segment. These deformations are mostly associated with E–W lateral compression and vertical thrust.

3.2. Petrography and metamorphism of the Gaoligong Group

In the literature, the "Gaoligong Group" is referred to the high-grade metamorphic complex exposed in the NIC blocks (i.e., the Tengchong, Baoshan and Gongshan blocks) (e.g., YBGRM, 1990; Zhong, 1998). This group has long been described as the Precambrian basement of the NIC because of the high-grade metamorphism (Zhai et al., 1990; Zhong, 1998; Wang et al., 2006). In our study area, the Gaoligong Group mainly crops out along both sides of the Gaoligong shear zone in the southern Gongshan block. It consists of high-grade pelitic gneiss, migmatite and abundant garnet-bearing leucogranite pods/veins (see below).

Peltic gneisses from the Gaoligong Group (samples NJ32, NJ54 and NJ56, Fig. 1c) contain a mineral assemblage of gt + sil + ksp + bi + pl + q (+ ilm + tour + zir + mon) (Fig. 5a). Muscovite is an unstable phase and occurs as relics of the reaction: gt + mu + pl = bi + ksp + Al2SiO5 + melt during anatexis (Fig. 5b and c). Perthite appears both in some peltic gneisses and in the leucogranite (Fig. 5d). Kyanite is observed in some samples coexisting with garnet, sillimanite, K-feldspar and biotite (Samples NJ07, Fig. 5e), suggesting medium- to high-pressure metamorphism along the kyanite-sillimanite phase boundary.

3.3. Strike-slip shearing deformation in the Gongshan block

Strike-slip shear zones are well developed in our study area and have been previously described as “the Gaoligong fault system” (see Wang and Burchfiel, 1997; Socquet and Pubellier, 2005). These shear zones trend N–S in the south and turn gradually to NW towards north. They cut through the high-grade metamorphic rocks of the Gaoligong Group, granitoid plutons and Carboniferous strata. Mylonites in the
shear zones consist of low-grade greenschist facies minerals of muscovite + chlorite + albite, which overprint the early amphibolite to granulite facies assemblages (Fig. 5d). Ar–Ar dating of amphibole, biotite and muscovite gave inconsistent ages from 24 to 12 Ma (Wang and Burchfiel, 1997; Ji et al., 2000a,b).

4. Anatexis in the Gongshan block

Garnet-bearing leucosome and S-type granite are widespread as small lenses and veins of varying size within both high-grade metamorphosed “Carboniferous strata” and “Gaoligong Group”. These anatexitic granites include garnet-muscovite granite, fine-grained garnet-bearing biotite-muscovite granite and tourmaline granite.

Field observations suggest that leucogranite (garnet-muscovite granite) is internally derived. Fig. 6 displays snapshots of the processes of leucogranite generation through partial melting (anatexis) of metapelite. Melts produced from the metapelite are extracted (Fig. 6a) as pockets or veins with varying thickness (~5 to 80 cm; Fig. 6b and c). Foliations inherited from the metapelite can also be locally preserved in leucogranite pockets (Fig. 6d). Some leucosome occurs as veins intruding the Carboniferous marble and sandstone layers, and cut the schistosity of their country rocks (Fig. 6e and f). Most of the leucogranite shows a medium- to coarse-
grained granoblastic texture with weak foliation. The mineral assemblage includes varying modal content of garnet, muscovite, plagioclase, perthite and quartz with or without sillimanite, which represent the product of anatexis during high-grade metamorphism. Most leucosome and S-type granite are weakly deformed and are petrogenetically unrelated to the lateral shear deformation.

Fine-grained garnet-bearing biotite-muscovite granite (sample NJ38, Fig. 1c) occurs as lenses with the long axis parallel to the tectonic trend. Contacts between the granite and meta-sandstone are unclear because of the tectonic juxtaposition and shear deformation. The granite consists of quartz (30–35%), plagioclase (20–25%), K-feldspar (~35%), biotite (5–8%), muscovite (2–3%) and minor garnet (~1%).

