Intra-continental transpression and gneiss doming in an obliquely convergent regime in SE Asia

Bo. Zhang¹, Zhi. Chai¹, Cong. Yuan. Yin¹, Wen. Tao. Huang², Yang. Wang¹, Jin. Jiang. Zhang¹, Xiao.

Xian. Wang³, Kai Cao⁴

¹ The Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, China.

² Geosciences department, University of Arizona, Tucson 85716, USA.

³ Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, China.

⁴ School of Earth Sciences, China University of Geosciences, Wuhan 430074, China.

Corresponding author: Bo Zhang (geozhangbo@pku.edu.cn).

Abstract:

The Tengchong terrane comprises a sequence of linear dome-like zones, cored by granite and migmatitic layers. These cores are mantled by predominantly gneiss and subordinate schist sequences, decreasing in deformation intensity outward from extensive mylonitization to weak mylonitization. The pre-doming deformation was characterized by the formation of large-scale top-to-the-east shearing (D1) in the gneiss terrane, locally preserved flat-lying foliation (S1), weak folding (F1) and emplacement of the Mangbang granite during the Cretaceous (114-104 Ma). The second stage of deformation (D2) consisted of map-scale east-verging folds (F2, dome amplification) and minor lateral strike-slip shear zones between the anticlines in the gneiss and migmatitic sequences. Extensive partial melting and emplacement of 67-30 Ma synkinematic granitoid bodies/veins occurred, leading to the emplacement of wedges of granite into the easterly directed F2 fold cores. These wedges formed kilometer-scale granitoid domes. The post-doming D3 deformation with transpression recorded strain partitioning with simple shear-dominated high-strain zones along the Gaoligong and Nabang dextral lateral strike-slip shear zones (active during 30-11 Ma). Late transtensional deformation (D4) during cooling of the entire terrane involved the localized low-temperature Gaoligong west and east detachment faults that controlled the late exhumation of the Gaoligong metamorphic zone (since 10 Ma). Our structural observations, combined with previous studies, suggest that this style of doming is a representative type of intra-continental deformation in the Cenozoic during the oblique India-Asia collision. The actual dome shapes reflect formation of antiforms during compression-dominated transpression, prior to localized strike-slip shearing, in the accommodation belt around the Eastern Himalayan Syntaxis. Vertical exhumation of crustal material by contractional doming played an important role in absorbing the vast majority of the internal deformation of crustal fragments during oblique collision.

Keywords: Tengchong, dome, oblique collision, Cenozoic, strike-slip shear zone, transpression

1. Introduction

Intra-continental deformation and metamorphism are related to crustal thickening, crustal thinning, exhumation of high-grade metamorphic rocks, and basin formation during the terminal stages of continental collision (Davis et al., 1986; McDonough and Simony, 1988; Lee et al., 2004; Faure et al., 2005; Charles et al., 2009). Most of these processes involve ductile deformation, such as large-scale ductile shear zones in the crystalline basement, which weaken the crust (Davis et al., 1986; Leloup et al., 1995). Zones of crustal weakness, combined with the effects of ductile layers, commonly contribute to the rapid exhumation of structurally deep layers (Leloup et al., 1995; Yin, 2004; Rosenberg and Handy, 2005; Searle, 2013). Gneiss and granite domes are classic structures for exposed continental middle crust in the thickened crust of orogenic belts (e.g., Brun, 1980; Burg, 1987; Kapp et al., 2000; 2003; Teyssier and Whiney, 2002; Whitney et al., 2004). The cores of gneiss domes can be differentially exhumed relative to surrounding host rocks (Whitney et al., 2004). They are composed of a core of high-grade metamorphic or plutonic rocks mantled by upper crustal rocks (Burg, 1987; Teyssier and Whitney, 2002; Kapp et al., 2003; Yin et al., 2004). An elliptical shape in map view is a common feature of gneiss or granite domes, whose long axes tend to parallel the axial trend of the orogenic belt. Large-scale folds often characterize the internal portions of the domes, and their borders are defined by shear zones at various scales (e.g., Davis et al., 1986; Faure, 1995; Whitney et al., 2004).

The origin of gneiss domes are still extensively debated because a given dome geometry may result from different mechanisms (e.g., Coney, 1980). Several emplacement mechanisms are proposed, including: (1) shortening resulting in duplex structures and/or folding interference (e.g., Ramsay, 1967; Burg et al., 2004; Zhang et al., 2014); (2) diapirism driven by buoyant upwelling with inversion of the rock densities due to melting of granitic basement (e.g., Brun, 1981; Teyssier and Whitney, 2002; Whitney et al., 2004; Xu et al., 2015); (3) tectonic denudation localized along major shallowly dipping extensional detachments (Davis and Coney, 1979; Lee et al., 2004) or isostatic rebound caused by extension along a large-scale detachment (Axen et al., 1995); (4) duplex-related folding (Yin, 2004); or (5) some combination of these processes (e.g., Ramberg, 1980; Whitney et al., 2004; Charles et al., 2009). Nevertheless, understanding of dome structures and their roles is necessary to reveal the regional geodynamics of Archean to Phanerozoic orogens, worldwide (Whitney and Teyssier, 2004).

The Indochina block is a classic region of Cenozoic continental lithosphere deformation and localization in response to the collision of India and Eurasia (Fig. 1A). Deformation is intensively partitioned and localized along a few large-scale shear zones/faults. From east to west, these structures include the Ailao Shan-Red River, Chongshan, Gaoligong and Nabang shear zones (Fig. 1B). The Ailao Shan-Red River shear zone is a main boundary structure that separates the South China block from Indochina. The Chongshan shear zone separates the Lanping-Simao terrane and Baoshan block, and the Gaoligong shear zone lies between the Baoshan block and Tengchong

terrane (Fig. 1B). These linear boundary structures were interpreted in terms of their bulk geometries, kinematics, ages, emplacement processes, and tectonic settings, to be synchronous and accommodate the extrusion of continents (Fig. 1, 2) (e.g., Tapponnier and Molnar, 1977; Tapponnier et al., 1990; Leloup et al., 1995; Searle, 2006; Liu et al., 2012) or rotation of blocks (Wang and Burchfiel, 1997; Burchfiel and Wang, 2003; Kornfeld et al., 2014). The complete kinematics and deformation behavior over the entire intra-continent/intra-block are not well understood. Existing kinematic models are mainly derived from the data along these boundary structures, and do not effectively incorporate data from within the blocks in between. Three of these actively deforming, secondary blocks of lie in China, including the Lanping-Simao terrane, Baoshan block and Tengchong terrane (Fig. 1B). Between the Gaoligong shear zone and Nabang shear zone, the central portion of the Tengchong terrane contains a particularly well-exposed example of a regional-scale anticline (Fig. 1B, 2). It is an ideal region for tracing the intra-continental deformation and evolution in an oblique collision region. More than four gneiss/granite domes have formed during the Cenozoic in the Tengchong dome zone (Xu et al., 2015) (Fig. 2).

Fig. 1

Compared to well-documented geochemical data and structures on the boundary shear zones (Figure 2), the characterization of the gneiss, migmatite and granitic pluton that define the main dome zone of the Tengchong terrane has not been meaningfully done previously. Complex fold- and foliation-overprinting relationships in the Tengchong terrane indicate a polyphase deformation history, but the number of stages and their tectonic significance were not yet well understood.

In this study, we conduct field-based structural, kinematic analyses, and gather geochronological data to understand the structural evolution in the Tengchong terrane. Combined with previous structural and geochronological data, we discuss the kinematic evolution and emplacement mechanism of the domes in the terrane. We finally explore how intra-continental deformation and strain-partitioning might occur and play a role in an obliquely convergent regime of the India and Asia collision.

Fig. 2

2. Regional geology

The Tengchong terrane is considered a part of Gondwana during the late Paleozoic that accreted to SE Asia during the middle Mesozoic, based on the presence of glacial deposits of Carboniferous age (Wang, 1983). Abundant granitoid plutons of Mesozoic to Tertiary age are emplaced into the older rocks, and the magmatic belt is generally interpreted as the eastward continuation of the Gangdese Batholith around the eastern Himalayan syntaxis (Hou et al., 2009; Lin et al., 2012). To the southwest, the Tengchong gneiss-granite terrane transitions into the Mogok metamorphic belt in Burma (Fig. 1A). The western boundary of the Tengchong terrane was originally proposed to lie along the Indus-Tsangpo Suture Zone (ITSZ) that separates the Indian plate and the Lhasa-West Burma accreted fragments (Fig. 1A) (Wang and Burchfiel, 1997;

Searle et al., 2016). Its eastern boundary is defined as the Gaoligong shear zone, which lies both at and within the westernmost part of the Baoshan block (Fig. 1B) (Ding, 1991; Zhong et al., 2000; Ji et al., 2000; Wang and Burchfiel, 1997).

