1 **Dynamics of the Tengchong volcanic region in the southeastern**
2 **Tibetan plateau: a numerical study**

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11 **Abstract:** The constraints of surface heat flow and lithospheric structure were used to
12 investigate the dynamics of the Tengchong volcanic region based on
13 thermal-mechanical modeling. Three different boundary conditions representing three
14 types of tectonic movements were modeled to discuss the thermal state and
15 lithospheric deformation. The compressive model shows that the subduction of the
16 Indian plate causes the upwelling of asthenosphere beneath the Tengchong block. In
17 this process, upwelling of the asthenosphere causes thinning of the lithosphere
18 beneath the Tengchong block. However, the surface heat flow of this model is not
19 consistent with the observations. The regional extension model shows that, under the
20 extension, the asthenosphere upwells along the preexisting weak suture zone in the
21 southeastern Tibetan plateau. The thickness of lithosphere is the thinnest along the
22 suture zone, and the surface heat flow is the highest. However, the extension time was

found to generally need 10-15 Myr to conform to the surface heat flow, however, this is not consistent with accepted geochronological data. When a boundary condition from compression to extension is imposed, both the surface heat flow and the lithospheric structure fit well with the observations. The results show that the subduction of the Indian plate leads to the upwelling of the asthenosphere which causes a thinned lithosphere beneath the Tengchong block. Since the late Miocene (8-5 Ma), the extension or extrusion has been predominant. The thermal erosion of the lithosphere caused by upwelling of the asthenosphere renders the lithosphere even thinner along the Bangong-Nujiang suture zone. The upwelling of the asthenosphere provides an upward driving force and high-temperature environment for the Tengchong volcanic region. These findings suggest that the origin of the Tengchong volcanic region is caused by both the subduction of the Indian plate and regional extension across the Bangong-Nujiang suture zone.

Keywords: Tengchong volcanic region; numerical model; dynamics; subduction; extension;

1. Introduction

The strong collision between the Indian and Eurasian plates since approximately 50 Ma (Klootwijk et al., 1992; Leech et al., 2005; Najman et al., 2010) has caused significant deformation and rotation in southeastern Asia. Extrusion occurs in the southeast margin of the Tibetan plateau (Molnar and Tapponnier, 1975; Tapponnier et

al., 1982). The Tengchong volcanic region (24°40'-25°30' N, 98°15'-98°45'E) is located along the southeast edge of the collision zone, away from the eastern boundary of the Indian plate by about 300 km (Figure 1). Volcanic eruptions have occurred in this region since the late Miocene. The last eruption might have occurred in 1609 (Huangfu, 1997; Wang et al., 2007; Zhu et al., 1983). Southwest of the Tengchong volcano, many volcanoes, such as Popa and the Singu Plateau (Figure 1) are distributed along the Sagaing fault, which is the eastern boundary of the Indian plate (Luhr and Haldar, 2006). These volcanoes belong to the Sumatra volcanic chain which is caused by the subduction of the oceanic plate. However, geochemical studies suggest that the Tengchong lavas come from the mantle (Mu et al., 1987; Zhai et al., 2013; Zou et al., 2010; Zou et al., 2014). These lavas are different from the volcanoes along the oceanic plate boundary, whose volcanic rocks come from the crust. The Tengchong volcano is far from the plate boundary, and geochemical studies indicate that the formation of the Tengchong volcanic region has a special tectonic setting (Wang et al., 2007). It has not yet been determined whether the Tengchong volcano is an interplate or intraplate volcano (Wang and Huangfu, 2004; Wang et al., 2007; Whitford-Stark, 1983). The dynamics of its origin are still in debate.

Many models have been proposed to explain the mechanism of the Tengchong volcanic region. The first one is the Big Mantle Wedge (BMW) model. Deep seismic tomography shows there to be a low-velocity anomaly from the surface to 410 km beneath the Tengchong block (Huang and Zhao, 2006; Lei et al., 2013; Lei et al., 2009; Li et al., 2008; Wei et al., 2012; Zhao, 2007; Zhao and Liu, 2010). This

67 indicates that the subducting Indian plate penetrates 410 km under the Tengchong
68 block. The deep subducting and stagnant slab collapses into the mantle transition
69 zone, triggering the upwelling of mantle above the subducting slab which results in
70 the slab-plume interactions. This process forms a big mantle wedge from the
71 subduction slab to the upwelling mantle, providing hot mantle material for the
72 volcanic eruption. This model was used to explain the intraplate magmatism, such as
73 the Changbaishan and Wudalianchi volcanoes in northeastern China (Lei et al., 2013;
74 Zhao and Liu, 2010). The second one is the regional extension model. Geological
75 surveys show that the Tengchong block, the Baoshan block, and the Simao block,
76 which are part of the southeastern Tibetan plateau, have undergone regional extension
77 during the extrusion process (Figure 2) (Socquet and Pubellier, 2005; Wang et al.,
78 2008; Wang et al., 2007). In the Tengchong block, there are a series of rift basins and
79 normal faults (Figure 1-2). These studies show that the regional extension results in
80 thinned lithosphere and an upwelling of the asthenosphere beneath the Tengchong
81 block. The third one is the subducting slab break-off model. Geological surveys and
82 geochemical studies have led many scholars to believe that Cenozoic volcanic rocks
83 in the Tengchong block are related to the upwelling of mantle materials caused by the
84 break-off of the subducting Paleo-Tethys oceanic slab (Hu et al., 2008; Ji et al., 2000a;
85 Xu et al., 2012b; Yang et al., 2013; Zhang et al., 2012). After the closure of the
86 Paleo-Tethys Ocean, coupled with the continuous convergence between the Indian
87 and Eurasian plates, the subducting Paleo-Tethys oceanic slab is under a downward
88 drag force and negative buoyancy force. The subducting slab finally broke off,

resulting in the upwelling of mantle materials, causing a volcanic eruption (Huw Davies and von Blanckenburg, 1995; Liu et al., 2000). However, geochronological studies suggest that the plate broke off during in the Eocene Epoch (Xu et al., 2008). This is not consistent with the Cenozoic eruption of the Tengchong volcano, which occurred after the late Miocene.