The tourmaline granite (samples ST122 and NJ74) occurs as small sheet-like bodies of 30–50 m² in size within the metamorphosed Carboniferous strata (see the locality in Fig. 1b). It is fine- to medium-grained with an assemblage of quartz (30–35%), plagioclase (25–30%), K-feldspar (30–35%), tourmaline (~5–8%) and minor garnet and white mica. The mineral assemblage and whole-rock composition suggest that the tourmaline granite is also a peraluminous (or S-type) granite of anatectic origin.
5. Mineral chemistry and P–T estimates

Mineral compositions were analyzed using a JEOL JXA-8100 EPMA (electron probe micro-analyzer) at Peking University. The operation conditions are 15 kV acceleration voltage, 10 nA beam current and 2 μm spot size. Synthetic silica (Si), spessartine (Mn) and Cr₂O₃ (Cr), natural sanidine (K), pyrope (Mg), andradite (Fe, Ca), albite (Na, Al) and rutile (Ti) as well as relevant standard minerals (from SPI corp. US) were used as calibration standards for relevant elements given in parentheses. Representative analyses for various minerals and garnet compositional profiles are given in Appendix A (Tables A1-A7).

5.1. Compositional variation of garnet

Garnet in metapelites from the Gongshan block is euhedral to subhedral with variable grain size from 0.5 to 2 mm. Six porphyroblastic garnets from six samples were chosen for zoning profile analyses (Appendix A, Tables A2–A7). As shown in Fig. 7a and b,
garnet from the staurolite-bearing schist (ST56 and NJ49) exhibits pronounced bell-shaped profiles with antithetic zoning of spessartine relative to almandine and pyrope contents; the $X_{\text{sp}}$ decreases from the core ($0.198$–$0.235$) to the rim ($0.084$–$0.118$), whereas the $X_{\text{alm}}$ and the $X_{\text{pyr}}$ increase from the core ($\text{Alm} 0.651$–$0.704$, $\text{Pyr} 0.044$–$0.081$) to rim ($\text{Alm} 0.783$, $\text{Pyr} 0.098$–$0.103$). $X_{\text{gr}}$ in garnet from ST56 decreases from 0.075 in the core to 0.042 at the rim and $X_{\text{gr}}$ from NJ49 increases from 0.016 to 0.028 but decreases to 0.005 at the outer rim. Garnet from the K-feldspar-bearing schist/gneiss (NJ39, NJ43 and NJ54) and leucogranite (NJ44) shows relative flat profiles with weak variations (Fig. 7c–e). In the sample NJ43 (Fig. 7c), garnet is zoned with $X_{\text{alm}}$ increasing from 0.791 in the core to 0.825 at the rim, $X_{\text{pyr}}$ decreasing from 0.132 to 0.106, $X_{\text{sp}}$ from 0.063 to 0.046 and $X_{\text{gr}}$ from 0.027 to 0.017. Garnet from sample NJ54, just opposite to others, is zoned with $X_{\text{sp}}$ increasing from 0.084 in the core to 0.098 at the outer rim, $X_{\text{alm}}$ decreasing from 0.765 to 0.746 and $X_{\text{pyr}}$ from 0.136 to 0.113 (Fig. 7e). Garnet from NJ39 shows flat profiles from the core ($X_{\text{alm}} 0.687$, $X_{\text{pyr}} 0.181$, $X_{\text{sp}} 0.078$, $X_{\text{gr}} 0.036$) to the rim ($X_{\text{alm}} 0.709$, $X_{\text{pyr}}$...
0.174, $X_{sps} = 0.083$, $X_{gro} = 0.046$); spessartine increases and pyrope decreases rapidly at the outermost rim (Fig. 7e). Garnet from leucogranite (NJ44) also shows flat compositional profiles with relatively high spessartine and low grossular ($X_{alm} = 0.228$–$0.218$, $X_{pyr} = 0.181$–$0.174$, $X_{sps} = 0.078$–$0.083$, $X_{gro} = 0.036$–$0.046$) (Fig. 7f).