The interior of the terrane consists predominantly of ortho- and paragneisses, Meso-Cenozoic granites, rare exposures of upper Paleozoic (Devonian-Permian) weakly metamorphosed rocks, late Tertiary to Quaternary rocks (Fig. 2, 3, 4) (e.g., BGMRY, 1990; Wang and Burchfiel, 1997). The emplacement ages of the granitoid plutons in the terrane range from 128-40 Ma (e.g., Xu et al., 2008; Xu et al., 2015), suggesting a Cordilleran-style continental margin during the Late Cretaceous-early Cenozoic (Xu et al., 2012). The ortho- and paragneisses envelop these granitoid plutons and are exhumed along N- to NE-striking antiforms (Fig. 2B) (BGMRY, 1990). The high-grade metamorphic rocks are traditionally regarded as the Precambrian basement of the Tengchong Terrane (BGMRY, 1990) and yield an age range of 21-17 Ma based on $^{40}\text{Ar}/^{39}\text{Ar}$ mica cooling ages from the Mogok metamorphic belt (Bertrand et al., 2001) and 35-22 Ma from the Tengchong region (Xu et al., 2015). Their dimensions vary greatly, but large forms predominate and are approximately 30-50 km long (even reaching 60-100 km) and 10-20 km wide. Xu et al. (2015) suggested subdividing the Tengchong terrane into three tectonic units that from west to east, are the Nabang shear zone, the dome zone, and the Gaoligong shear zone (Fig. 2). The dome zone features granite cores, various-scale anticlines, and minor strike-slip shear zones (Fig. 2) (Xu et al., 2015). Rocks exhibit near-universal N-S or NE-SW striking with four domes (Fig. 2). From west to east, the Sudian, Guyong, Yinjiang, and Lianghe domes are roughly defined by the geometry of the foliations in the gneiss and granitic rock sheets. The eastern side of the dome zone is structurally limited by a brittle or brittle-ductile detachment fault known as the Gaoligong west detachment fault (GWDF) (Fig. 2, 3, 4) (Wang et al., 2008). During the late Tertiary (Miocene-Pliocene; See Wang et al., 2008), conglomerate, coarse-grained sandstone, and pelite filled the Mangbang rift basin that formed by the normal-dextral motion of the GWDF (Fig. 2) (Wang et al., 2008; Xu et al., 2015).

3. Lithotectonic units

The lithotectonic units include several kilometer-thick gneiss and granite sheets that occur in the dome zone in the interior portion of the terrane, and two large-scale boundary strike-slip zones in the east and west sides, which show spatially and temporally heterogeneous stages of deformation and metamorphism.

3.1. Gaoligong shear zone

The Gaoligong shear zone represents an important boundary between structural and metamorphic units (Wang and Burchfiel, 1997). The 5 to 8-km-wide, greater than 650-km-long mylonitic and ultramylonitic zone runs along the Gaoligong massif from the Eastern Himalayan Syntaxis in Tibet into the Burma Mogo Massif, southward close to the Sagaing zone (Fig. 1, 2) (Socquet and Pubellier, 2005; Lin et al., 2009; Zhang et al., 2014). This array of mylonites was interpreted to have developed within a ~10- to 15-km-deep zone of moderate-temperature (400-600°C) (e.g., Wang et al., 2006; Akciz et al., 2010; Zhang et al., 2012). The zone comprises

amphibolites, gneisses, migmatites and granites with a pervasive mylonitic foliation that strikes 340-020° with steep dips of 50-88° in the northern segment, shifting to NE-SW-trending foliation in the southern segment (Fig. 1A, 2). The mineral lineation plunges 5-20° (average 10°) (Fig. 3, 4). Hornblende has yielded $^{40}\text{Ar}/^{39}\text{Ar}$ dates of 32 Ma (Xu et al., 2015), whereas biotite and muscovite from the mylonites have yielded $^{40}\text{Ar}/^{39}\text{Ar}$ dates of 19-10 Ma and 22-11 Ma, respectively in the southern segment of the shear zone (Wang et al., 2006; Lin et al., 2009; Zhang et al., 2012; Xu et al., 2015).

In the Longling-Ruili-Luxi region, the shear zone consists of two faults, the GEDF and SW-striking GWDF (Fig. 2, 3, 4) (Wang et al., 2008). Based on the geological and morphological field evidence by Wang and Burchfiel (1997), the GWDF is thought to be a young normal fault. Two elongate basins developed along the fault. The northern basin, termed the Mangbang basin, contains alluvial deposits with Pliocene and middle Pleistocene ages, and the southern basin, termed the Zhefang basin, is filled with Pliocene sedimentary rocks and a thick sequence of Pliocene and lower Pleistocene volcanic rocks (Fig. 2) (Wang and Burchfiel, 1997; Wang et al., 2008). The age of the sediments and lavas implies that the detachment fault began or was active in Pliocene time (Wang et al., 2008). Fission-track dates of 8.4 to 0.9 Ma were also reported by Wang et al. (2008), indicating rapid cooling due to normal faulting since the Miocene along boundaries of the shear zone in the region.

Fig. 3

3.2. Nabang shear zone

The Nabang shear zone is exposed as a 5- to 15-km-wide and 300-km-long high-strain zone along the boundary between China and Burma (Fig. 2). This high-strain zone, within gneiss and igneous rocks, is a nearly NNE-SSW-striking structure composed of several tectonic units with distinct associations of heterogeneously sheared and metamorphosed rocks (Fig. 2) (Zhong, 2000). The mylonitic foliation has a prominent, gently-to-steeply plunging (average 15°) mineral stretching. The zone is dominated by amphibolite-facies gneisses with minor mica schists, quartzites and marbles. A metamorphic basalt with granulite-facies metamorphic grade (750-860°C, 0.8-1.0 GPa; 76-74 Ma based on $^{40}\text{Ar}/^{39}\text{Ar}$ dates by Zhong et al., 2000; Ji et al., 2000) was reported in the zone. Ji et al. (2000) suggested that the zone experienced two metamorphic events. The early metamorphism was a granulite-facies event and the later metamorphism was an amphibolite-facies event. Development of mylonitization in the amphibolites, quartzofeldspathic gneisses, mica schists and marbles is associated with low-pressure (0.6-0.8 GPa) and medium- to high-temperature (720-640°C) metamorphism (Ji et al., 1998; 2000; Xu et al., 2015). $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende dating ranged from 33 to 19 Ma for the mylonitic gneiss (Xu et al., 2015), indicating dextral strike-slip shearing since Oligocene.

3.3. Dome zone

Four key structures, the Sudian, Yinjiang, Guyong, and Lianghe domes, are well exposed in the terrane (Fig. 2). These domes originated as N-S- to NE-SW-elongated dome shapes, which are separated by narrow, shear zones, such as the Sudian, Yinjiang, and Lianghe shear zones (Fig. 2, 3,

4). These domes appear to be roughly defined by concentric envelopes of augen gneiss, migmatites, and anatectic granite from rim to core. However, just south of the Yinjiang-Lianghe-Longling region, the dome systems and high-strain shear zones become NE-SW striking (Wang and Burchfiel, 1997; Wang et al., 2008).

3.3.1. Granite and migmatite core

The cores of the Sudian, Yinjiang, Guyong, and Lianghe domes mainly consist of migmatites and granite (Fig. 2). Gneiss sheets 4-10 km thick structurally mantle the granitic cores. Toward the granitic core, migmatites and migmatitic gneisses progressively grade into the anatectic granite (Xu et al., 2015). Zircons from the granite in this terrane yield U-Pb chemical ages of 120-110 Ma in the Longling-Lianghe region, 75-60 Ma in the Guyong-Yinjiang region, and 60-40 Ma in the Sudian-Nabang region (e.g., Xu et al., 2012; Li et al., 2012; Ma et al., 2013; Tan et al., 2013). These age sequences indicate southwestward magmatic migration in the Tengchong terrane. Similar Early Cretaceous plutons and dykes have also been reported in the Mogok metamorphic belt (Mitchell, 1993; Searle, 2006). Therefore, the Gangdese magmatic arc, the Tengchong terrane, and the Mogok metamorphic belt were structurally linked since the Early Cretaceous (Zhong, 2000; Xu et al., 2015).

3.3.2. Basement gneiss

The basement rocks are mainly composed of orthogneiss, paragneiss, migmatitic gneiss, and augen granitic gneiss. The pelitic paragneiss has heterogeneous textures with well-defined mineralogical banding, and consists of garnet-biotite-sillimanite-quartz-plagioclase. The orthogneisses vary in composition from hornblende-biotite granodiorite to biotite granodiorite to leucocratic monzonite with homogeneous fabrics that are locally obscured by migmatization and abundant injection of leucogranitic veins (Fig. 2, 3, 4). Close to the cores of granite, extensive migmatization formed 5-100-cm leucocratic layers in the more mafic-rich gneisses. Several generations of leucocratic veins, sills and dikes are deformed parallel to or crosscut the foliation of the gneisses. Sills may have indistinct boundaries that can be traced continuously into dikes that clearly were intruded along structural planes. An augen orthogneiss yields zircon U-Pb ages of 450-500 Ma, interpreted as the post-Pan-African magmatic event (Song et al., 2007; Liu et al., 2009). Therefore, we interpret that the Tengchong gneiss terrane are not a totally Precambrian basement covered by a Paleozoic series.

