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Westward migration of high-magma addition rate events in SE Tibet

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ABSTRACT

Arc magmatism is an important process in the formation and evolution of the continental crust. Various arcs developed in the southern margin of Eurasian continent that recorded the final formation and growth of these micro-continent before the final India-Eurasia amalgamation. We have examined the often neglected Tengchong arc segment in southeastern Tibet using compiled zircon U-Pb-Hf and whole-rock geochemistry with GPS location and lithology control. The aim is to better understand the driving mechanism of spatial migration and temporal evolution of multi-stage high-MAR (magma addition rate) events and its role in formation and growth of Tengchong arc segment.

Results indicate three magmatic "flare-ups" during east-to-west arc migration, from ~131–111 Ma (eastern), ~76–64 Ma (central), to ~55–49 Ma (western), during amalgamation of Lhasa-Tengchong and Qiangtang-Baoshan blocks and final collision of India-Asia plate following subduction of Neo-Tethys. Zircon Hf isotopes and geochemical analyses shows the significant increasing juvenile and/or mantle-derived materials and the range of isotopes also broaden during flare-ups, indicating the melting of diverse lithospheric and upper plate domains. Through comparison with geophysical parameters, these pulses are closely coupled with the arc migration along with changes of crustal thickness, but not correlated with angle and rates of convergence. The spatial arc migration of the multi-stage high-MAR events in Tengchong arc segment was potentially driven by slab steepening and break-off following the initial collision, and abrupt changes of subduction slab dynamics. These processes are well coupled with multi-stage interactions of crust-mantle and transitional Moho-depths.

1. Introduction

Episodic high-volume magmatism in arcs lasting ca. 5–40 m.y., also known as "magmatic flare-ups", have played a key role in building oceanic and continental crust as well as driving long-term surface processes such as weathering, erosion and greenhouse events (Paterson and Ducea, 2015; Ducea et al., 2015; Lee et al., 2012; Cao and Paterson, 2016, Chapman et al., 2021; Li et al., 2022). Continental arcs are some of the most important locations for mountain building, ore deposit formation, water resources, climate change, and various geological hazards (Lee et al., 2012; Li et al., 2019). These processes are closely associated with the spatial and temporal evolution and distribution of episodic high-MAR events (Paterson and Ducea, 2015; Ducea et al., 2015; Li et al., 2022).

The mechanism(s) driving flare-ups are either related to external forcing and/or internal, upper plate processes (Paterson and Ducea, 2015). One upper plate process driving flare-ups may be episodic mantle processes (Anderson, 1982; Gurnis, 1988). Alternatively, upper-plate processes, including episodic addition of melt-fertil materials by underthrusting of retroarc lower crust (DeCelles et al., 2009), crustal/lithospheric thickening during subduction (Ducea and Barton, 2007), and the role of arc migration into subduction-related metasomatized material (Chapman and Ducea, 2019) have been suggested as drivers of arc flare-ups.

Flare-ups may also be driven by episodic increases in mantle magma addition into the arc (Martinez-Ardila et al., 2019). Attia et al. (2020) suggests increased mantle magma input not only drives arc flare-ups but also represent significant continental crust formation in continental arcs. Flare-ups of the Mesozoic Median Batholith could be from the underlying mantle and triggered by an external dynamic mantle process

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(Schwartz et al., 2017). Both fertile upper-lithospheric and juvenile magma from the mantle could provide significant contributions to flare-ups.

As an interesting comparison to Cordilleran systems, a series of magmatic arcs developed from the Mediterranean, along the Himalayan system to Sumatra during the long Tethyan closure before final India-Asian welding. During the Cretaceous to Early-Cenozoic, an Andean-style continental arc associated with the northward subduction of Neo-Tethyan oceanic lithosphere developed on the southern margin of the Eurasian continent (Fig. 1A) (Searle et al., 1987). It has been proposed for the Neo-Tethyan arc system that the changes in slab dynamic parameters in the subduction zone and subsequent amalgamation could induce episodic magmatism with both juvenile mantle-like and fertile continental crustal characteristics (Zhu et al., 2011; Zhang et al., 2019; Shafaii Moghadam et al., 2020; Guo et al., 2022).