In this study, the dynamics of the Tengchong volcanic region are investigated using thermal-mechanical modeling under the constraints of observed surface heat flow, lithospheric structure and geochronology. The effects of different tectonic boundary conditions on the thermal and lithospheric structures beneath the Tengchong volcanic region are emphasized. This study may improve understanding of the dynamics of the Tengchong volcanic region.

2. Tectonic setting

2.1 Geological structure and magmatic features

The Sanjiang region (three rivers: Nujiang River, Lancangjiang River, Jinshajiang River), which includes the southeastern Tibetan plateau and the western Yunnan region, constitutes a collage of Gondwana-derived micro-continental blocks in the southwestern China. From west to east, there is the Tengchong block, the Baoshan block and the Simao block (Figure 1). These blocks are divided by the Sagaing fault (SGF), Bangong-Nujiang suture zone (BNS), Lancangjiang fault (LCJF) (along with the Lancangjiang River (LCJR)) and the Ailaoshan-Red River fault (RRF), respectively. These faults and suture zones were formed by the closure of the

Tethys Ocean and continental collision. Due to the Indo-Eurasian collision, extrusion of different blocks have formed along large faults or suture zones (Burchfiel and Wang, 2003; Molnar and Tapponnier, 1975; Tapponnier et al., 2001). Large ductile shear zones have developed along major suture zones (Deng et al., 2014; Wang and Burchfiel, 2000; Zhong et al., 2004). The ductile shear zones generally have low strength and are prone to plastic deformation. The Gaoligong ductile shear zone, which is the boundary between the Tengchong and Baoshan blocks, was formed along the Bangong-Nujiang suture zone (Figure 1). The low strength of the Gaoligong ductile shear zone (GLGDSZ) provides a preexisting weak zone in the southeastern Tibetan plateau.

The Tengchong volcanic region is located in the Tengchong block, whose western and eastern boundaries are the Sagaing fault and the Bangong-Nujiang suture zone, respectively (Figure 1). The Tengchong block experienced the closure of the Nujiang Ocean and the Myitkyina Ocean (Fan et al., 2015). Since the Cenozoic, the Indo-Eurasian continental collision has led to the rotation, extrusion and shear deformation of the Tengchong block (Mo and Pan, 2006). Magmatism in the Tengchong block was active in both the Mesozoic and Cenozoic (Dong et al., 2006; Li et al., 2011a). Late Cenozoic volcanic rocks in the Tengchong block are mainly distributed in the NE-NNE trending arc basins and are widely exposed in the Mesozoic granites and sedimentary strata. The distribution of late Cenozoic volcanic rocks covers an area of 792 km². In the Tengchong volcanic region, there are 145 hot springs, 68 volcanoes, and 25 preserved volcanic craters and cones (Jiang, 1998; Jiang

et al., 2003). Cenozoic volcanic rocks in the Tengchong volcanic region are mainly composed of andesitic basalt and andesite. There is also some olivine basalt, pyroxene basalt and dacite, and others. The composition suggests that these volcanic rocks are high-K calc-alkaline series of magma formed in the collision zone (Mu et al., 1987; Zou et al., 2014). Low velocity anomalies and high conductivity indicates that shallow crustal magma chambers may exist beneath the Tengchong block (Bai et al., 2001; Wang and Huangfu, 2004; Xu et al., 2012b; Yang et al., 2013); however, geochemical studies suggest that the Tengchong lavas come from the mantle. U-series isotope data, together with major and trace elements and Nd–Sr–Pb isotope data, indicate that the Tengchong lavas are derived from partial melting of an enriched subcontinental lithospheric mantle (Tucker et al., 2013; Zou et al., 2010; Zou et al., 2014). Petrologic and geochemical studies for the Tengchong volcanic rocks indicate that they probably originated from the melting of an enriched-mantle source, not the shallow crust as suggested by some observations (Chen et al., 2002).

2.2 Earthquake distribution and lithospheric structure

The distribution of earthquakes indicates that the Indian plate subducts beneath the Burma arc (Figure 2-3). Unlike the volcanoes along the oceanic plate boundary, the Tengchong volcano is located about 300 km from the plate boundary. It is different from the other volcanoes distributed along the volcanic chain, which were produced from the dehydration melting of the oceanic plate (Zhao et al., 2011). The earthquake focal mechanisms show that extension is dominant in the Tengchong volcanic region

(Figure 2).

Seismic observations show that the crust and lithosphere beneath the Tengchong volcanic region are relatively thin (Figure 3), only 28 km, and it shows low-velocity anomalies, indicating that the lower crust beneath the Tengchong volcanic region has been eroded by the mantle and stored magma chambers (Bai et al., 2001; Wang and Huangfu, 2004; Xu et al., 2012b; Yang et al., 2013). The lithosphere-asthenosphere boundary (LAB) is only 70-80 km beneath the Tengchong volcanic region. However, the LAB in the surrounding region is 100-120 km deep (Figure 3) (Hu et al., 2012; Zhang et al., 2015). Thermal structure also suggests that the lithosphere beneath the Tengchong block is only 80km thick. In comparison, the lithosphere beneath the Baoshan block is 100-120 km thick (An and Shi, 2006; Sun et al., 2013b; Zhou et al., 1996).

Large-scale seismic tomography and the distribution of earthquakes show that the Indian plate subducts eastward with a high angle beneath the Burma arc. The subduction depth reaches 410 km and may even reach 660 km (Huang and Zhao, 2006; Lei et al., 2009; Li and van der Hilst, 2010; Wei et al., 2012). Many scholars have shown that low-velocity anomalies extend from the surface down to about 410 km beneath the Tengchong volcanic region. Scholars believe that the Tengchong volcanic region resulted from the upwelling of hot mantle materials. This process is triggered by the dehydration of a stagnant slab that collapses down into the mantle transition zone (Lei et al., 2013; Lei et al., 2009). However, other results show that the low-velocity anomalies are limited above the depths of 300 km (Huang and Zhao,

2006; Wei et al., 2012). Although there are many differences, these observations indicate that the lithospheric thickness (either the thermal thickness or the seismic thickness) beneath the Tengchong volcanic region is thinner than that of its surroundings.