An earlier medium-pressure metamorphic event is documented by the rare occurrence of granulite-facies relics seldom preserved in amphibolite blocks in the gneiss in the Nabang region (Ji et al., 1998). The migmatization preserves a metamorphic history evolving of medium-pressure granulite-facies conditions evolving to retrograde metamorphism defined by newly grown plagioclase and amphibole textures (Ji et al., 1998). The P-T conditions of the migmatitic gneiss formation, calculated using the Garnet-CPX geobarometer combined with the garnet-CPX-plagioclase-quartz geobarometer, indicate peak metamorphic conditions at 750-860°C and 0.8-1.0 GPa, followed by lower P-T retrogression to 640-720°C and 0.59-0.80 GPa (Ji et al., 1998).

4. Structures and kinematics

Despite the intense weathering and vegetation in the region, newly built roads provide relatively well-exposed outcrops across the Tengchong dome zone. The following observations and analysis depend extensively on the six cross-sections (Fig. 2, 3, 4), supplemented by scattered outcrops along the rivers.

4.1. Top-to-east shearing of deformation D1

In this study, D1 was responsible for top-to-the-east shearing and folding (F1), that is preserved only locally (Fig. 2). The S1 fabric and lithological contacts are concentrically preserved, roughly defining a 100 X 150 km area in the Longchuan-Ruili-Luxi region (called Domain-1, Fig. 2, also see sections V-V' and VI-VI' in Fig. 4, 5), characterized by a weakly folded surface/gneissosity with a NE-striking hinge (Fig. 2, 4, 5).

The S1 fabric is well developed and characterized by a gneiss/migmatitic gneiss foliation that is moderately steep (10-50° to the NW and SE) near the contact with the granite sheets and locally steeper at 50-75° to the SE (section III-IV in Fig. 5B). The gneissosity becomes progressively shallower (dipping from 5°NW to 25°NW) or subhorizontal toward the central parts of Domain-1 (Fig. 4, 5). The pervasive foliation is expressed by compositional layering and the grain-shape preferred alignment of all mineral components in the metasedimentary rocks and amphibolite, and by quartz and feldspar ribbons or bands or foliation-parallel oriented leucosomes in the migmatites (Fig. 6A, C, D). In some sites, compositional bands are developed parallel to S1 (Fig. 6C, D). S1 is associated with a prominent mineral stretching lineation (L1 in Fig. 6B) that exhibits very consistent NE or NNE plunges of 10°-25°, regardless of the orientation of the folded S1 surface throughout Domain-1 in the Longling-Ruili-Luxi region (Fig. 4, 5A, B). L1 is well defined by amphibole-plagioclase aggregates in amphibolites (Fig. 6A), quartz-feldspar aggregates in the gneiss (Fig. 6D).

Fig. 4

Kinematic indicators, including abundant millimeter-scale rotated feldspar porphyroclasts, asymmetric porphyroblasts, and S-C fabrics occur in the amphibolites and gneiss, support an interpretation of a top-to-the-northeast sense of shear (Fig. 6C, D). These kinematic indicators are consistent with the kinematics interpretation for the boudinaged leucogranitic veins and Z-type granitic veins (Fig. 6A, D).

Fig. 5

Fig. 6

4.2. Doming of deformation D2

The D2 deformation dominates the outcrop patterns and mesoscopic structures for much of the terrane via the major regional folds, F2, and the major regional gneissosity, S2 (Fig. 2, 3, 4). D2 refolded the S1 foliation in Domain-1. The transition from D1 to D2 structures is sharply marked by the boundary along the Lianghe shear zone, where the flat-lying S1 fabrics are overprinted by a penetrative moderately to steeply dipping foliation, S2 (Fig. 2, 5A, B). The S2 fabric is dominantly displayed in the Sudian, Yinjiang, Guyong and Lianghe domes (Fig. 2, 3, 4).

4.2.1. The Sudian dome

In the Sudian region, metamorphic rocks show well-defined foliation (S₂) (Fig. 2, 3, 7A). The S₂ foliation strike is relatively constant: N-S with local variations (Fig. 2). The S₂ foliation is roughly parallel to the long axis direction of the Sudian granite. They commonly dip moderately to the E along the W flank of the Sudian granite (see the I-I' section in Fig. 3), and to the W along the W and E flanks of the Sudian granite (across the II-II' section in Fig. 3). Dips of the S₂ foliation in the region are more variable: gentle-to-steep along section I-I', and flatness along section II-II'' (Fig. 3). The Sudian geometry of the S₂ foliation thus is similar in shape to a domal structure, in which the Sudian granite is mantled by the ductile fabrics S₂. At the eastern limb of the Sudian dome, mylonitic foliation (S₂) is steep, and dipping toward the W to define the dextral strike-slip Sudian shear zone (Fig. 7D), which separates the Sudian dome in the west from the Guyong dome to the east (Fig. 2, 7).

4.2.2. The Guyong dome

In the Guyong region, gneiss shows well-defined foliation (S₂) (Fig. 2, 3, 7B). The S₂ foliation strike is N-S (Fig. 2, 3). They commonly dip moderately or steeply to the W along the E and W flanks of the Guyong granite core (see the I-I' and II-II' sections in Fig. 3). Regionally, the strike of the S₂ foliation and plane is parallel to the long axis direction of the Sudian granitic sheet (Fig. 2). Dips of the granitic flow plane and weakly-deformed foliation (S₂) in the core granite are more variable: gentle-to-steep in the east limb of the granite (Fig. 7B), and flatness on the top of the Guyong granite (see the section II-II' in Fig. 3). The Guyong geometry of the S₂ foliation defines a domal structure, where the Guyong granite is mantled by the S₂ foliation.

4.2.3. The Yinjiang dome

In the Yinjiang region, metamorphic rocks show well-defined foliation (S₂) (Fig. 2, 4). The S₂ foliation strike varies from: NE-SW across the V-V' section to NEE-SWW across the VI-VI' section (Fig. 4). These foliations commonly dip moderately to the W and NNW along the WN and SE flanks of the Yinjiang granite (Fig. 2, 4). The S₂ foliation is roughly parallel to the long-axis direction of the Yinjiang granitic sheet. The geometry of the S₂ foliation defines a domal structure around the Yinjiang granite, where the granite core is mantled by the S₂ foliation. Along the eastern side of the granite core, the massif is limbed by the Sudian shear zone, which also separates the Yinjiang dome from the Lianghe granite (Fig. 2). The west boundary of the Yinjiang dome is defined by the dextral strike-slip Nabang shear zone (Fig. 2, 4).

4.2.4. The Lianghe dome

In the Lianghe dome, gneiss and granite present a well-defined foliation (S₂) (Fig. 2, 4, 7C). The S₂ foliation strike is relatively constant: NE-SW (Fig. 4), roughly parallel to the long axis direction of the Lianghe granitic sheet (Fig. 2). They commonly dip moderately to the SE or NW along the E flank of the Lianghe granite core (see the V-V' and VI-VI' sections in Fig. 4). The core granite contains a pervasively mylonitic foliation that is parallel to S₂ gneissosity in the mantled gneiss (Fig. 7C). The Lianghe geometry of the ductile S₂ fabric defines a NE-SW striking domal structure, in which the Lianghe granite is mantled by the S₂. The west boundary of the Lianghe dome is

defined by the sinistral strike-slip Yinjiang shear zone (Fig. 2, 4, 7E). Along the eastern side of the dome, the dextral strike-slip Lianghe shear zone separates the dome from the Domain-1 (Fig. 2, 4, 5, 7F).

Based on the observations across the four domes, the main D2 structures are a series of variously sized folds (F2) associated with S2 gneissosity and mylonitic foliation, formed by inter- and intra-layer shearing, including: (1) centimeter-, meter- and kilometer-scale open to asymmetrical anticlines with west-dipping axial surfaces (east-verging kinematics) (Fig. 3; 4); (2) small-scale asymmetric folds in the migmatitic gneiss and granitic gneiss (Fig. 7A, B, C). Regionally, these asymmetric anticlines and minor folds consistently indicated a top-to-the-east shearing in the dome zone (Fig. 2, 3). Kinematic indicators, such as asymmetric porphyroclasts, S-C fabrics, rolling porphyroclasts in the deformed granite, also suggest a top-to-the-east sense of shear for the D2 deformation (Fig. 7B, C).