In this contribution, we focus on the Tengchong arc, an often overlooked arc segment at the southeastern end of the Tibetan Plateau. Similar to the Kohistan and Gangdese arcs in the Southern Tibetan Plateau, the Tengchong arc segment records the formation and evolution of continental crust in the southern margin of the Eurasian plate before the final welding of India-Asia. The westward spatial distribution of episodic magmatic arcs (predominately preserved as granitoid batholiths) through temporal evolution from Early-Cretaceous to early-Cenozoic in southeastern Himalayan-Tibetan orogenic system is shown in Fig. 1B. Using zircon U-Pb geochronology, Lu-Hf isotopes, bulk-rock geochemistry, crustal thickness and other geophysical parameters, we not only trace the role of the crust-mantle source contribution of Tengchong arc magmatism but explore insights into the role of deep crust-mantle dynamic processes during subduction and subsequent collision of two continental plates. We also calculate the evolution of Moho depth through space and time and reconstruct the geochronology and evolving isotopes. We then synthesize these data with the aim of better understanding the mechanisms of migration and multi-stage flare-ups, the interaction of the crust and mantle through space and time and its role in formation of this continental boundary.

2. Geological background

The Greater Tibetan Plateau, including Pamir and Tibet plateau (Chapman et al., 2018), is regarded as part of a single contiguous orogenic plateau (Himalaya) consisting of a series of allochthonous Gondwanan continental fragments that were accreted to Asia during the early-Mesozoic (Allegre et al., 1984; Burtman and Molnar, 1993; Robinson et al., 2012; Chapman et al., 2018), culminating in the India collision with Asia during the Late-Cretaceous to Early-Cenozoic (Hu et al., 2016; Bouilhol et al., 2013; Chung et al., 2005). In this orogenic system, the fragments include the Songpan-Ganzi, Qiangtang, Lhasa and Himalayan terranes, separated by the Jinsha, Bangong-Nujiang, and Indus-Yarlung sutures (Yin and Harrison, 2000). The Qiangtang terrane, from north to south, is laterally equivalent to the central Pamir terrane, the south Pamir terrane, and the Karakoram terrane (Chapman et al., 2018), but has no direct equivalence with the Lhasa terrane in Pamir (Robinson et al., 2012). The Lhasa terrane is laterally equivalent to the Tengchong terrane of southeastern Tibet (Xie et al., 2016), although rotated ca. 87° at ca. 40 Ma (Kornfeld et al., 2014; Xu et al., 2015) (Fig. 1A). These accreted processes are typical of the Cordillera and/or Andes, where long belts of deformation and magmatism are associated with the subduction of oceanic plates beneath continental plates (DeCelles et al., 2009). Multi-stage continent-continental collision events resulted in the final convergence and uplift of the Tibetan Plateau (Yin and Harrison, 2000), to form the highest mountains on Earth.

The Tengchong arc segment forms the southeastern extension of the Lhasa terrane (Xu et al., 2015; Xie et al., 2016; Fig. 1B) and is separated from the eastern Baoshan terrane by the Nujiang–Longling–Ruili fault (NLRF) and from the western Burmba terrane by the Putao–Myitkyina suture zone (Xu et al., 2015; Metcalfe, 2013). The terrane contains