2.3 Block movement and surface heat flow

The kinematics and geochronology of the strike-slip faults show that the Ailaoshan-Red River fault and the Sagaing fault are the eastern and western boundaries of the southeastern Tibetan plateau (Ji et al., 2000b; Ji et al., 2000c). Previous studies have shown that, like the absorption of the Indo-Eurasian collision, extrusion into the southeastern Tibetan plateau is a multi-stage process (Burchfiel and Wang, 2003; Ji et al., 2000b). Continuous collision has resulted in significant movement and deformation of the Tengchong block since the late Miocene (8-5 Ma). The Tengchong block extruded south and rotated clockwise. Many north-south trending normal faults and rift basins, such as the Longchuanjiang fault (LCJF), have developed along the eastern boundary of the Tengchong block (Figure 1) (Ji et al., 2000b; Socquet and Pubellier, 2005; Wang et al., 2008; Zhang and Zhong, 1996). Paleomagnetic studies have also shown that the faults which nearly conjugated with the Red River-Ailaoshan left-lateral strike-slip fault changed slip direction about 5 Ma. These faults include the Gaoligong ductile shear zone, the Wanting fault, and the Nanting River fault (Kornfeld et al., 2014; Tong et al., 2013; Yang et al., 2001). These studies indicate that the stress environment around the Tengchong block has changed

to extension from compression since 8-5 Ma.

Contemporary surface heat flow is closely related to the block movement. In the Tengchong volcanic region, the surface heat flow reaches 80-150 mW/m², which is nearly 2 times larger than the average continental value in China (about 63 mW/m²) (Hu et al., 2001). With the increasing distance from the Tengchong volcanic region, the surface heat flow slowly decreases (Figure 3). The surface heat flow reaches 60 mW/m² in the Simao block. However, there is also a high heat flow region (80-100mW/m²) in the Chuandian block, which is near the Ailaoshan-Red River fault. In the high heat flow region, there are many rift basins and normal faults indicating that the extension is predominant (Socquet and Pubellier, 2005; Wang et al., 2008; Wang et al., 2001).

3. Numerical model

3.1 Governing equations

Elastic constitutive equations are usually used to study the short-term deformation of the crust or lithosphere (Coblentz and Richardson, 1996; Richardson, 1978). In order to describe the large-scale and long-term deformation, the continental lithosphere must be considered a continuum, in accordance with Newtonian rheology (Clark et al., 2005; England and Houseman, 1986; England and McKenzie, 1982; Houseman and England, 1986; Royden et al., 1997). In plate interiors, deep faults always play a significant role during lithospheric deformation (Avouac and Tapponnier, 1993; Tapponnier et al., 2001). Thus, a visco-plastic rheology was used in

this study. It is an effective and convenient way to model the effect of strain localization equivalent to the effect of faults (Beaumont et al., 2001; Beaumont et al., 2004; Fullsack, 1995; Vilotte et al., 1982; Vilotte et al., 1986). The equations that describe conservation of momentum for quasi-static incompressible creeping flows in two-dimension are written as follows:

$$-\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i} \left(\eta_{eff} \frac{\partial v_j}{\partial x_i} \right) + \rho g_j = 0 \quad i \text{ or } j \text{ is either } x \text{ or } y \quad (1)$$

$$\frac{\partial v_j}{\partial x_j} = 0 \quad (2)$$

In these equations, P is the pressure, v_j is the velocity components, η_{eff} is the effective viscosity, $\rho = \rho_0[1 - \alpha(T - T_0)][1 + \beta(P - P_0)]$ is the density under the condition of specific temperature T and pressure P . ρ_0 is the standard density at $T_0 = 298 K$ and $P_0 = 0.1 MPa$. In this study, $\alpha = 3 \times 10^{-5} K^{-1}$ and $\beta = 1.0 \times 10^{-5} MPa^{-1}$ are the thermal expansion coefficient and the compressibility, respectively.

$g_j = [0, g]^T$ is the gravitational acceleration. The constitutive equations are as follows:

$$\sigma_{ij} = -P\delta_{ij} + 2\eta_{eff}\dot{\epsilon}_{ij} \quad (3)$$

Here, σ_{ij} is the stress tensor (taken as negative in compression) and δ_{ij} is the Kronecker delta tensor. The strain rate tensor $\dot{\epsilon}_{ij}$ is as follows:

$$\dot{\epsilon}_{ij} = \frac{1}{2} \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \quad (4)$$

In the models, the frictional-plastic flow is adopted to distinguish the brittle and ductile state, which is independent of temperature (Stockmal et al., 2007). The von Mises yield criterion is used for the frictional-plastic deformation (Fullsack, 1995). The yielding criteria obey the following:

$$\sqrt{J_2} = \sigma^y \quad (5)$$

where $J_2 = \frac{1}{2} \sigma'_{ij} \sigma'_{ij}$ is the second invariant of the deviatoric stress tensor. σ^y is the yield strength threshold.

Viscosity is an important parameter in the calculation. It depends on the material properties, temperature and strain rate. However, constant viscosity and yield strength are assigned for each region defined in Table 1 and Figure 4. The viscosity will change if yielding occurs. The model does not consider the effect of temperature on the viscosity. The subduction characteristics in the models denote the initial state of the continent-continent collisional belt, which is less affected by the thermal state. However, the fault or plastic deformation has a large effect on the lithospheric deformation. When the stress gets to the yield strength, the effective viscosity of plastic flow η_{eff}^p becomes

$$\eta_{eff}^p = \frac{1}{2} (J_2)^{\frac{1}{2}} / (\dot{I}_2)^{\frac{1}{2}} \quad (6)$$

where $\dot{I}_2$ is the second invariant of the deviatoric strain rate. If yielding occurs in some part, the viscosity will follow the equation (6). The stress will then be calculated with the new viscosity. The viscosity is carried by the plastic flow and will not be changed until the next yielding occurs. We did not take into account the 'healing' of viscosity in this study.