### 5.2. Other minerals

Composition of other minerals in the metapelites is weak zoned or unzoned from the core to the rim. Biotite occurs mainly in the matrix; no grain was found as inclusion in garnet. Biotite compositions from all analyzed samples have variable TiO$_2$ (1.17–3.04 wt%), FeO (17.12–23.22 wt%) and Fe/[Fe+Mg] (0.50–0.70) and TiO$_2$ content shows a rough increase with the metamorphic grade from the north to south. White mica from the pelitic schist or gneiss is muscovite with Si content ranging from 3.05 to 3.14 cations per formula unit (p.f.u.) on the basis of 11 oxygen. Muscovite that occurs as second generation along the shearing foliation is enriched in Na$_2$O (e.g., Na/[Na+K] = 0.24–0.26 in sample NJ49) than that in other samples. Plagioclase is unzoned but shows large compositional variation (e.g., Ab$_{47}$–$83$, An$_{16}$–$52$ and Or$_{0.3}$–$2.6$) in different samples. Albite of second generation is Na rich (Ab$_{90}$) and is associated with muscovite and chlorite along shearing foliations (e.g., in sample NJ49). K-feldspar has typical compositions (Or$_{87.2}$–$92.3$, Ab$_{7.7}$–$12.2$ and An$_{0.0}$–$0.1$). Perthite was found in the metapelite NJ43 and the leucogranite NJ44, which comprises almost pure albite exsolutions (Or$_{0.2}$–$2.2$, Ab$_{97}$–$98$, An$_{0.0}$–$2.5$) in a K-feldspar-rich host. Staurolite has high Fe (e.g., Mg$^+$ = Mg/[Mg+Fe] = 0.14–0.16 in sample ST56 and NJ49).

### 5.3. Pressure (P) and temperature (T) estimates

Metamorphic conditions of all garnet-bearing metapelite samples (see Table 1 and Fig. 5) were determined by average $P$–$T$ methods using mineral compositional data and the THERMOCALC (version 3.23; Powell et al., 1998) with the internally consistent thermodynamic dataset (Holland and Powell, 1998; November 2003 updated file tcds55.txt). Quartz and the fluid phase that is assumed to be pure H$_2$O, are considered to be in excess. In finding an average $P$–$T$ of a mineral assemblage, an independent set of reactions between mineral end-members in the assemblage are used. The appropriate linear sets of independent reactions used are given in Appendix B. All mineral formulae in Table A1 and end-member activities were calculated using $AX$ by Holland (see http://www.esc.cam.ac.uk/astaff/holland/ax.html). Rim or near rim compositions of the garnet, staurolite, mica and plagioclase are used in average $P$–$T$ calculations. Gt-bi geothermometry of Holdaway (2000) was also used for temperature calculations.

Mineral assemblages and calculated average $P$–$T$ conditions are given in Table 1 and Fig. 8. $P$–$T$ estimates for the staurolite bearing schists (ST56 and NJ49) give $P = 7.1$–$8.3$ kbar and $T = 650$–$660$ °C. Other samples with K-feldspar + Al$_2$SiO$_5$ assemblage yield $T = 685$–$750$ °C and $P = 6.5$–$8.4$ kbar. The $P$–$T$ diagram exhibits a tendency of
Zircon was analyzed using the Concordia plot, based on the fact that all measured \(^{208}\text{Pb}/^{206}\text{Pb}\) ratios in the samples were corrected using zircon 91500 (Wiedenbeck et al., 1995) as external standard. Zircon standard TEMORA (417 Ma) from Australia (Black et al., 2003) is also used as a secondary standard to supervise the deviation of age measurement/calculation. Ten analyses for the standard TEMORA yielded apparent \(^{206}\text{Pb}/^{238}\text{U}\) ages of 408–420 Ma with a weighted mean of 415.7±4.2 Ma (MSWD=0.36). Isotopic ratios and element concentrations of zircons were calculated using GLITTER (ver. 4.4, Macquarie University). Concordia ages and diagrams were obtained using Isoplot/Ex (3.0) (Ludwig, 2003). The common lead was corrected using LA-ICP-MS Common Lead Correction (ver. 3.15), followed the method of Andersen (2002).