Fig. 7

4.3. Simple strike-slip shearing of deformation D3

D3 structures are characterized by a N-S trending or NE-SW trending, vertical mylonitic foliation, S3, which is associated with lateral strike-slip shearing along the Nabang and Gaoligong shear zones (Fig. 2, 3, 4). The granitoid gneisses immediately west of the Sudian and Yinjiang domes show two crosscutting fabrics (Fig. 3, 4). A moderately to steeply northwest-dipping and partly migmatitic planar fabric (S2) is extensively modified by subvertical mylonitic foliation (S3) (the section II-II' in Fig. 3, the sections V-V' and VI-VI' in Fig. 4). Due to its orientation and migmatitic nature, relics of the moderate to steeply northwest-dipping foliation are interpreted as the S2 fabric (Fig. 3, 4, 8A). The crosscutting fabric, termed S3, developed under greenschist- and amphibolite-facies conditions, as documented by the ductile deformation of feldspars in the Nabang strike-slip shear zone (Fig. 8B). Along the Gaoligong massif, towards the east and southeast, a gradual transition of the D1 or D2 fabrics into the subvertical orientation of the mylonitic S3 foliation has been identified (Fig. 3, 4, 5, 8C).

The lineation L3 is horizontal or subhorizontal (Fig. 3, 4, 8B, C). Rotated asymmetric K-feldspar porphyroclasts, S-C fabrics, and objects in the mylonitic orthogneisses generally record a dextral sense of shear in the Gaoligong (Fig. 8C) and Nabang zones (Fig. 8B).

4.4. Detachment faulting of deformation D4

Numerous discrete shear zones/faults, featuring brittle-ductile deformation, formed parallel to or cutting the subvertical S3 ductile fabric along the western and eastern boundaries of the Gaoligong shear zone (Fig. 2, 3, 8D, E). The detachment faults with a normal-slip component (Fig. 8D, E) controlled the formation of the Mangbang basin and Zhefang basin (Fig. 2, sections II-II', III-III' and IV-IV' in Fig. 3, section VI-VI' in Fig. 4). The detachment fault marks a clear metamorphic boundary between the Tengchong gneiss sequences above and the Paleozoic-Mesozoic sedimentary sequence below (Fig. 2, 3). Along the Longling-Luxi-Ruili valley, late Paleozoic-Mesozoic sequences are overlain by the mylonitic gneiss (D3 fabrics) along the GEDF (D4 fabrics) (see sections II-II', III-III', IV-IV' in Fig. 3). In the Longling region, the southeastern part

of the Luxi granite and Cambrian rocks was cut by the GEDF (Fig. 2, section VI-VI' in Fig. 4). Based on the map, the GWDF may continue to the NNE, cutting the shear zone and merging into the GEDF in Longling region (Fig. 2).

Fig. 8

5. Microstructures

5.1. Granoblastic fabrics of the gneiss

Most gneisses in the Tengchong terrane preserve a typical granoblastic fabric (S1-S2) in the major mineral grains, where the medium- to coarse-grained, inequigranular to equigranular, granoblastic elongate mineral grains have well-developed crystal faces, commonly straight or slightly bent grain boundaries and very common triple junctions (Fig. 9A-D). Triple point junctions, indicating an approach to microstructural equilibrium by annealing, are distinctive in some sections (Fig. 9B). Internally, the quartz grains are commonly strain-free and display straight extinction under the microscope (Fig. 9B-D). Feldspars and quartz tend to form networks of equidimensional grains (Fig. 9D), and micas form oblong shapes isolated between quartz and feldspar grains (Fig. 9A, C, D). A prominent foliation defined by anastomosing biotite intergrowths surrounding variably recrystallized porphyroclasts of potassium feldspar also is ubiquitous (Fig. 9A, C, D). These granoblastic fabrics are interpreted to have developed in high-grade metamorphic conditions where recrystallization and diffusion processes can proceed relatively quickly (Passchier et al., 1990; Miller and Paterson, 1994).

5.2. Solid-state fabrics in the transition layers between granite and gneiss

The gneisses close to the granite plutons exhibit well-developed solid-state deformation fabrics under the microscope (Fig. 9E-I). Microstructural changes include the development of shape preferred orientations accompanied by the moderate internal deformation of crystals in the granite (Fig. 9E-J). The quartz grains are elongated or are partly consumed by fine recrystallized grains organized in ribbons (Fig. 9E, F, H, J). Serrated grain boundaries (Fig. 9G) and numerous recrystallized grains (Fig. 9F, H, I) suggest bulging and/or subgrain rotation and dynamic recrystallization (at temperatures ranging from 400-500°C; Law, 2014) during crystal plastic deformation of the quartz grains in the transition position between the granite and mantle gneiss. Some lobate shapes (Fig. 9E) are developed in local areas, implying a high mobility of quartz boundaries and a high temperature of deformation by grain boundary migration recrystallization (approximately 500-650°C or greater; Passchier et al., 1990; Law, 2014) in the layer in the transition layers between the Lianghe granite and gneiss mantle (Fig. 9E, location in the section I-I' in Fig. 3). A preferred orientation of elongated biotites commonly defines a mineral lineation (L2) or foliation (S2) in the transition layers (Fig. 9E, G, H, I). Kinematic indicators, including mica fish, rolling quartz grains and asymmetric plagioclases, indicate a top-to-the-east shearing (Fig. 9E-I). These microstructures of the contact layers indicate that high-strain shearing and strain localization occurred under medium- to high-temperature conditions between the gneiss and granite during the D2 deformation in the domes.

5.3. Slight solid-state fabrics in the granite

Slight solid-state deformation microfabrics are locally present in the granite cores (Fig. 9K, L-N). The magmatic fabric is locally or slightly overprinted by solid-state deformation in the form of discrete shear bands/layers with no obvious textural heterogeneities. Microstructural differences occur along or within the development of a weak foliation (S2), defined by a slightly planar (S2) or planar-linear orientation of feldspar porphyroblasts and mica (Fig. 9K, L, M). Newly recrystallized and fine quartz grains formed in some micro-domains (Lower-left in Fig. 9L), which suggests that the strain localization occurred via a dynamic recrystallization process. Some subhedral feldspar crystals exhibit myrmekite structures and weakly undulatory extinction (Fig. 9K). These microstructures of the major minerals indicate a superimposed process of high-temperature magma crystallization and a transitional rheological state between magmatic and solidus states (Miller and Paterson, 1994).

5.4. Magmatic microstructures in the granitic core

In the core granite, microfabrics of quartz grains are characterized by magmatic fabrics, including anhedral, planar boundaries, weak undulatory extinction, and incipient chessboard extinction (Fig. 9O-S). A few plagioclases exhibit oscillatory zoning and present euhedral crystals (Fig. 9R). Feldspar grains record magmatic fabrics rather than ductile deformation features (Fig. 9O, P). Biotite fragments are euhedral, commonly located as isolated grains in the matrix of quartz and feldspar with magmatic microstructures (Fig. 9R, S). All these microstructures indicate that the major minerals formed during high-temperature magma crystallization in the granitic plutons.

Fig. 9

6. Geochronology of syntectonic granite veins

We present new U-Pb isotopic data from LA-ICP-MS analyses that provide age constraints on the magmatism and deformation associated with the development of the Tengchong dome zone. The U-Pb analytical procedure and all analytical data are provided as an electronic supplement (Appendix A). The samples from veins provided better age constraints on the magmatic and structural evolution within the terrane. Two samples were from Domain-1, and five samples were from the domains of the D2 deformation (Fig. 2).

6.1. Synkinematic granitic veins in Domain-1

Sample GLG-084 was taken from a boudinaged granitic vein preserved within augen gneisses in Domain-1 close to GLG-082 (Fig. 10). These leucogranitic sills/veins intrude K-feldspar augen orthogneiss. They are strongly folded, boudinaged, and mostly parallel to the shallowly dipping S1 foliation in the host gneiss (Fig. 10A, B). These veins clearly crosscut S1 metamorphic fabrics in some places but elsewhere in the same outcrop appear to be parallel to the S1 gneissosity (Fig. 10A, B, D, E). The structures (GLG-082 and GLG-084) are characterized by synkinematic granitic veins during the D1 deformation. The crosscutting veins (GLG-084) and boudinaged veins (GLG-082) were dated and are interpreted to have intruded mainly during the latest stage of D1 deformation.

The zircon grains are commonly euhedral, up to 250 μm in size in sample GLG-084. They are

characterized by moderate to low luminescence with variable internal zoning patterns, such as oscillatory zoning and slight homogeneity (Fig. 10C). Patchy zoned domains are characterized by weakly or moderately luminescence. Their rims are typically euhedral, but show localized rounding of terminations. Oscillatory zones on the tips were analyzed. The spots in the oscillatory zoned rims yielded approximately three distinct populations: one along or near the concordia curve with an age of approximately 99 Ma, and the other two with ages of approximately 104 Ma and 108 Ma (Fig. 10C). The average ages are 99.3 ± 1.1 Ma, based on three data points (MSWD = 0.34); 104.8 ± 1.2 Ma, based on five data points (MSWD = 1.50); and 108.8 ± 1.2 Ma, based on four data points (MSWD = 0.34). The oscillatory zones rims, where the analyses were performed, are characterized by generally high Th/U ratios (between 0.14 and 1.10). The nature the analyzed zircon rims indicates crystallization from a melt. Therefore, the mean ages (108-99 Ma) are interpreted as the crystallization ages of the granitic veins, i.e., the intrusion age of the granitic veins in the host magma during the Cretaceous.