The temperature follows the energy conservation equation:

$$\rho c \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) + \rho c u \nabla T = Q \quad (7)$$

where T denotes the temperature, changing with the time t . ρ and c represent the density and the unit heat capacity, respectively. k is the thermal conductivity. u

represents the velocity vector. Q represents heat production (W/m^3). In this model, $Q = Q_r + \sigma'_{ij}\dot{\epsilon}_{ij}$ is composed of two parts: Q_r and $\sigma'_{ij}\dot{\epsilon}_{ij}$ representing the radioactive heating and the frictional heating, respectively.

The ALE (Arbitrary Lagrange-Euler) and MIC (marker in cell) method is adopted to solve the thermal-mechanical coupled equations. During the numerical experiments, the numerical grid is continually modified according to the velocity field and used to track the external boundaries of the model domain. The nodes' positions in the internal model domain are updated by solving the Laplace's equations to avoid mesh distortion (Tezduyar et al., 1992). The information of material properties is tracked by using tracing particles (Gerya and Yuen, 2003). Interpolation is carried out between the particles and the computational grid in each time step providing a Lagrangian description for large deformation (Gerya and Yuen, 2003; Hieber and Koumoutsakos, 2005).

The finite element code was developed using the commercial finite element package FEPG (www.ectec.asia). We verified the numerical model by comparing it with the sandbox experiment used to benchmark viscoplastic models (Buiter et al., 2006) and the sinking of a rectangular block with different viscosities by contrasting the sinking block with its surrounding weak medium (Gerya and Yuen, 2003). The code has also been used to study the lithospheric deformation of North China (Sun et al., 2015). These tests prove the accurate conservation properties of our numerical model for the large and plastic deformation.

3.2 Finite element mesh and boundary conditions

A two-dimensional (2D) finite element model was constructed for the collision between the Indian plate and southeastern Tibetan plateau (Figure 4). The model domain was 1400 km long (x direction) and 300 km deep (y direction), with three layers: the crust, the mantle lithosphere, and the asthenosphere. Based on the geophysical observations (Lei et al., 2014; Li and van der Hilst, 2010; Wang et al., 2003; Wang and Huangfu, 2004; Yao et al., 2010), the initial crustal thicknesses of the Indian plate and southeastern Tibetan plateau were observed to be 40 km and 60 km, respectively. The crustal thickness changed linearly across the transition. The lithosphere remained 100 km thick.

The mechanical boundary condition was imposed as follows. A full free boundary condition was imposed on the top surface of the model. The bottom surface of the model was assumed to be a free-slip boundary condition ($v_y = 0$, $\frac{\partial v_x}{\partial y} = 0$).

Different boundary conditions were applied to the other two sides of the model according to different cases. For the thermal boundary condition, a constant temperature of 0°C and 1420°C was imposed on the top and bottom surfaces of model, respectively. The left and right sides of the model were the adiabatic boundary

condition ($\frac{\partial T}{\partial x} = 0$). The total number of nodes and quadrilateral elements used were

9715 and 9504, respectively. The grid sizes of the model were approximately 10 km in the horizontal direction and approximately 5 km in the vertical direction, respectively.

There were 144000 markers to trace the movement of the different materials.

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308 **3.3 Model parameters**

309 Seismic tomography showed that the mantle lithosphere had a high velocity
310 anomaly for the Indian plate and a low velocity anomaly for the southeastern Tibetan
311 plateau. However, the crust had a low velocity anomaly for both of them (Lei et al.,
312 2009; Li and van der Hilst, 2010; Wei et al., 2012). This implies that the lithospheric
313 strength of Indian plate is larger than that of the southeastern Tibetan plateau. Based
314 on the constraints of heat flow, strain rate, crustal structure and lithology, (Sun et al.,
315 2013a,b) evaluated the lithospheric temperature and rheology beneath China and its
316 surrounding region. According to these results, we selected the viscosity and yield
317 strength (Table 1). There were some uncertainties of the parameters. However, in this
318 study, we wanted to investigate the effect of tectonic boundary conditions on the
319 lithospheric deformation and thermal structure. Thus, the parameters were nearly the
320 same for all cases. Since the mechanical or thermal parameters had an effect on the
321 final results, the parameters adopted in this study ensured that the slab had a high
322 angle subduction (Table 1). We will discuss the effect of different factors in the
323 discussion. For some cases, a weak zone (lower viscosity and low plastic yield
324 strength), representing the plate boundary, was added between the Indian plate and
325 southeastern Tibetan plateau. When we considered the effect of preexisting suture
326 zones on the deformation in the strong block, a similar weak zone was added within
327 the southeastern Tibetan plateau.

328 In this study, we considered the effect of the Indian plate subduction and regional

extension on the deformation of the lithosphere. Three cases were discussed as follows.

In case 1, we considered the effect of subduction of the Indian plate on the lithospheric deformation and thermal structure. A weak zone, which represented the plate boundary, was added between the Indian plate and southeastern Tibetan plateau. A 40 mm/yr horizontal velocity boundary was imposed on the left side of the model ($v_x = 40 \text{ mm/yr}$), representing the movement of the Indian plate. The vertical velocity was free on the left side. On the top surface of the model, a full free boundary condition was applied. Free-slip boundary conditions were imposed on the bottom ($v_y = 0$, $\frac{\partial v_x}{\partial y} = 0$) and right sides ($v_x = 0$, $\frac{\partial v_y}{\partial x} = 0$) of the model. The computing time was 15 Myr.

In case 2, we considered the effect of regional extension on the lithospheric deformation and thermal structure beneath the southeastern Tibetan plateau. There were no weak zones between the Indian plate and the southeastern Tibetan plateau. However, a preexisting weak zone was added within the southeastern Tibetan plateau representing a suture zone in the southeastern Tibetan plateau. A 40 mm/yr horizontal velocity boundary was imposed on the right side of the model ($v_x = 40 \text{ mm/yr}$). The vertical velocity was free on the right side. On the top surface of the model, full free boundary conditions were applied. Free-slip boundary conditions were imposed on the left ($v_x = 0$, $\frac{\partial v_y}{\partial x} = 0$) and bottom sides ($v_y = 0$, $\frac{\partial v_x}{\partial y} = 0$) of the model. The computing time was 15 Myr. In this case, we did not consider the Indian plate

subduction. With case 1 and case 2, we considered the independent effect of the Indian plate subduction and regional extension on the lithospheric deformation.