The analytical data are given in Tables 2, 3, 4 and 5, and presented on U-Pb Concordia diagrams with 1σ errors in Figs. 10 and 11. The mean ages are weighted means at 95% confidence levels (Ludwig, 2003).

6.2. Granulite-facies Pelitic Gneisses of the Gaoligong Group

Zircons from the garnet-sillimanite gneisses (samples NJ32, NJ54 and NJ56) are subhedral to oval with long axes varying from 50 \(\mu\)m up to 250 \(\mu\)m and length/width ratio from 1.5 to 2.5. CL images of zircons from these pelitic gneisses show clear internal zoning with inherited detrital cores and metamorphic rims (Fig. 9). The irregularly-shaped detrital cores display luminescence of varying strength and clear oscillatory bands or sectors. The metamorphic rims are generally characterized by irregular and weak zoning. Mineral inclusions of garnet, sillimanite, quartz and K-feldspar were detected in rim portions by a micro-Raman spectroscopy (Ranisow RM–1000) with the 514.5 nm line of an Ar-ion laser at Peking University (Fig. 9b).

Zircons from two pelitic gneisses (NJ32 and NJ54) were analyzed using the SHRIMP method. The cores show huge U variation (93 to 2037 ppm; Th/U ratio from 0.19 to 1.49). Twenty-two core analyses yield ages varying from 74 ± 1.2 Ma (\(^{206}\text{Pb}/^{238}\text{U}\)) to 2752 ± 21 Ma (\(^{207}\text{Pb}/^{206}\text{Pb}\)). In U-Pb concordia diagrams, analyses of four zircon cores define a concordia line with an upper-intercept age of 2690 ± 35 Ma and a lower-intercept age of 1152 ± 120 Ma (MSWD=0.49). Analyses of two zircon cores define a concordia curve with an upper-intercept age of 1873 ± 19 Ma and a lower-intercept age of 467 ± 50 Ma (MSWD=0.09) (Fig. 10a). Other concordant spot ages include 1557 ± 21 Ma, 1053 ± 18 Ma, 636 ± 10–691 ± 11 Ma, 470 ± 11 Ma, 203 ± 5–255 ± 7 Ma and 74 ± 1–140 ± 4 Ma.

By contrast, zircon rims of sample NJ54 have relatively uniform U (730–1063 ppm) and low Th (3–9 ppm), thus giving significantly lower Th/U ratios (0.004–0.012) than cores, which have been commonly interpreted as typical features of “metamorphic overgrowth” in granulite-facies (Williams and Claesson, 1987; Vavra et al., 1996; Williams, 1996) and eclogite-facies rocks (Rubatto et al., 1999; Song et al., 2006). Eleven rim analyses give \(^{206}\text{Pb}/^{238}\text{U}\) ages of 20.4 to 23.8 Ma with a weighted mean of 22.5 ± 0.6 Ma (MSWD=1.9) (Table 2, Fig. 10b), close to the Oligocene–Miocene boundary. Zircon rims of NJ32 were too narrow to analyze.
Zircons from a similar metapelite sample NJ56 were analyzed by LA-ICP-MS (Table 3). The cores also give huge variations in U (37 to 2064 ppm) and Th/U (0.10–2.50). Sixty core analyses yield $^{206}\text{Pb}/^{238}\text{U}$ ages varying from 64 Ma to 2563 Ma. In contrast to SHRIMP dating of NJ32 and NJ54, eight detrital magmatic zircons from sample NJ56 gives Jurassic ages (157 to 165 Ma). It should be noted that all these zircon cores with Jurassic and Cretaceous ages (165–64 Ma) show clear magmatic oscillatory bands, high Th/U ratios (0.35–2.50) and are large enough for precise dating. Six zircon rims from sample NJ56 show relatively uniform U (663–919 ppm) and significantly lower Th/U ratios (0.004–0.009) than the inherited cores and yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 20.7 to 22.3 Ma with a weighted mean of 21.6±0.6 Ma (MSWD=1.8).