Zircon grains collected from GLG-082 are mostly transparent, euhedral, and approximately 150-100 μm in size. Their internal textures feature strong oscillatory zoning with variable luminescence typical of a magmatic origin, and thin black-gray oscillatory zoned rims (Fig. 10F). The oscillatory zoned rims were analyzed and yielded an average age of 114.2 ± 0.70 Ma and high Th/U ratios (between 0.07 and 0.45, most ratios > 0.10) based on twelve data points (MSWD = 0.40). Therefore, the mean age (114 Ma) is interpreted as the crystallization age of the granitic veins (GLG-082).

The results for two samples from synkinematic granitic veins produced a range of ages from 114 to 99 Ma (1 σ), which is interpreted to represent the ages of zircon crystallization in the host magma during the D1 deformation in the Late Cretaceous.

Fig. 10

6. 2. Deformed granitic veins in the D2 domain

Five samples (GLG-094, GLG-076, GLG-067, GLG-056, and GLG-057) were taken from boudinaged granitic veins that were preserved within the gneisses with the D2 fabrics in the domes. The sampling locations, structures of the veins, zircon morphologies and analytical results are listed in Fig. 11A-D, and Fig. 12A-E. The host migmatitic gneiss or gneiss presents well-developed mylonite fabrics and clearly contains boudinaged leucogranites (Fig. 11A, C; Fig. 12A, C). The granitic veins of the five sampling sites show similar structures and are all thin, strongly folded, and boudinaged with the S2 foliation in the host gneiss. Careful observation revealed weakly ductile fabrics in these sills, implying pre-kinematic intrusions (Fig. 11A, C, 12A, C). At the sampling sites of GLG-094, GLG-056 and GLG-076, granitic veins are clearly parallel to the S2 foliation, but leucosome sills elsewhere in the same outcrop locally crosscut S2. We interpret these granites veins as having intruded during or after the formation of the S2 foliation.

The euhedral to subhedral zircon crystals separated from GLG-094 are characterized by transparent, and length-to-width ratios from 3:1 to 1.5:1. Most crystals have concentric oscillatory zoning in their relict cores (Figure 10B). Recrystallized zircon rims with prominent high

CL intensities are around the relict cores of the crystals. Patchy structures are common in the low-CL cores (Fig. 11B), suggesting that these inherited cores were most susceptible to recrystallization during the post-metamorphic event (Pidgeon et al., 1998). Our analyses yielded a relatively wide range of Th/U ratios (0.07-0.20, with 13 analyses yielding relatively low ratios of 0.06-0.09) and an age range of 32-30 Ma for these rims (Fig. 11B). Zircon grains separated from other four samples (GLG-076, GLG-067, GLG-056, and GLG-057) are transparent, euhedral, and approximately 150-250 μm in size. Their oscillatory zoned rims (GLG-067 and GLG-057) and patchy structure rims (GLG-076 and GLG-056) were analyzed (Fig. 11D, 12B, 12D). These analyses yielded a relatively wide range of Th/U ratios of 0.01-0.73 and an age range of 42-37 Ma for GLG-076 (Fig. 11D), Th/U ratios of 0.10-1.91 and an average age of 67.20 ± 0.10 Ma for GLG-067 (MSWD = 0.2) (Fig. 12B), Th/U ratios of 0.20-1.15 and an average age of 60.30 ± 0.46 Ma for GLG-056 (MSWD = 0.2) (Fig. 12E), and Th/U ratios of 0.12-0.94 and an average age of 54.60 ± 0.29 Ma for GLG-057 (MSWD = 0.5) (Fig. 12D).

The results of the five samples produced a range of ages from 67 to 30 Ma (1σ), which are interpreted to represent synkinematic granitic emplacement mainly during D2 deformation.

Fig. 11

Fig. 12

7. Discussion

7.1. Structural and geometric evolution

The preservation of the D1 domain in the terrane west of the Gaoligong shear zone is key evidence that the evolution of the moderately or steeply west-dipping gneissosity defined the fabrics (S2) of the D2 deformation, reworking the pre-existing S1 gneissosity and migmatitic foliation. On the basis of the large scale of the gentle fabrics S1 and L1, it seems reasonable that stage D1 folding is characterized by a large wavelength (possibly 40-50 km). The various-scale kinematic indicators document a major top-to-the-east shearing in Domain-1. The quartz CPO patterns show the dominant activation of prism $\langle a \rangle$ slip and prism [c] slip in the mylonitic gneiss of Domain-1 (Xu et al., 2015), indicating deformation/metamorphism at medium-to-high temperatures (400-650°C).

The regions where S2 planes can be observed show dome shapes, and their cores correspond to granite or migmatitic extrusion, giving rise to thermal metamorphism to some extent. Asymmetric folds striking N-S and NE-SW are compatible with overall top-to-the-east/northeast motion (Fig. 2). The shape of the domes is characterized by a N-S- and NNE-SSW-elongated long axis compatible with approximately E-W shortening. The development of steep or moderate west-dipping S2 foliations coincided with the emplacement of foliation-parallel granite/leucosomes in all lithologies in the Sudian, Guyong, Yinjiang and Lianghe domes (Fig. 2, 3, 4). Moreover, in the Sudian dome, a weak N-S down-dip lineation (granitic flow lineation) is preserved in the granite and is associated with top-to-the-north and top-to-the-south senses of shear in the northern and southern ends of the dome, respectively (Fig.2). This kinematic pattern suggests that the development of the gneiss dome was originally coupled with the interference

between upward/inflating diapirism controlled by granite emplacement and a regional strain field characterized by N-S stretching and E-W shortening, accommodated by lateral movement. Further, flow foliation, weakly-deformed plane in granites is roughly parallel to the S2 gneissosity in the Sudian, Guyong and Lianghe domes (Fig. 7A-C). Migmatite and granite dominate the central domains of the domes. These granites are exposed in N-S or NE-SW elongated sheet-like shapes, which are roughly parallel to and consistent with the S2 foliation and F2 axial plane trends, implying harmonious emplacement along the S2 fabric. At the contact between the gneiss and the granite, the granitic rocks are characterized by weakly developed solid-state deformation fabrics and flow planes (S2), roughly associated with top-to-the-NEE shearing in the Guyong and Lianghe domes (Fig. 7B, C). These findings suggest that vertical exhumation of structurally deep units (gneiss and granite) may have occurred at the same time as the horizontal translation to the east in a transpressional setting across a wide region of the terrane. Therefore, D2 deformation may have been initiated in a transpressive setting, resulting in the vertical protrusion of wedges of basement gneisses, migmatitic gneisses, and granites into the overlying rock sequence.

Stage D3 deformation becomes more localized in style with decreasing structural depth. More precisely, F2 or F1 folds were completely replaced by the vertical mylonitic foliation S3, and large amounts of strain were localized along the dextral strike-slip Gaoligong shear zone and Nabang shear zone. Late D4 deformation occurred via brittle-ductile or brittle detachment faulting in an extensional or transtensional setting between 10 Ma and the present (Wang et al., 2008), which has contributed to the exhumation of the Gaoligong metamorphic rock zone.

7.2. Chronology of the units

7.2.1. Pre-doming plutonism

The elongated kilometer-scale pluton (Mangbang granite) with well-defined borders intruded the migmatites and gneisses in Domain-1 (Fig. 2). The magmatic planar features of the pluton show continuity with respect to the migmatitic foliation or gneissosity (S1 foliation). In map view, the margins of the pluton are at right angles or parallel to the S1 foliation of the country gneisses (Fig. 5). In outcrops, the Mangbang granitic pluton and the numerous granitic veins (such as at stations GLG-084 and GLG-082) that cut across the Domain-1 migmatites/gneisses or are parallel to the host gneiss segments indicate that the pluton was emplaced during the late stage of the development of the D1 deformation or simultaneous with the D1 deformation (Fig. 10 A, D). Zircons from the major Mangbang pluton yield chemical U-Pb LA-ICP-MS ages of 121-115 Ma (Xie et al., 2010; Tan et al., 2013). The synkinematic granitic veins have ages of 114-104 Ma from the zircon U-Pb ages in this study. Therefore, this plutonism can be considered a syn-D1 to slightly prior to D1 event (Fig. 13).