In case 3, both the effects of the Indian plate subduction and regional extension on the lithospheric deformation were considered. Two weak zones were added in the model (Figure 4). The total computing time was 20 Myr. From 0 to 12 Myr, a 40 mm/yr horizontal velocity was imposed on the left side of the model ($v_x = 40 \text{ mm/yr}$) while free-slip boundary conditions were imposed on the right side ($v_x = 0, \frac{\partial v_y}{\partial x} = 0$). From 12 to 20 Myr, a 40 mm/yr horizontal velocity was imposed on the right side ($v_x = 40 \text{ mm/yr}$) of the model while the left side had a free-slip boundary condition ($v_x = 0, \frac{\partial v_y}{\partial x} = 0$). From 0 to 20 Myr, the top and bottom surfaces of the model were imposed full free and free-slip boundary conditions, respectively. The boundary conditions imposed in case 3 were consistent with the geological surveys. Surveys from the structure geology and geochronology suggest that the stress environment around the Tengchong block changed to rotation or extension from compression since 8-5 Ma (Kornfeld et al., 2014; Tong et al., 2013; Wang et al., 2008; Yang et al., 2001).

The material parameters for the three cases were given in the Table 1. The same thermal boundary conditions were imposed for all three cases. To quantitatively evaluate the results of each case, the surface heat flow and lithospheric structure from observations were used to constrain the calculation results. The surface heat flow in the Tengchong volcanic region is larger than that of other regions. The depths of

Moho surface and LAB beneath the Tengchong volcanic region are smaller than in other regions (Figure 3).

4. Results

4.1 Indian plate subduction (Figure 5)

In case 1, the effect of the Indian plate subduction on the movement of the asthenosphere and the lithospheric deformation beneath the southeastern Tibetan plateau is considered. The initial crustal thickness of the southeastern Tibetan plateau is larger than that of the Indian plate. Thus, under isostasy, the mantle substance beneath the Indian plate would be pushed to the underside of the southeastern Tibetan plateau. Continuous compression has thickened the crust and mantle lithosphere for the Indian plate and the southeastern Tibetan plateau. The Indian mantle lithosphere subducts beneath the southeastern Tibetan plateau. In the retro-side, the asthenosphere beneath the southeastern Tibetan plateau upwells because of the driving force from the subducting plate. The upwelling asthenosphere reduces the thickness of the lithosphere beneath the west side of the southeastern Tibetan plateau for 10-30 km at 10 Myr and 30-50 km at 15 Myr, which is thinner than in other areas (Figure 5). However, the relatively thin lithosphere does not cover the whole southeastern Tibetan plateau. The area with thinned lithosphere, a result of the subducting plate, is limited. The width of thinned lithosphere in front of the subduction is 400 km at 15 Myr.

Thermal structures show there to be a low-temperature zone along the subduction in this case. Low temperatures and brittle deformation produce deep-epicenter

earthquakes. On the retro-side, the upwelling of hot asthenosphere leaves the thermal thickness of the lithosphere smaller than on the pro-side. Compression for 15 Myr has left the surface heat flow relatively low in the Indian plate (50 mW/m^2). However, the surface heat flow is relatively high (75 mW/m^2) beneath the southeastern Tibetan plateau (Figure 5). In this model, the thermal thickness of the lithosphere beneath the southeastern Tibetan plateau was not uniform. The thermal thickness of the lithosphere in front of the subducting slab is thinner than in other areas. Thus, the high surface heat flow corresponds to the upwelling of the asthenosphere and the relatively thin lithosphere beneath the southeastern Tibetan plateau. However, unlike the observed data, the calculation did not show a high surface heat flow area in the Tengchong block (Figure 5). In addition, the Moho surface and LAB was relatively uniform for the thinned lithosphere in case 1, which is also different from what was observed (Figure 3 and Figure 5).

The Tengchong volcanic region is located in the southeastern Tibetan plateau away from the plate boundary by about 300 km. The upwelling asthenosphere, which is caused by the subducting slab, provides an upward driving force and high temperature environment for the bottom of the lithosphere. This process causes the mantle lithosphere to thin. However, this thinned lithosphere only extends 300-400 km in front of the subducting slab (10-15 Myr in Figure 5). The effect of deep subduction, such as the dehydration melting after penetrating the 410 km, was not considered in this study (Li et al., 2013; Li et al., 2015). However, this model shows that the subduction of the plate causes the upwelling of the asthenosphere on the

retro-side, which leads to a relatively thin lithosphere in front of the subducting slab.

4.2 Regional extension (Figure 6)

In case 2, only the effect of regional extension on the deformation and thermal structure of the lithosphere is considered. A weak zone is added within the southeastern Tibetan plateau. It represents the preexisting suture zone (such as Bangong-Nujiang suture zone). With the continuous extension on the right side of the model, the lithosphere, both for the Indian plate and southeastern Tibetan plateau, is thinned. However, the lithosphere of the southeastern Tibetan plateau is thinner because of its low yield strength. There are two regions where the lithosphere has thinned notably. One is located in the weak zone where the asthenosphere upwells. The other is located near the transition between the Indian plate and the southeastern Tibetan plateau where the crustal thickness changes (Figure 6).

According to the thermal structure, the surface heat flow generally correlates with the thickness of the lithosphere. High surface heat flow is associated with the relatively thin lithosphere, and vice versa. These characteristics denote the basic relationship between the deformation of the lithosphere and geological observations. For instance, high heat flow is generally observed in the rift or oceanic basin where the extensive deformation is predominant. In this way, the regional extension plays an important role in the deformation and thermal structure of the lithosphere. After an extension of 15 Myr, the surface heat flow in the southeastern Tibetan plateau (75-85 mW/m²) was higher than that in the Indian plate (65-75 mW/m²). The highest surface

heat flow emerges in the weak zone ($120\text{-}140\text{ mW/m}^2$), where the deep asthenosphere upwells. The simulated surface heat flow is generally consistent with the observations in most regions (Figure 6). However, the extension should last for 10-15 Myr in order to reach this thermal state. This is longer than the observed data, which indicate 5-8 Myr. In this case, the general shape of the extended lithosphere beneath the weak zone is consistent with that of the observed Moho and LAB (Figure 3 and Figure 6). However, the calculated thickness of the thinned lithosphere is even thinner than what was observed. The calculated lithospheric thickness beneath the southeastern Tibetan plateau decreases to 80-90 km after 10-15 Myr extension. In the weak zone, the thickness of the lithosphere has thinned to 50-60 km. This is thinner than the observation by 10-20 km (Figure 3 and Figure 6).