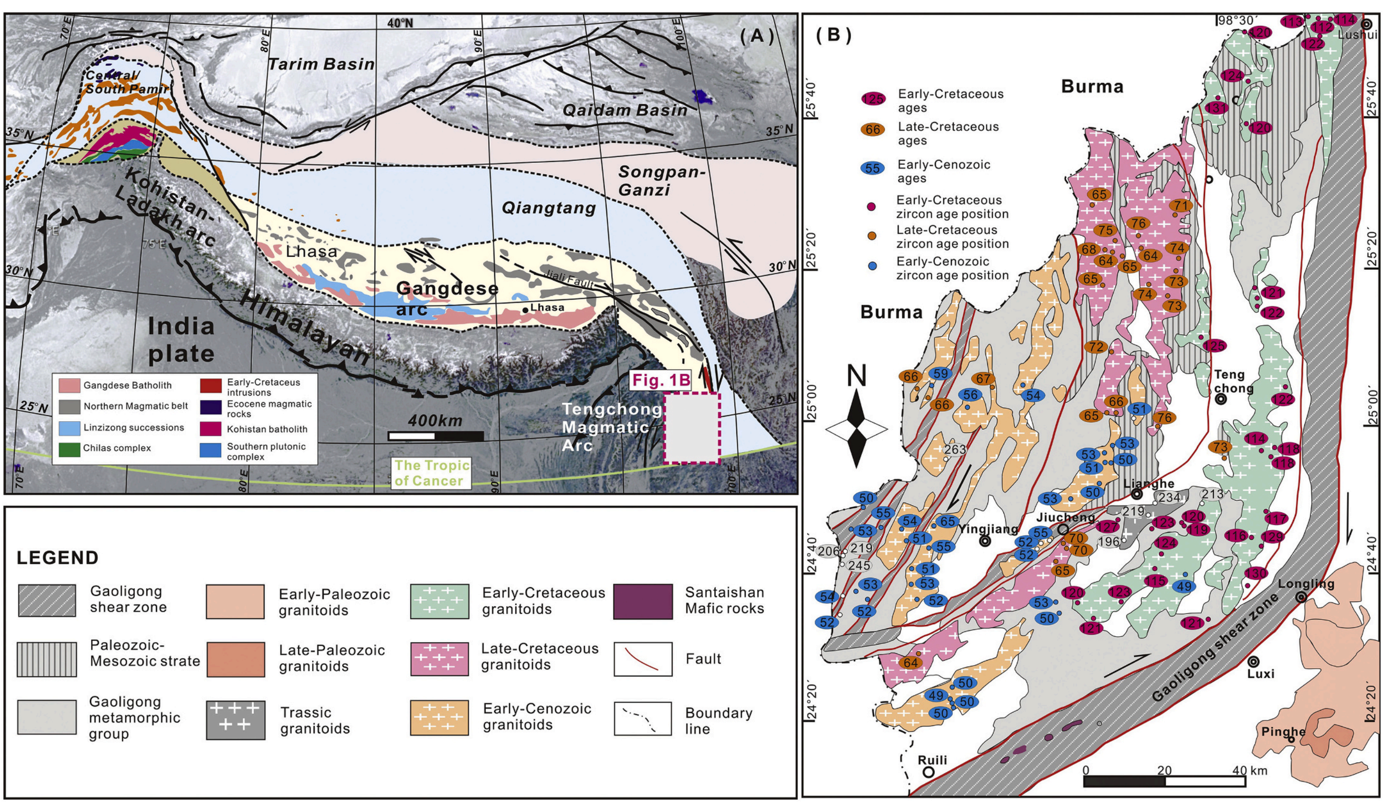

Fig. 1. A. Distribution of main continental blocks in the Tibet-Pamir orogenic system (Chung et al., 2005; Chapman et al., 2018). B. The geological and mainly magmatic map of Tengchong terrane in the SE Tibet orogen (Xu et al., 2015).

Mesoproterozoic metamorphic basement belonging to the Gaoligong Mountain Group and upper Paleozoic clastic sedimentary rocks and carbonates. Mesozoic to Tertiary granitoids were emplaced into these strata (Zhu et al., 2015; Zhu et al., 2018a) and were then covered by Tertiary–Quaternary volcano-sedimentary sequences (YNBGMR, 1991). The Tengchong arc segment is typical of old arcs that have been eroded down to plutonic levels, where little coeval volcanic rocks remain: older units are covered by recent late-Cenozoic to Quaternary volcanic sequences. Today there is little arc-related volcanic rocks preserved in this region compared to the extensive granitoid plutons.

A series of N-S and NE-SW trending faults developed in the Tengchong Terrane (Fig. 1B). The Nujiang-Lushui-Longling-Ruili fault and Gaoligong shear zone separates the tectonic mélange to the west and the Cambrian-Ordovician granitoids to the east (Zhao et al., 2016; Zhu et al., 2018b). Three faults divide the Tengchong Terrane into three magmatic belts: Mingguang-Menglian, Guyong-Longchuan and Sudian-Tongbiguan magmatic belts, separated by the Dayingjiang, Gudong-Tengchong and Binlangjiang faults (Xie et al., 2016; YNBGMR, 1991) (Fig. 1B). The three magmatic belts are ~120 km in width and ~240 km in length, each with a ca. 30–40 km wide trench parallel band.