7.2.2. Syn-doming plutonism

The zircon U-Pb dating method was applied to date plutonism in the dome zone (Fig. 13), which yielded ages of 76-65 Ma around the Guyong pluton (Xu et al., 2012), 66-50 Ma in the Sudian pluton (Xu et al., 2012), 65-52 Ma in the Yinjiang pluton (Xu et al., 2012; Ma et al., 2013), and 55-40 in the Nabang region (Xu et al., 2012; Ma et al., 2013; Xu et al., 2015). Preliminary

geochronological studies by Xu et al. (2015) indicate that the cooling ages of the migmatitic layers and gneiss range from 35-23 Ma in the dome zone. These data are thought to reflect crustal melting/magmatic events, ranging from 76-40 Ma across the Tengchong dome zone. Our data also indicate that synkinematic granitic emplacement occurred at a range of ages from 67 to 30 Ma for D2 doming (Fig. 13). The Lianghe shear zone is the boundary between the Lianghe dome and Domain-1, and the shear zone yielded a biotite $^{40}\text{Ar}/^{39}\text{Ar}$ age of 35 Ma (Xu et al., 2015). The age ranges of magmatic events are roughly coeval with the gneiss folds of the D2 deformation.

Fig. 13

7.3. Deformation and metamorphic evolution

In the Tengchong terrane, Domain-1 is characterized by a roughly east-directed and northeast-directed shearing sheet (Fig. 14). Local D1 shearing of basement migmatites and gneisses over their low-grade metasedimentary or non-metasedimentary cover, as observed in the Luxi region, and the development of the inverted metamorphism from Nabang to Luxi support our interpretation. Ji et al. (1998; 2000) estimated peak metamorphic pressures of ~10 kbar at ~850°C for the westernmost region of the dome zone. Metamorphic conditions in Domain-1 were estimated at ~650°C (Xu et al., 2015), which are consistent with the observed partial melting and the large volume of migmatization during D1 deformation. Evidence for an earlier medium- or high-pressure history of the terrane has been suggested by Ji et al. (2000), who described inclusions of granulite facies in the low-pressure assemblages. The low-pressure re-equilibration of the westernmost part of the Tengchong terrane indicates the onset of equilibration of metamorphic conditions in the high-temperature western portion and transition to the medium-temperature eastern portion, which probably formed during east-directed shearing D1. Broadly, high-temperature metamorphism and migmatization in the western part of the terrane and medium- to high-temperature metamorphic conditions in the eastern part of the terrane suggest that D1 top-to-the-east shearing created a tectonically inverted metamorphic gradient in the Tengchong gneiss terrane. The flat-lying locally preserved S1 foliation was inherited from the thickening episode. Based on our structural analysis and data on the synkinematic granite veins, there was one magmatic event, which accompanied D1 deformation, in the terrane during 120-100 Ma, which allows the observed D1 shearing to be interpreted as Cretaceous.

Refolding of S1 in the D1 domains and subsequent development of a medium to steeply dipping S2 foliation is associated with the subhorizontal L2 lineation. These fabrics indicate that the gneiss and migmatitic gneiss were dominated by strong, roughly E-W-oriented shortening and N-S stretching. The terrane experienced pure shear-dominated deformation, in which large-scale folds refolded the early metamorphic fabrics, developing the elongated dome shapes. The D2 deformation was also characterized by strike-slip shear zones, which were concentrated in the narrow contact regions between the domes. The combination of pure shear deformation (map-scale F2 folds) and simple shear movement (strike-slip shear zones) within the dome zone suggests classic transpression (Sanderson and Marchini, 1984; Tikoff and Teyssier, 1994). Pure-

and simple-shear components are also partitioned into separate deformation domains temporally as well as spatially (Jones et al., 2004; Gessner et al., 2007; Rey et al., 2009). As a result of such strain-partitioning, broader, weakly strained domains are typically associated with anticlinal doming, such as the Sudian, Guyong, Yinjiang and Lianghe domes, whereas the simple shear component is localized in narrower shear zones, such as the Sudian, Yinjiang and Lianghe shear zones, during progressive transpression.

We argue that the D2 structures and their evolution in the dome zone are as follows. The contrasting thermal state between the colliding Tengchong terrane and the Baoshan block, as well as a high degree of obliquity, led to concentration of deformation in the rheologically weaker gneiss and migmatitic gneiss levels of the Tengchong terrane after maximum thickening of the Tengchong terrane had been achieved (Xu et al., 2012). The concentration of deformation in various gneiss sequences along the contact layers between the hot migmatitic layers and granite plutons promoted large-scale asymmetric folds (Fig. 14). The intensive deformation almost reworked the D1 fabrics to the west due to strong shortening, which lead to the formation of linear antiforms greater than four kilometers in scale in the central portion of the terrane (Fig. 14). Extensive migmatization occurred, and solid-stage deformation commonly developed in these migmatitic gneisses and granites, facilitating the D2 deformation. Granitoids were emplaced along the S2 fabrics located in the cores of the antiforms. These observations are the best evidence that east-verging asymmetric F2 folding coincided with migmatization and the emplacement of a large volume of hot granite magma in the country rock. The ca. 70-40 Ma granite plutons and related granitic veins may be synkinematic plutons at structural depth coeval with transpressive tectonics. Therefore, the N-S- and transitional NE-SW-striking magmatic cores and the top-to-the-northeast kinematics of the folded gneiss are associated with the development of transpressive tectonics on the terrane (Fig. 14). The transpressive deformation may have lasted until the emplacement of the youngest post-migmatitic granite, approximately 40-30 Ma.

Cooling of the terrane may have influenced structural heterogeneities, resulting in enhanced strain localization during the evolution of the internal deformation (Gessner et al., 2007; Rey et al., 2009). Weak and strong solid-state deformation of the Mesozoic-Cenozoic granite, as well as medium- to low-temperature mylonitic fabrics, suggests that the extensive strain localization of D3 deformation played an important role during decreasing temperatures. The Gaoligong and Nabang shear zones represent locations of concentrated D3 deformation along the two boundaries of the terrane (Fig. 14). Since the start of D3 deformation (after 30 Ma), large-scale boundary strike-slip shear zones dominated the development of the transpressional strain within the terrane and have accommodated most of the lateral extrusion (Zhang et al., 2012).

The late stage of the tectonic evolution, D4, in the Tengchong terrane, after approximately 10 Ma, corresponds to the exhumation and uplift of the Gaoligong shear zone between the GWDF and GEDF in a transtensional setting.

Fig. 14

7.4. Dynamics of the intra-continental deformation

In previous studies, a diapiric model was suggested to play a role in the original emplacement of the dome zone in the Tengchong terrane (Xu et al., 2015). In this model, a positive feedback between decompression and near-isothermal melting at mid-crustal levels would be responsible for the formation of many diapiric gneiss domes (Whitney et al., 2004). This diapirism model also suggests that the narrow high-strain zones with strike-slip shear kinematics located on each side of the domes accommodate the lateral movement of the domes (Xu et al., 2015).

However, our observations reveal three separate deformation stages in the terrane (Fig. 15), which are primarily the result of compressional/transpressional tectonics involving the interaction of early top-to-the-east shearing structures (Figure 15A), subsequent reworking by large-scale folds with east-directed kinematics (Fig. 15B), followed by localization deformation along the lateral strike-slip shear zone (Fig. 15C) and late brittle-ductile transtension. For our model, the D1-D2 deformation represents sub-horizontal shearing and doming as a dynamic mechanism responsible for crustal deformation of the Tengchong terrane (Fig. 15A, B).

We interpreted the first sub-horizontal shearing (D1) in the gneiss to be a crustal-scale tectonic thermal event in the terrane corresponding to subduction of the Nujiang Tethys Ocean (Bangong-Nujiang Ocean) during the Cretaceous (114-104 Ma) (Fig. 15A). The D2 east-verging asymmetric folds in the gneiss and the migmatization and granite emplacement formed during the dual collision of the Baoshan block in the west and the Indian Plate in east (Fig. 15B). The D2 stage is suggested to have developed at approximately 67-40 Ma and continued to 30 Ma throughout the terrane. Geochronological data available for granites and migmatites of the Tengchong terrane (Xu et al., 2012; Xu et al., 2015) show that partial melting of the mid to lower crust started about 30-20 Ma after the onset of the dual collision, leaving sufficient time required for crustal thickening to accumulate heat, increase temperature and begin melting (Teyssier and Whitney, 2002). Large-scale strike-slip shearing, i.e., D3, occurred after 30 Ma along the Nabang and Gaoligong shear zones during intra-continental deformation (Fig. 15C). Combined with upward exhumation of the Gaoligong metamorphic zone, late strain-partitioning has played a role in forming right-lateral strike-slip structures along the GWDF and GEDF in the brittle-ductile transtension level corresponding to post-convergence gravitational collapse (D4, since 10 Ma) (Fig. 15C). The Gaoligong metamorphic zone has been progressively exhumed vertically to the current exposure level.

In a word, during the Cenozoic, crustal material in the interior of the terrane was extensively deformed by map-scale folding/bending of the crust at structural depth during the early stage, followed by strike-slip shearing in the upper level during collision between the Indian Plate and the Tengchong terrane. Vertical exhumation of crustal material by doming played an important role in absorbing the vast majority of the internal deformation of these crustal fragments during the first stage of oblique India-Asia collision. Later, deformation was accommodated by strain localization along lateral strike-slip shearing and brittle-ductile detachment faulting.