4.3 Indian plates subduction and regional extension (Figure 7)

In case 3, from 0 to 12 Myr, a 40 mm/yr push velocity boundary condition is imposed on the left side of the model. From 12 to 20 Myr, a 40 mm/yr pull velocity boundary condition is imposed on the right side of the model, while the left velocity is imposed as 0. The purpose of the imposed boundary conditions is to investigate the joint effect of the Indian plate subduction and the regional extension on the lithospheric deformation. With continuous compression (0-12 Myr), the Indian plate subducts beneath the southeastern Tibetan plateau. Unlike in case 1, the southeastern Tibetan plateau has a weak zone. The lithospheric deformation is generally consistent with case 1, except in the weak zone (Figure 5 and Figure 7). The upwelling

asthenosphere causes the lithosphere to be relatively thin beneath the left part of the southeastern Tibetan plateau. However, the crust and mantle lithosphere along the weak zone are thickened because of its low viscosity under compression. This indicates that thermal erosion of the lithosphere along the weak zone has not occurred under compression. After 12 Myr, the push velocity on the left side of the model is suspended and the pull velocity on the right side is predominant. During extension, the weak zone in the southeastern Tibetan plateau plays an important role in the lithospheric deformation. During the extension, the lithosphere along the weak zone rapidly thins. At 18 Myr, the depths of the Moho and LAB are about 30km and 75km, respectively. Increasing the distance from the weak zone gradually increases the depth of LAB to 120 km. The lithospheric structure is consistent with the observations (Figure 3 and Figure 7).

During compression (0-12 Myr), the thermal structure shows the surface heat flow in the southeastern Tibetan plateau to be higher than that in the Indian plate. There are two possible reasons for this. One is that the thick crust in the southeastern Tibetan plateau may have more radioactive heating. The other one is that the thinned lithosphere caused by upwelling of the asthenosphere beneath the southeastern Tibetan plateau. During extension, the lithospheric thickness of the weak zone in the southeastern Tibetan plateau rapidly decreases. The temperature gradient and surface heat flow along the weak zone increases accordingly. Thus, the weak zone is the center of the high surface heat flow. However, the effect of extension on the Indian plate subduction is not obvious. The extensive deformation is mostly localized to the

southeastern Tibetan plateau since it has a low yield strength and a weak zone. The calculated surface heat flow at 18 Myr is highly consistent with the observation (Figure 7). The highest surface heat flow is localized to the weak zone, which reaches 140 mW/m². By increasing the distance from the weak zone, the surface heat flow decreases to 50 mW/m² on the right side of the model. The extension time lasts for 6 Myr in the calculation, which is consistent with that of the Tengchong block (since 5-8 Ma).

In case 3, we calculate the second invariant of the deviatoric strain rate (Figure 8) and the second invariant of the deviatoric stress (Figure 9). The strain rate reflects the degree of deformation. In general, a stable block has a low strain rate and an active fault or suture zone has a high strain rate. The magnitude of stress is consistent with that of the strain rate for the viscous deformation. The model does not take into account the healing of viscosity in this calculation. When the stress reaches the yield strength, the viscosity decreases sharply because of plastic deformation. Thus, plastic deformation generally corresponds to low stress.

In the compressive progress, the high strain rate is mainly distributed along the plate boundary and the suture zone. In the initial compression (0-10 Myr), the high strain rate concentrates on the plate boundary. However, with further compression (10-12 Myr), the high strain rate becomes localized to the weak zone in the southeastern Tibetan plateau (Figure 8). This indicates that the compressive deformation propagates from the collision boundary to the interior of the southeastern Tibetan plateau. In the initial compression (0-10 Myr), high stress is localized to the

Indian plate. With further compression (10-12 Myr), high stress is distributed in the southeastern Tibetan plateau (Figure 9). However, when the pull velocity is imposed on the right side (>12 Myr), the high strain rate is mainly localized to the weak zone in the southeastern Tibetan plateau (Figure 8). This indicates that the deformation of the weak zone is under the plastic deformation state. The stress along the weak zone is smaller than that of the other areas. The subducting Indian plate has both a high stress and low strain rate, since it has high strength (Figure 8 and Figure 9).

Case 3 can be used to understand the dynamics of the Tengchong volcanic region. The subducting Indian plate results in the upwelling of the asthenosphere beneath the southeastern Tibetan plateau, providing an upward driving force and a high-temperature environment for the Tengchong volcano. It also thins the lithosphere beneath the Tengchong block. When the regional extension is dominant, the lithosphere thins rapidly because of the weak zone in the southeastern Tibetan plateau. Due to the lithospheric extension, the upwelling asthenosphere further erodes the lithosphere. The substance of the mantle erupts into the crust or surface, which becomes the volcanic eruption. In case 3, both the lithospheric structure and surface heat flow are highly consistent with the observation. Thus, the subduction of the Indian plate and local extension jointly promote the formation of the Tengchong volcanic region.

5. Discussion

5.1 Why the Cenozoic volcano occurs only in the Tengchong volcanic region

The previous cases show that the weak suture zone plays an important role in the formation of the Tengchong volcanic region. To investigate this issue, we calculated two additional cases. In case S1 (Figure S1), the weak zone only extends to the upper crust, which represents a fault. One of the differences between the suture zone and the fault is that the suture zone cuts through the lithosphere, and the fault is limited to the crust. The parameters and boundary conditions are the same as in case 3. The results show that the depth of the LAB does not change sharply beneath the weak zone, although the surface heat flow is consistent with the observation (Figure 3, Figure 7 and Figure S1). This shows that the extension of the suture zone is more propitious to the upwelling of the asthenosphere. The extension of the faults in the upper crust also leads to the high surface heat flow. However, magmatic activity coming from the mantle is not obvious because the mantle lithosphere beneath the weak zone is not strongly eroded.