6.3. Leucogranite within the Gongshan block

Zircons from leucogranite sample NJ66 are euhedral, but have complex internal structures; all have a dirty “corroded” core and a dark luminescent rim with magmatic oscillatory bands (Fig. 12a). SHRIMP analysis gives relatively uniform but very high U (3169 to 5015 ppm) and low Th/U (0.007–0.024). Two analyses on the core domains yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 44.8±0.7 Ma and 53.2±0.9 Ma. Analysis of seven rims gives ages varying from 22.0 to 34.6 Ma, five of which give a weighted mean of 22.7±0.8 Ma (MSWD = 1.8). These data may suggest a two-stage growth of zircons in the leucogranite at ~45–53 Ma and the peak anatectic age of 22.7 Ma. However, it is possible that the cores could have been crystallized from earlier melt of the same magmatism, but the later melt may be compositionally different and may thus have corroded the growing zircons with Pb leaching. As a result, the cores give older and inconsistent (~8 Myrs difference) apparent ages of 45 and 53 Ma. In any case, further work is needed to verify this hypothesis, but the ~22.7 Ma rim age is a genuine age of the leucogranite petrogenesis.

6.4. Tourmaline granite within high-grade metamorphic rocks

Zircon crystals from the tourmaline granite (ST122) are euhedral and about 100–250 μm in length and 60–120 mm in width. They display oscillatory bands in CL images (Fig. 12b) and contain extremely high U (1827–21523 ppm) and Th (233–2666 ppm) with Th/U ranging from 0.05 to 0.25 by SHRIMP analyses. These data are consistent with the magma parental to the granite being highly evolved and enriched in volatiles (e.g., tourmaline bearing) and incompatible elements (e.g., high Th and U). Twelve analyses of zircon crystals yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 22.8 to 26.9 Ma and ten spots give a weighted mean of 24.4±0.7 Ma (MSWD = 1.7) (two old spots were discarded because they are possibly influenced by the old core) (Table 4, Fig. 11b). LA-ICP-MS analysis of zircons from another tourmaline granite sample NJ74 gives high U (728–11116 ppm) and...
Th/U (0.04–0.52) (Table 5). Five analyses give $^{206}\text{Pb}/^{238}\text{U}$ ages of 34.3–41.8 Ma and twelve analyses give ages of 24.2–27.2 Ma with a weighted mean of 25.5±0.5 Ma (MSWD=1.5), suggesting two stages of zircon growth from the anatectic melts (Fig. 11c). One bright-luminescent core contains low Th and U and yields a $^{207}\text{Pb}/^{206}\text{Pb}$ apparent age of 2455±34 Ma.

7. Discussion

7.1. Neoarchean basement in the NIC?

Precambrian basement of the Indochina continent was thought to be mainly formed in the early Proterozoic; Sm-Nd TDM model ages of high-grade metamorphic rocks in this region range from 2.3 to 1.0 Ga (Zhai et al., 1990; Zhang and Schärer, 1999), and detrital zircon and baddeleyite grains from sediments from four major rivers in the Indochina continent yield ages younger than 2.5 Ga (Bodet and Schärer, 2000). Although Lan et al. (2001) reported Neoarchean ages from gneisses in northern Vietnam, they inferred that this Neoarchean complex was genetically associated with the Late Archean Kangding complex at the western margin of the Yangtze Craton and therefore concluded that the Indochina continent was sinistrally offset ~600 km by the Red River shear zone. However, geochronological data indicated that the Kangding complex in western Sichuan actually formed in the Neoproterozoic (Li et al., 2003; Chen et al., 2005; Zhao et al., 2006) rather than in the Late Archean.

Concordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 2752–2686 Ma and the upper-intercept age of 2690±35 Ma from detrital cores of samples NJ32 and NJ54, together with high Th/U ratios (0.63–1.35) and magmatic CL internal structures of these four old detrital zircon cores, indicate a Neoarchean magmatic event. The concordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1866–1896 Ma and a similar upper-intercept age of 1873±19 Ma suggest another magmatic event in the Paleoproterozoic. These new findings indicate the presence of early Precambrian basement in the NIC region.

7.2. Crustal evolution and provenance of the NIC

The concordant ages of detrital zircon cores from pelitic gneisses of the Gaoligong Group (NJ32, NJ54 and NJ56) and from the gneissic granite (NJ65) record multiple episodes of magmatism from the Neoproterozoic to the Mesozoic in the source region.
gneissic granite (Song et al., 2007) indicate geologic events that are in fact widespread throughout the ancient Gondwana continent (Li et al., 1999; Avigad et al., 2003; Hanson et al., 2004). The 487 ± 11 Ma peraluminous (S-type) granite in the Gongshan block is interpreted as resulting from a crustal melting event (Song et al., 2007). Similar granites are also reported in the Baoshan block with zircon U-Pb ages of 470–490 Ma (Chen et al., 2004), which indicates that the Gongshan and Baoshan blocks have experienced the same magmatic event at this time. These granites correspond to the widespread subduction-related magmatism on the northern margin of Gondwana (Schelling, 1992; DeCelles et al., 2000). This age spectrum differs from those of the Yangtze Craton where there is no evidence for early Paleozoic magmatism (Chen and Jahn, 1998; Li et al., 1999). However, data from DeCelles et al. (2000) and Yin (2006) indicate that the Himalayan orogenic belt and the northern Indian Plate lack records of the Late Paleozoic to Mesozoic (~300–65 Ma) magmatism (Fig. 13) although some mafic volcanic and intrusive rocks of early Cretaceous ages (~130–145 Ma) have been reported (Zhu et al., 2008). This suggests that the NIC should have separated from Gondwana continent and collided with Eurasian Plate at the Triassic time. On the other hand, the Lhasa Block, in comparison with the NIC blocks, has similar ages of magmatism especially from Neoproterozoic to Mesozoic times (850–70 Ma) (Xu et al., 1985; Yin and Harrison, 2000; Hu et al., 2004; Kapp et al., 2005a,b; Chu et al., 2006; Guynn et al., 2006) suggesting an important magmatic event that may have occurred in the Triassic (~250–200 Ma). Triassic granites have also been recognized in the southeastern Indochina continent, and have been interpreted as the result of collision between the Indochina continent and the South China Craton (DeCelles et al., 2000). The twenty-eight 165–64 Ma detrital zircon cores from the three pelitic gneiss samples are consistent with the Gaoligongshan being magmatically active during the Late Jurassic to Cretaceous (140–65 Ma) (Yan et al., 2002; Chen et al., 2006). This magmatic belt is temporally comparable to the magmatic belt of the Gangdese granitoids in the Lhasa Block in southern Tibet (see below).