The three 30–40 km wide ribbons of arc magmatism reflect a westward migration of arc magmatism through time (Fig. 1B). The eastern magmatic belt is located in the eastern Tengchong terrane and is composed mostly of three batholiths: (1) The Pianma-Mingguang-Gudong batholith intruded into Paleozoic to Mesozoic strata and Gaoligong metamorphic group, containing the Pianma diorite-granodiorite-monzogranite association (Zhu et al., 2017b), Mingguang-Gudong highly fractionated I-type granites (Zhu et al., 2015), and Dajujie alkaline granites (Zhu et al., 2018b). (2) The Xinhua-Menglian batholith intruding the Gaoligong metamorphic group consisting mostly of granodiorite-monzogranites and associated abundant mafic magmatic enclaves (Xie et al., 2016; Zhu et al., 2017a). (3) The Xiaotang-Mangdong batholith containing mainly mozodiorite-tonalite-granodiorite and associated mafic magmatic enclaves (Cong et al., 2011; Zhu et al., 2017a). The central magmatic belt is located in the central Tengchong terrane and is separated by the eastern Tengchong-Dayingjiang and western Binliangjiang faults. From north to south, the Guyong, Lailishan, Jiucheng, Bangwan and Longchuan plutons intrude the Paleozoic to Mesozoic strata and are composed mainly of granodiorite and monzogranites with minor mafic intrusions and mafic enclaves in some granodiorites (Chen et al., 2015; Zhao et al., 2016; Zhu et al., 2019) (Zhao et al., 2016). The western belt is located in the western Tengchong terrane and is composed mainly of meta-gabbroic rocks, amphiboles, diorites, granodiorites and monzogranites with associated mafic enclaves, and small amounts of mafic-ultramafic rocks as lenses within the gneisses (Wang et al., 2014, 2015; Ma et al., 2021; Zhao et al., 2019).

3. Data and results: westward spatial distribution of three-stage intensive magmatism through temporal evolution in the Tengchong arc segment

To explore the spatial and temporal distribution of continental arc magmatism and its causes, comprehensive geochronologic ($n = 82$), in situ zircon Hf isotopic ($n = 820$) and geochemical ($n = 328$) data of the three Tengchong "flare-ups" are compiled and examined (Figs. 2–3). The data were mapped with detailed spatial control using MATLAB (Fig. 4) and the Mohodepth and elevation (Fig. 6) were calculated using methods by Chapman et al. (2015) and Hu et al. (2016)'s method and most recently by Luffi (2019), with findings summarized in the figures and supplementary dataset.