In case S2, the initial weak suture zone is located away from the plate boundary by 600 km (Figure S2), which is farther than in case 3 (400 km in Figure 4). The results of case S2 show that neither the lithospheric structure nor surface heat flow fit the observation. If the weak zone is far enough from the plate boundary, the effect of the upwelling asthenosphere on the lithospheric thinning beneath the weak zone is not pronounced. In the extension process, the lithosphere would not be thinned beneath the weak zone. Around the Tengchong volcanic region, the Bangong-Nujiang suture

zone is the nearest suture zone from the plate boundary between the Indian plate and the southeastern Tibetan plateau and is obviously affected by the Indian plate subduction (Figure 1). The Cenozoic volcanic activity is not obvious along other suture zones, such as the Jinshajiang suture zone because they are farther away from the thinned lithosphere caused by the upwelling asthenosphere.

5.2 Rheological parameters

This study principally considers the effect of boundary conditions, which represent the tectonic constraints. However, the rheological parameters are very important to the calculation. Previous studies have shown that subduction characteristics and lithospheric structures are related to the viscosity and strength of the lithosphere (Chen et al., 2013; Cook and Royden, 2008; Li et al., 2011b). In this study, earthquake distribution and tomography show that the Indian plate subducts beneath the southeastern Tibetan plateau with a high angle (Figure 3) (Huang and Zhao, 2006; Lei et al., 2009; Wei et al., 2012). With this constraint, the adopted rheological parameters should guarantee that the characteristics of subduction are consistent with the observation. To investigate the effect of viscosity and yield strength, two additional cases, case S3 and case S4, were calculated. The boundary conditions for these two cases are the same as case 3.

In case S3, the viscosity of the crust and mantle lithosphere for the southeastern Tibetan plateau was 80% lower than in case 3. In the compressive process for case S3 (Figure S3), the lithosphere of the southeastern Tibetan plateau has become thicker

than in case 3 because of its low viscosity. However, when the extension is dominant, the lithosphere is thinner, especially for the left part of the southeastern Tibetan plateau (on the left of the suture zone). Although the extension time is longer than case 3, the surface heat flow and lithospheric structure in case S3 are consistent with the observation at 20 Myr (Figure S3, Figure 3).

In case S4, the yield strength of the crust and mantle lithosphere for the southeastern Tibetan plateau is 40% lower than case 3. In the compressive process of case S4 (Figure S4), the effect of the upwelling asthenosphere on the left part of southeastern Tibetan plateau is obvious. The lithosphere beneath the left part of the southeastern Tibetan plateau is thinner than in other regions. During extension, the thickness of the lithosphere beneath the left part of the southeastern Tibetan plateau is thinned even further. The surface heat flow is also consistent with the observation (Figure S4). Under the constraint of subduction characteristics, case S3 and case S4 show that the limited change of rheological parameters does not change the characteristics of the surface heat flow and the lithospheric structure.

5.3 Boundary conditions and surrounding tectonic setting

The main factors considered that affect the results of this numerical model are the boundary conditions, which represent the tectonic constraints. The boundary conditions in case 3 are consistent with geological settings. The convergence rate between the Indian plate and the southeastern Tibetan plateau is consistent with the GPS observation. The stretching structure of geological observation implies that the

Tengchong block and Bangong-Nujiang suture zone have been under nearly east-west or northwest-southeast extension since 8-5 Ma. Although the specific stretching rate and dynamics are unclear, the results show that the extension, with a rate of 40 mm/yr for 3-5 Myr, has already caused a thinned lithosphere beneath the Tengchong block. The change from compression to extension since 8-5 Ma may have a relationship with the surrounding tectonic setting. Extrusion of the southeastern Tibetan plateau is generally considered to be caused by the expansion of the Andaman Sea and South China Sea. Paleomagnetic studies and sedimentological studies from the seafloor show that the extension of the South China Sea has been suspended since 15 Ma. However, the Andaman Sea has been opening since 13-4 Ma (Briais et al., 1993; Curray, 2005; Hall, 2002; Hsu et al., 2004; Kido et al., 2001; Morley and Alvey, 2015; Xu et al., 2012a; Yin, 2010). The cessation of the extension of the South China Sea promotes the dextral slip of the Red River-Ailaoshan fault zone, which may change the slip direction of active faults in the southwestern Yunnan. The opening of the Andaman Sea enhances the sinistral slip of the Sagaing fault and the clockwise rotation of the Tengchong block. Further investigation into this issue should be carried out in the future.

6. Conclusion

Based on the tectonic setting and geological observation, a series of numerical models were here constructed to study the dynamics of the Tengchong volcanic region. The effect of different boundary conditions on the lithospheric deformation

and thermal structures were the principal issues considered. The following conclusions were drawn:

(1) The compressive model shows that the subduction of the Indian plate causes upwelling of the asthenosphere beneath the Tengchong block, which produces the upward driving force and a high-temperature environment found in the Tengchong volcanic region. In this process, thermal erosion of the lithosphere caused by upwelling of the asthenosphere renders the lithosphere especially thin beneath the Tengchong block. However, if there is no extension, the surface heat flow for this case is not consistent with the observation.

(2) The regional extension model shows that the asthenosphere would uplift along the preexisting weak suture zone in the southeastern Tibetan plateau. However, the thinned lithosphere is not uniform beneath the southeastern Tibetan plateau. Extensive deformation and a thinned lithosphere along the suture zone are obvious. The lithosphere is the thinnest and the surface heat flow is the highest along the suture zone. However, an extension of 10-15 Myr is generally needed to fit well with the surface heat flow. This is not consistent with the data from the structure geology and geochronology.

(3) With the constraints of kinematics of tectonic deformation, geochronology and paleomagnetism, a boundary condition from compression to extension is imposed on the numerical model. The results of this case show that the lithosphere beneath the Tengchong block is eroded and thinner than in other regions for 10-30 km in the compressive process. During extension (8-5 Ma), the upwelling of the asthenosphere

would cause an even thinner lithosphere along the preexisting Bangong-Nujiang suture zone. Thus, the formation of the Tengchong volcanic region can be attributed to the result of the Indian plate subduction and the regional extension.