The age spectrum of a continental block records its thermotectonic histories and thus can be used to trace its origin and tectonic affinity in the context of plate tectonic reconstructions. The Neoarchean to Early Paleozoic ages (2690–430 Ma) of both detrital zircons from the Gaoligong pelitic gneisses and zircon from the gneissic granite resemble those of the Himalayan Orogen in Nepal, which was suggested to have been accreted onto northern Gondwana and intruded by crustal melts during the Cambrian-Ordovician time (DeCelles et al., 2000). This age spectrum differs from those of the Yangtze Craton where there is no evidence for early Paleozoic magmatism (Chen and Jahn, 1998; Li et al., 1999). However, data from DeCelles et al. (2000) and Yin (2006) indicate that the Himalayan orogenic belt and the northern Indian Plate lack records of the Late Paleozoic to Mesozoic (~300–65 Ma) magmatism (Fig. 13) although some mafic volcanic and intrusive rocks of early Cretaceous ages (~130–145 Ma) have been reported (Zhu et al., 2008). This suggests that the NIC should have separated from Gondwana continent and collided with Eurasian Plate at the Triassic time. On the other hand, the Lhasa Block, in comparison with the NIC blocks, has similar ages of magmatism especially from Neoproterozoic to Mesozoic times (850–70 Ma) (Xu et al., 1985; Yin and Harrison, 2000; Hu et al., 2004; Kapp et al., 2005a,b; Chu et al., 2006; Guynn et al., 2006) suggesting an important magmatic event that may have occurred in the Triassic (~250–200 Ma). Triassic granites have also been recognized in the southeastern Indochina continent, and have been interpreted as the result of collision between the Indochina continent and the South China Craton (DeCelles et al., 2000). The twenty-eight 165–64 Ma detrital zircon cores from the three pelitic gneiss samples are consistent with the Gaoligongshan being magmatically active during the Late Jurassic to Cretaceous (140–65 Ma) (Yan et al., 2002; Chen et al., 2006). This magmatic belt is temporally comparable to the magmatic belt of the Gangdese granitoids in the Lhasa Block in southern Tibet (see below).

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All errors are 1 sigma of standard deviation.

7.3. Crustal thickening at ~53–22 Ma

The detrital core ages of zircons from the three pelitic gneisses are consistent with Phanerozoic magmatic events within the Gongshan block. Twenty-eight detrital zircon cores with Jurassic to Cretaceous ages (165–64 Ma) are of clear magmatic origin; they have high Th/U ratios, concordant ages and CL images of oscillatory crystallization, as are zircons from the Gaoligongshan magmatic belt. All the above observations demonstrate that protoliths of the high-grade metamorphic rocks of Gaoligong Group must have been sourced locally and deposited later than the Cretaceous Gaoligongshan magmatic belt. Therefore, we conclude that the Gaoligong Group was most probably deposited later than the Cretaceous Gaoligongshan magmatic belt.
deposited during the India-Asia collision in the Paleocene (~65–55 Ma) (e.g., Vin and Harrison, 2000).

Medium to high-pressure granulite-facies metamorphic rocks of Paleogene sediments in the southern Gongshan block (this study) and in the Baoshan Block (YBCM, 1990; Zhai et al., 1990; Zhong, 1998), and high-pressure granulite (T = 750–800 °C and P = 8–10 kbar) at 23–24 Ma in the Tengchong block (Ji et al., 2000b) indicate a regional high P-T metamorphic event. Compositional zonation of garnet suggests a P-T reflects prograde metamorphic event, which we interpret as indicating crustal thickening that buried the Paleogene sediments to depths of ~24–30 km prior to ~22 Ma. The ~53–22 Ma magmatism of crustal melting (samples NJ66, NJ74 and ST122), as well as high-grade metamorphism, suggests that the duration of crustal thickening may be ~30 m.y. Occurrence of the high-grade metamorphic rocks and leucogranites suggests that they must have resulted from regional metamorphism prior to ~22 Ma rather than associated with spatially restricted narrow lateral-slip shear zones (see below). Microstructural analyses show that the mylonite formed by right-lateral slip is a later low-grade metamorphic event (see above), and overprints the earlier high-grade regional metamorphism.

High-grade metamorphic rocks and leucogranites of ~35 Ma to ~17 Ma along the Ailaoshan–Red River fault zone have been interpreted as a result of strike-slip deformation (Schärer et al., 1999; Harrison et al., 1992; Leloup et al., 1995, 2001; Zhang and Schärer, 1999; Gilley et al., 2003). However, Searle (2006) pointed out that mylonites along the Red River Fault with left-slip kinematic indicators are also lower-temperature fabrics formed after peak sillimanite metamorphism, suggesting that the left-lateral strike-slip shearing along the Red River fault started after ~21 Ma.