We use volumetric magmatic flux in this paper defined using Darcy's

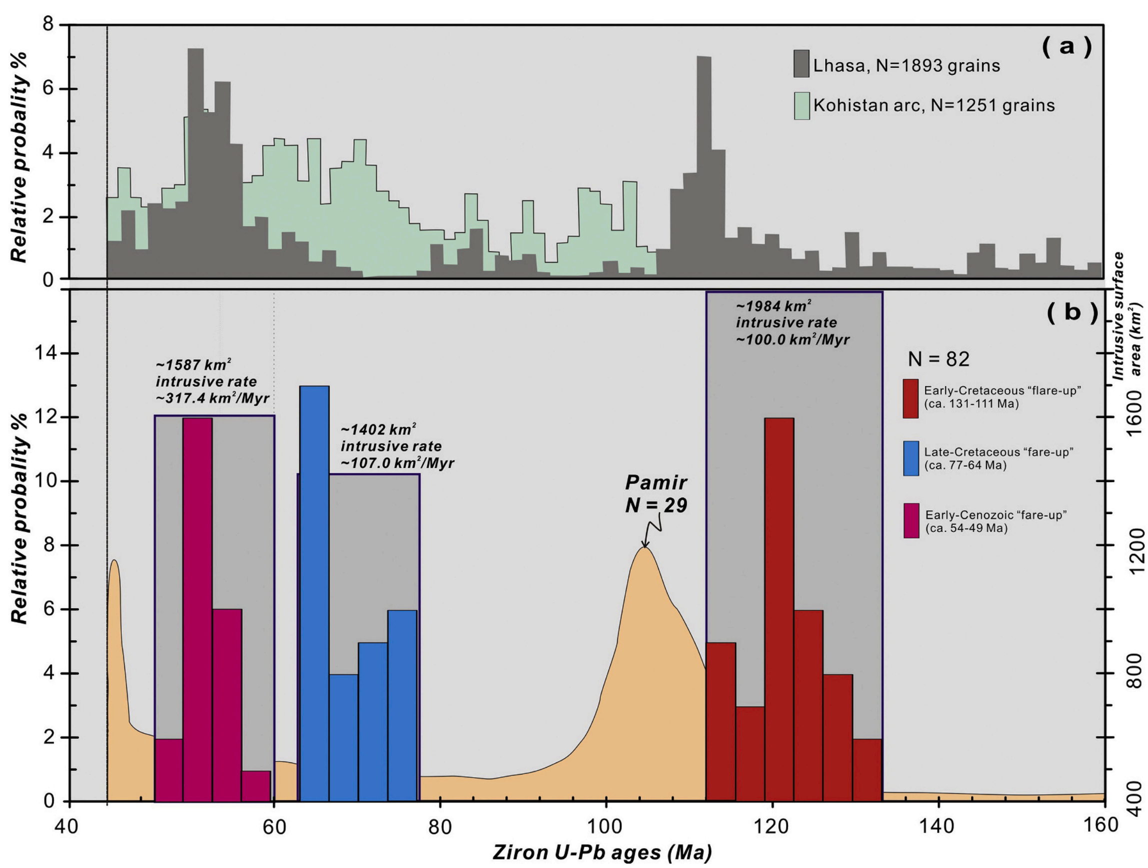

Fig. 2. The mainly geochronological distribution of magmatic events in the Tibet-Pamir orogenic system (a) modified from Pamir (Chapman et al., 2018) and Kohistan-Lhasa (Bouilhol et al., 2013) and based on background values in above associated literatures, and (b) magmatic flare-up and lull of Tengchong arc segment.