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Table 1 Parameters used in this study.

Layers	Indian plate		Southeastern Tibetan plateau	
	Viscosity (Pa.s)	Yield strength (Pa)	Viscosity (Pa.s)	Yield strength (Pa)
Crust	5.0E22	20.0E6	5.0E22	50.0E6
Mantle lithosphere	5.0E22	100.0E6	5.0E22	50.0E6
Asthenosphere	1.0E21	----	1.0E21	----
Weak zone in crust	5.0E20	20.0E6	1.0E21	10.0E6
Weak zone in mantle	5.0E20	20.0E6	1.0E21	10.0E6

In all cases, densities of the crust and mantle were 2800 kg/m^3 and 3300 kg/m^3 , respectively. Radioactive heat productions of the crust and mantle were $1.28\text{E-}6 \text{ W/m}^3$ and 0, respectively. Heat conductivities of the crust, mantle lithosphere and asthenosphere were $3.0\text{W}/(\text{m.K})$, $3.4\text{W}/(\text{m.K})$ and $3.8\text{W}/(\text{m.K})$, respectively. Heat capacity was $1300 \text{ J}/(\text{kg.K})$ for all layers. The crust and mantle lithosphere follow the visco-plastic rheology. The asthenosphere follows the viscous rheology.

Figure 1 Tectonic setting of the southeastern Tibetan plateau.

Red triangles indicate volcanoes in the southeastern Tibetan plateau and surrounding area. Black solid lines indicate the faults. Black arrows represent the slip direction of faults. The black dashed line indicates the ductile shear zone. Red dash lines indicate the suture zones in the Tibetan plateau. White arrows in the inset map represent the crustal movement direction relative to the Eurasian plate (Gan et al., 2007). YZS: Yarlung-Zangbo suture zone; BNS: Bangong-Nujiang suture zone; JSS: Jinshajiang suture zone; GLGDSZ: Gaoligong ductile shear zone; MFTF: Main frontal thrust fault; SGF: Sagaing fault; LCJF: Longchuanjiang fault; WDF: Wanding fault; NTF: Nantinghe fault; RRF: Red River fault; XSHF: Xianshuihe fault; DBFF: Dianbianfu fault; NJR: Nujiang river; LCJR: Lancangjiang river; JSJR: Jinshajiang river. TV: Tengchong volcano; SV: Singu plateau volcano; PV: Popa volcano.

Figure 2

Figure 2 Map of the topography, earthquakes, surface heat flow and GPS velocity distribution in the southeastern Tibetan plateau.

Squares indicate the heat flow values at different sites (<http://www.geophysik.rwth-aachen.de/IHFC/heatflow.html>). Black arrows represent the GPS velocity (Gan et al., 2007; Maurin et al., 2010). Red triangles indicate the distribution of volcanoes in this region. The earthquake focal mechanisms ($M_w \geq 5.0$) are from the Harvard CMT catalogue (1976-2010). Blue lines indicate the AA' and BB' profiles, which are shown in Figure 3.

Figure 3

Figure 3 Distribution of earthquakes, surface heat flow and elevation variation along the AA' and BB' profiles.

The gray areas in the profiles are limited by the maximum and minimum elevations within a 30 km wide swath along the profiles. Solid blue lines represent the average elevations along the profiles. Dashed blue lines indicate the Moho surface based on the Crust2.0 model. Black dashed lines represent the lithosphere-asthenosphere boundary (LAB) (Hu et al., 2012; Zhang et al., 2015). The red triangle indicates the position of the Tengchong volcano. Green squares indicate the surface heat flow values along the profiles. Black dots indicate the distribution of relocated earthquakes ($M \geq 3.0$) along the two profiles during 1970 -2006 (Engdahl et al., 1998; Wei et al., 2012). SGF: Sagaing Fault.

Figure 4

Figure 4 Finite element model and boundary condition for Case 1.
1. Indian crust; 2. Eurasian crust; 3. Indian mantle lithosphere; 4. Eurasian mantle lithosphere; 5. Asthenosphere; 6. Weak zone for crust; 7. Weak zone for mantle lithosphere.
x is the horizontal coordinates. y is the vertical coordinate pointing upward.

Figure 5

Figure 5 Materials, temperature (°C) (white lines) and surface heat flow (redlines) for case 1. Red lines indicate the surface heat flow. Green squares indicate the observed heat flow values along the profile AA'. In this projection, the position of the observed surface heat flow is relative to the plate boundary. The red triangle indicates the position of the Tengchong volcanic region corresponding to the surface heat flow. White lines denote the isotherm. Different colors in the background represent different materials.

Figure 6

Figure 6 Materials, temperature ($^{\circ}\text{C}$) (white lines) and surface heat flow (red lines) under extension in case 2. Green squares indicate the observed heat flow along the profile AA'. In this projection, the position of the observed surface heat flow is relative to the weak zone, which presents the Bangong-Nujiang suture zone. The red triangle indicates the position of the Tengchong volcanic region corresponding to the surface heat flow. Labels and illustrations are similar to those used in Figure 5.

Figure 7

Figure 7 Materials, temperature (°C) (white lines) and surface heat flow (red lines) for case 3. Green squares indicate the observed heat flow along the profile AA'. In this projection, the position of the observed surface heat flow is relative to the weak zone, which presents the Bangong-Nujiang suture zone. The red triangle indicates the position of the Tengchong volcanic region corresponding to the surface heat flow. Labels and illustrations are similar to those used in Figure 5.

Figure 8

Figure 8 The second invariant of the deviatoric strain rate in case 3. Dashed lines show the general boundaries of different parts and layers. The red triangle indicates the possible position of the Tengchong volcanic region corresponding to the high surface heat flow.

Figure 9

Figure 9 The second invariant of the deviatoric stress in case 3. Dashed lines show the general boundaries of different parts and layers. The red triangle indicates the possible position of the Tengchong volcanic region corresponding to the high surface heat flow.