Boitite and muscovite K-Ar and 40Ar/39Ar ages from the Gaoligong mylonitic shear zone range from 32 Ma to 11 Ma (Wang and Burchfiel, 1997; Ji et al., 2000a; Wang et al., 2006), which is interpreted as representing the duration of fault movement. Although this shear zone displays characteristics of right-lateral slip, it is petrographically...
apparent that these deformational features are rather late. Note that most biotite and amphibole for Ar-Ar dating, as described by Ji et al. (2000a,b) and Wang et al. (2006), are deformed porphyroclasts in mylonites, similar to those described above in Figs. 2 and 4. Petrographically, they are apparently generated by regional orogenic metamorphism prior to mylonization, and thus cannot represent ages of strike-slip shear zones. The Sagaing Fault, the west boundary fault of the Indochina continent, was active no earlier than 15 m.y. (Morley et al., 2001; Replumaz and Tapponnier, 2003), which places a constraint on the timing and scale of southeastward extrusion. In this context, it is important to note that there is no experimental proof that strike-slip shearing is an effective mechanism to cause anatexis and granitoid magmatism. All these observations and reasoning support our interpretation that the pre-22 Ma tectonism in this region was mostly predominated by vertical thickening.

The Gaoligong shear zone is only an internal fault within the NIC. Granitoid intrusions along the Gaoligongshan magmatic belt, as well as the Paleozoic strata, are cut and deformed by the Gaoligong shear zone and by later brittle faults without significant displacement (see Fig. 1b). The intense isoclinal folding and the development of vertical axial-plane schistosity with the accompanied regional medium- to high-grade metamorphism (Fig. 4) are strong evidence for crustal shortening and thickening as a result of the persistent northward compression of the Indian Plate. Such strong crustal shortening explains (1) clockwise rotation of Indochina around the Eastern Himalayan Syntaxis as revealed by the Tertiary paleomagnetic data from the northwestern Yunnan (Sato et al., 2001), which continues to the present as shown by the GPS data (e.g., Wang et al., 2004); (2) rapid underthrusting (Paleocene sediments down to depths of 25–30 km at ~22 Ma), high-grade metamorphism and related anatexis before ultimate exhumation to the surface in the NIC region; and (3) separation of the Indochina continent from the Lhasa Block around the Eastern Himalayan Syntaxis.

8. Conclusion

(1) The northern Indochina continent (NIC, including the Gongshan, Tengchong, and Baoshan blocks) near the Eastern Himalayan Syntaxis has the affinity with the Lhasa Block in southern Tibet. They may possess the same early Precambrian basement and have shared the same or similar multiple granitic magmatic events from the Neoproterozoic, early Paleozoic, Triassic, Cretaceous, and to the Cenozoic.

(2) Continued northeastward convergence of the Indian Plate led to significant crustal thickening in the NIC during the period of ~53–22 Ma, which involved rapid underthrusting of the Paleocene to Eocene sediments to depths of 25–30 km. Deep crustal high-grade metamorphism and anatexis produced the present-day observed metamorphic rocks and granitic intrusions in the NIC.

(3) Continued northeastward convergence of the Indian Plate and the resistance at the Eastern Himalayan Syntaxis resulted in the clockwise rotation and physical separation of the Indochina continent from the Lhasa Block.

(4) Gaoligongshan magmatic belt is the southern/eastern continuation of the Gangdese magmatic belt although the magmatism continued independently in the past ~30 m.y. since their separation.

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References


Fig. 12. Representative CL images for zircons from Cenozoic granite in the southern segment of the Gongshan block. (a) Leucogranite NJ66; and (b) tourmaline granite ST122.

Fig. 13. Comparison of zircon U-Pb age spectra on samples from the Himalayan Orogenic Belt (DeCelles et al., 2000), Lhasa Block (Hu et al., 2004; Kapp et al., 2005a,b; Guynn et al., 2006; Yang and Li, 2006; Duo et al., 2007) and Gongshan block of the NIC. Stars with black circles indicate intrusive bodies.