Fig. 15

8. Conclusions

Our observations show that, prior to the development of the large-scale Gaoligong and Nabang shear zones, a period of top-to-the-east shearing (D1) at 114-104 Ma led to the development of an approximately inverted metamorphic gradient in the Tengchong terrane, followed by medium- to high-temperature transpression (D2), which was responsible for the almost complete reworking of the earlier fabric. In the interior of the terrane, continuous transpression deformation was documented by the development of the linear dome zone and small-scale strike-slip shear zones during 67-30 Ma. After 30 Ma, the Gaoligong and Nabang shear zones of the D3 deformation followed the transpression. Late transtension was accompanied by a heterogeneous array of ductile-brittle detachment faults bounding the Gaoligong mylonite zone, which also contributes to the late exhumation of the Gaoligong metamorphic zone. The consistent kinematics and orientation of the stretching lineations in the medium- to high-temperature gneiss and migmatitic gneiss domes in the dome zone and in the medium- to low-temperature mylonites in the Gaoligong and Nabang shear zones suggest that the strain localization took over the role of intra-continental deformation during cooling of the terrane, further indicating that vertical exhumation gave way to lateral extrusion in this terrane.

During the early Mesozoic, during the closure of the Banggong-Nujiang Ocean, the Mesozoic granitoids and their country rocks (gneiss) in the crust experienced megascopic top-to-the-east shearing at structural depth in the Tengchong terrane. Simultaneously, the compressional tectonics were responsible for the formation of thrust sheets in the upper layer of the gneiss. Similar structural types were also documented in the Lanping-Simao block (Wang and Burchfiel, 1997) and the Baoshan/Sibumasu block (Wang and Burchfiel, 1997; Akciz et al., 2008). Crustal thickening, represented by deformed migmatites and plutons, developed coevally with the transpressional tectonics and was related to the Neo-Tethys ocean subduction and India-Asia collision. The microscopic observations indicate that the deformation experienced by the migmatites and granitic plutons that form the main part of the dome occurred under sub-solidus or weak solid-state rheologies during Tertiary doming. Both megascopic bending of the crust and thin-skinned shortening of the upper gneiss layers during intracrustal deformation led to the development of N-S-trending linear dome shapes and N-S-trending strike-slip zones. The interior deformation history of the Tengchong gneiss terrane is decoupled from that of its boundaries (Nabang and Gaoligong shear zones), which suggests that the Gaoligong shear zone was exhumed upward from mid-crustal depths between the two kinematically and dynamically linked opposite-sense detachment faults. We contribute the regional upright dome zone to shortening produced by horizontally pure shearing at deep levels during an oblique collision event. These antiformal domes resulted in crustal thickening of the Tengchong terrane that was contemporaneous with migmatization and partial melting.

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Captions

Fig. 1. Schematic structural map of the southeastern Tibet and southeastern Asia. (A) Simplified tectonic sketch map shows topographic and major tectonic features of southeastern Asia and adjacent areas, including major faults systems and metamorphic zones in the Indochina block (modified from Leloup et al., 1995; Wang and Burchfiel, 1997; Zhang and Schärer, 1999; Tapponnier et al., 2001; Lee et al., 2004; Searle, 2006; Zhang et al., 2012). (B) Regional structural map of the southwestern Yunnan, including the Tengchong terrane, Baoshan block, and Lanping–Simao terrane, and the Gaoligong, Chongshan, and Xuelongshan–Diancangshan–Ailao Shan zones (modified from Leloup et al., 1995; Wang and Burchfiel, 1997; Zhang et al., 2012; Xu et al., 2015).

Fig. 2. Detailed Structural map of the Tengchong gneiss terrane (modified after BGMRY, 1990; Wang et al., 2008; Xu et al., 2015) with geochronological data from this study and previous studies (Ji et al., 2000; Wang et al., 2006; Wang et al., 2008; Liu et al., 2009; Lin et al., 2009; Xie et al., 2010; Feng et al., 2011; Xu et al., 2012; Ma et al., 2013; Tan et al., 2013; Xu et al., 2015). GWDF: Gaoligong west detachment fault; GEDF: Gaoligong east detachment fault. Positions of seven cross sections are marked. six sections by this study, and the section VII – VII' by Xu et al. (2015).

Fig. 3. Four cross sections through the Tengchong gneiss dome zone and its boundary massifs (positions in Fig. 2), highlighting east-to-the-west variation in structures and structural domains. Stereograms of the foliation (large circle) and mineral stretching lineation/slickenside (block dot) for stations within the Tengchong gneiss terrane and its boundaries. All diagrams are equal – area Schmidt net, lower hemisphere.

Fig. 4. Three cross sections through the Tengchong gneiss dome zone and its boundary massifs (positions in Fig. 2), highlighting east-to-the-west variation in structures and structural domains. Stereograms of the foliation (large circle) and mineral stretching lineation (block dot) for stations within the Tengchong gneiss terrane and its boundaries. All diagrams are equal – area Schmidt net, lower hemisphere.

Fig. 5. Detailed geological map with structural relationships for D1-D3 deformations, particularly for Domain-1 (location shown with inset box in Fig. 2). (A) Detailed structural map for Domain-1 in the Luxi region. (B) Structural relationships and the internal fabrics among the Domain-1 (D1 deformation) and the D2-D3 deformations along two sections. All stereograms are equal-area Schmidt net, lower hemisphere. Stereograms of the foliations (large circle) and mineral stretching lineations (black dot) for stations along two sections.

Fig. 6. Field photographs of typical structures associated with D1 deformation observed in Domain-1. (A)-(C) Typical structures of D1 deformation showing a low-angle mylonitic gneissosity (S1) with down-dip lineation (L1) characterized by elongated feldspar and quartz crystals, and with boudinaged leucogranitic veins, indicating top-to-the-east shear sense of D1 deformation (observing site GLG-066 marked in Fig. 5B). (D) Gentle mylonitic gneissosity (S1) with folded granitic veins and S-C shear bands, indicating top-to-the-northeast shear sense of D1 deformation (observing site GLG-074 marked in Fig. 5B)

Fig. 7. Characteristic structures of D2 deformations in the Sudian dome, Guyong dome, Lianghe dome and their boundary shear zones. (A) Gentle NW-dipping gneissosity (S2) with folded S1 foliation in the gneiss of the Sudian dome (upper; station GLG-024). The primary magmatic layering (flow plane) of the Sudian granite is parallel S2 fabric in the Sudian granites (lower; station GLG-037). (B) Gentle NW-dipping gneissosity (S2) with preserved S1 foliation in the migmatitic gneiss of the Guyong dome (upper; station GLG-019). The primary magmatic flow plane and weakly – deformed bands of the Guyong granite are parallel S2 fabric of the Guyong gneiss (lower; station GLG-018). Rolling structures, asymmetric porphyroclasts and S-C fabrics in the foliated granite indicating top-to-the-northeast shearing in the Guyong granite. (C) Gentle NW-dipping gneissosity (S2) with strongly-reformed S1 foliation in the granitic gneiss of the Lianghe dome (upper; station GLG-077). The highly-deformed Lianghe granite shows a ductile foliation parallel to S2, rolling structures, asymmetric feldspar porphyroclasts and S-C fabrics indicating top-to-the-northeast shearing in the Lianghe granite (lower, station GLG-063). (D) Layered migmatitic gneiss showing extensively deformed leucogranitic veins parallel to penetrative S2 foliation with a subhorizontal lineation, showing a dextral strike-slip shearing

sense in the Sudian shear zone (station GLG-056). (E) Extensively sheared granite indicates a sinistral strike-slip shearing in the Yinjiang shear zone (station GLG-058). (F) Mylonitic granite shows a steep penetrative S2 foliation and a subhorizontal lineation in the Lianghe shear zone. Rolling structures and asymmetric quartz porphyroclasts indicate a dextral strike-slip shearing in the shear zone. All observing sites are marked in Fig. 3 and 4. All diagrams are equal-area Schmidt net, lower hemisphere. Stereograms of the foliations (large circle) and mineral stretching lineations (black dot) for observing sites.

Fig. 8. Field photographs of typical structures associated with D3 and D4 deformations within the Nabang shear zone and Gaoligong shear zone. (A) Tight to isoclinal folds with sub-vertical axial-planar S3 developed in the mylonitic high-grade garnet-bearing metapelite in the Nabang shear zone near Nabang (observing site GLG-047) (observed in the YZ-plane). (B) Sub-vertical S3 foliation in mylonitized granite with horizontal mineral lineation (L3) and S-C fabrics (observed in the XZ-plane), showing a dextral strike-slip shearing in the Nabang shear zone (observing site GLG-033). (C) Sub-vertical mylonitic gneiss foliation (S3) with sub-horizontal mineral stretching lineation (L3) characterized by elongated feldspar/quartz crystals and S-C fabrics, indicating dextral sense of shearing in the Daojie region (observing site GLG-093). (D) Normal faults and fractures (S4) bound the east side of the Gaoligong shear zone and adjacent area. Note: the damage zone along the normal fault (S4) shows strongly folded S3 in the Daojie region (observing site GLG-004). (E) The normal fault (S4), sub-parallel to the ductile foliation S3, bound the west side of the Gaoligong shear zone in the Mangbang region (station GLG-098). All observing sites are marked in Fig. 3 and 4.

Fig. 9. Microstructures of oriented thin sections of rocks from four domes. All thin sections are cut in the XZ plane. (A)-(D) The gneisses with inequigranular- to equigranular-granoblastic microstructures in the domes. Note the variation in grain size of the quartz-feldspathic phases. (A) Microstructures in the Sudian gneiss involve medium- to fine-grained grains of quartz, plagioclase and Potassic feldspar, which form inequigranular- to equigranular-granoblastic mosaics. (B) The Guyong gneiss is characterized by medium- to coarse-grained, inequigranular to equigranular, granoblastic microstructures. A prominent foliation roughly defined by

anastomosing biotite intergrowths surrounding variably recrystallized porphyroclasts of potassium feldspar also is ubiquitous. (C) Amphibolite facies Yinjiang gray gneiss containing the assemblage hornblende-biotite-microcline-plagioclase and quartz. The microstructure is medium grained granoblastic. (D) The Lianghe gneiss is featured by medium- to coarse-grained, inequigranular granoblastic elongate microstructures. A prominent foliation defined by anastomosing biotite intergrowths surrounding variably recrystallized porphyroclasts of potassium feldspar also is ubiquitous. (E)-(J) Microstructures of moderate to intensive solid-state deformation in the transition layers between the granite core and the gneiss mantle in the dome zone. (E)-(F) Intensively recrystallized grains with reduced grains size in the Sudian granite. Muscovite-fishes and rolling quartz grains indicating a top-to-the east shearing in the Sudian granite. (G) Numerous quartz grains with polygonized boundaries indicating a recrystallization under very high stress and high temperature during the top-to-the-east shearing in the Guyong granite. (H)-(I) Typical fabrics of dynamic recrystallisation in the Yinjiang granite. Numerous quartz grains are characterized by polygonized boundaries, undulose extinction, and elongate subgrains. Biotite-fish and asymmetric quartz grains indicating a top-to-the-east shearing. (J) Undulose extinction and subgrains in quartz are probably due to ductile deformation in the Lianghe granite. (K)-(N) Fabrics of slight-solid state deformation in the granite cores. (K) Biotite fragments slightly defined a foliation S2 in the Sudian granite. (L) Quartz grains are partially recrystallized to form a few new grains and lobate borders, and biotite grains and plagioclase porphyroblasts defined a weak foliation S2 in the Yinjiang granite. (M)-(N) Weak solid-state deformation is indicated by undulose extinction in quartz, orientated mica grains, and elongated quartz grains in the Lianghe granite. (O)-(S) Typical magmatic fabrics in the granite of the dome core. (O)-(P) Granitic fabrics with myrmekites developed perpendicularly to the magmatic flow plane S2 in the Sudian granite. (Q) Granitic fabrics in the Guyong granite. (R) Microstructures of the granodiorite in the Yinjiang granite core. (S) Weak flow plane in the Lianghe granite. Qz-Quartz, Pl-Plagioclase, Kfs-Potassic feldspar, Bi-Biotite, Ms-Muscovite, Ap-Amphibole, Myr-Myrmekite, S2-foliation S2. Locations of all samples are indicated in Fig. 3 and 4.

Fig. 10. Structures and geochronologies associated with ductile tectonic (D1 deformation) in the gneiss in the Domain-1. (A) and (B) Syn- to post-kinematic leucogranite veins in the laminated

migmatitic gneiss at observed site GLG-084. These veins are harmonious with the foliation S1, strongly boudinaged parallel to the S1, and cutting across the gneiss fabrics. The leucogranite sets dated by U-Pb zircon at 108-104 Ma. (C) Cathodeluminescence images of zircon grains with distinct oscillatory zoning mantles from the vein (GLG-084), showing the locations for LA-ICP-MS spot ages of zircon. Ages are $^{206}\text{Pb}/^{238}\text{U}$ and uncertainties are 1 – sigma. Concordia plots of LA-ICP-MS U-Pb dating results and mean ages for zircons for the sample. Histograms of $^{206}\text{Pb}/^{238}\text{U}$ data for these age distribution were given. MSWD: mean square weighted deviations. (D) and (E) Syn- to post-kinematic leucogranite veins in the gneiss at observed site GLG-082. (F) Cathodeluminescence images of zircons showing distinct oscillatory zoning mantles from the sample GLG-082 taken from the leucogranitic vein. Concordia plots of LA-ICP-MS U-Pb dating results, histograms of $^{206}\text{Pb}/^{238}\text{U}$ data and mean ages for zircons from the sample, suggesting an age at 114 Ma. Sampling site marked in Fig. 2.

Fig. 11. Structures and geochronology associated with ductile tectonics (deformation D2). (A) Boudinaged leucogranitic veins in the mylonitic augen gneiss at observed site GLG-094. These leucogranitic veins underwent weak ductile deformation. On the observed outcrop, the veins locally show lay-parallel, and weak cross-cutting. (B) Cathodeluminescence images of zircon grains from the deformed vein GLG-094, giving the sites for LA-ICP-MS ages ($^{206}\text{Pb}/^{238}\text{U}$ with 1-sigma uncertainties). Noted the old distinct oscillatory zoning cores developed thick metamorphic overgrowth tips. Concordia plots of LA-ICP-MS U-Pb dating results and histograms of data for zircons from the sample GLG-094. (C) Various scale boudinaged leucogranitic veins show parallel to the gneissosity S2 in the mylonitic augen gneiss at observed site GLG-076 in the Lianghe dome. (D) Cathodeluminescence images of zircon grains from the deformed vein GLG-076, giving the sites for LA-ICP-MS ages ($^{206}\text{Pb}/^{238}\text{U}$ with 1-sigma uncertainties). Noted the old cores have thin metamorphic overgrowth mantles. Concordia plots of LA-ICP-MS U-Pb dating results and histograms of data for zircons from the sample GLG-094. Weighted mean ages were calculated at 1-sigma confidence level. Sampling site marked in Fig. 2.

Fig. 12. Structures and geochronologies associated with ductile tectonics (D2 deformation). (A) Boudinaged leucogranitic veins in the mylonitic migmatitic gneiss at observed site GLG-067 with

the Yinjiang dome. On the observed outcrop, the veins show lay – parallel to gneissosity S2. (B) Cathodeluminescence images of zircon grains from the deformed vein GLG–067, giving the sites for LA-ICP-MS ages ($^{206}\text{Pb}/^{238}\text{U}$ with 1-sigma uncertainties). Noted the distinct oscillatory zoning mantles. Concordia plots of LA-ICP-MS U-Pb dating results, mean ages and histograms of data for zircons from the sample GLG-067. (C)-(E) Structural features of boudinaged veins, Cathodeluminescence images of zircon grains and concordia plots of LA-ICP-MS U-Pb dating for the samples GLG-056/GLG-057, taken from the boudinaged granitic veins at the site GLG-056/-057 in the Yinjiang dome. Sampling site is marked in Fig. 2.

Fig. 13. Space-time relationships of granitic plutons and gneiss domes in the Tengchong terrane. GWDF: Gaoligong west detachment fault. GEDF: Gaoligong east detachment fault.

Fig. 14. Three-dimensional structural model of the Tengchong dome zone and its eastern boundary. This model presents the structural geometries, kinematics and deformation types for the dome zone along with magmatic processes, which result in the formation of the Tengchong domes (modified after Kruckenberg et al., 2011; Zhang et al., 2012; Xu et al., 2015).

Fig. 15. Tectonic history for the Tengchong gneiss dome zone and its boundaries. (A) 114-104 Ma: Compressional tectonics (D1) setting with top-to-the-east shearing and folding coeval with crustal melting: migmatization, and Cretaceous pluton emplacement at depth. The early stage of east-directed shearing (D1) and synkinematic emplacement of the pluton/related granitic veins are associated to the subduction of the Banggong-Nujiang ocean. (B) 67-30 Ma: Post-migmatitic intrusion of Yinjiang, Guyong, and Sudian plutons and related granitic veins, east-directed vergence folding (F2) and dome amplification. The second stage of deformation of the domes is accommodated with regionally folding (overthickened crust), partly diapirism and transpressional tectonics during India-Asia collision (modified after Xu et al., 2012; Xu et al., 2015). (C) After 30 Ma: Post-thickening localized deformation along the shear zones, clockwise rotation, and final exhumation of the Gaoligong shear zone due to detachment faulting along the west and east boundary faults.

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