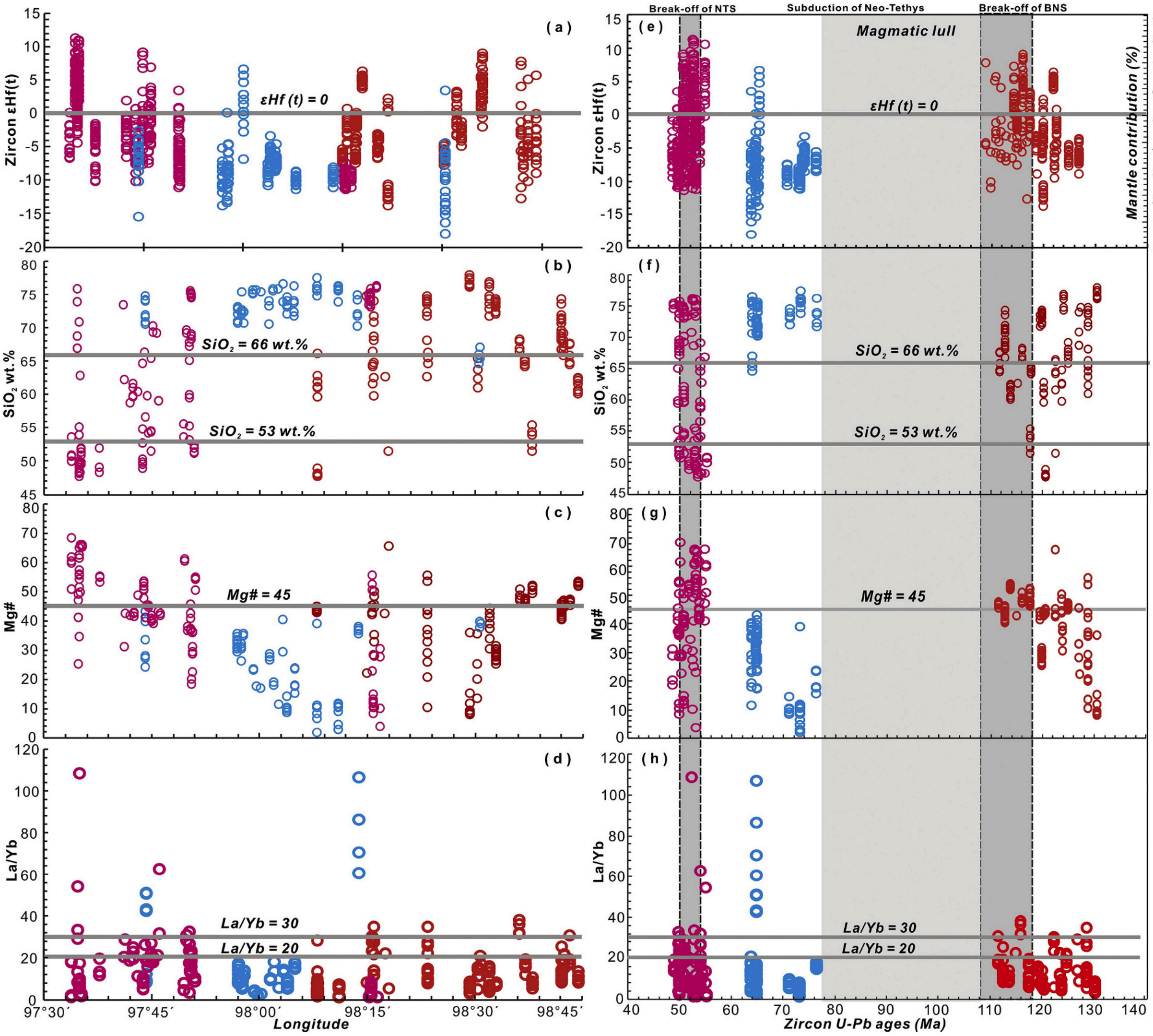

Fig. 3. Major high-MAR magmatic composition trend with spatial-temporal evolution.

law, as a volume passing through a designated area over a period of time (e.g., $km^3/km^2/yr = m/s$). Paterson et al. (2011) also defined the terms total added volume (km^3) as the volumetric amount of material added and volumetric addition rate (km^3/yr) as the total added volume per time. Volumetric addition rates are referred to as a magmatic flux by some, but little information has been preserved in paleoarcs about the actual volumetric magmatic flux (Ratschbacher et al., 2019): authors typically use more readily determined areal measurements to determine areal additions (km^2/yr). In this case, we use km^2/yr to compare the magmatic areal addition rates of the multi-stage magmatism in the Tengchong arc segment.

Fig. 1, shows a spatiotemporal trend as episodic magmatism migrates from east to west in the Tengchong arc segment, with an early-Cretaceous flare-up in the east, a late-Cretaceous to early-Cenozoic flare-up in the west. Before final collision in the early Cenozoic, this east -to- west represented a north to south migration (see Kornfeld et al. (2014) and Xu et al. (2015)). For ease of presentation, we use the present orientation. The temporal evolution of the Tengchong arc segment is shown in Fig. 2. In the Tengchong arc segment, the three high-MAR events occurred from east (ca. 131–111 Ma) to ~76–64 Ma (central), to ~55–49 Ma (western). The associated lulls range from ca. 110 to 80 Ma. The eastern flare-up resulted in an areal addition of ca. 1984 km^2 and addition rate of ca. 100 km^2 per million years, the central flare-up resulted in an areal addition of ca. 1402 km^2 and addition rate of ca. 107 km^2 per million years, and the western flare-up resulted in an areal addition of ca. 1587 km^2 and addition rate of ca. 317.4 km^2 per million years.

Major, trace element and isotopic compositions of the three high MAR events display very distinctive features from eastern, central to western parts (Figs. 3, 4 and 5), as follows: the early Cretaceous flare-up shows variable SiO_2 (47.7–77.9), MgO (0.03–7.07), Mg# (7.9–65.4), K/Na ratios (0.11–2.51), total Fe + Mg (0.73 to 15.8), A/CNK and Na/Ta ratios (3.53–22.8), but low La/Yb and Sr/Y ratios. Average SiO_2 values (67.5%) are similar to typical continental arc compositions, such as the Coast Mountains and Sierra Nevada batholiths (Ducea et al., 2015), and the continental crust (Taylor and McLennan, 1985 and Rudnick and Gao, 2003). The variable zircon Hf isotopic compositions range between +10 and − 15; the Late-Cretaceous flare-up displays high SiO_2 (average 72.5%), K/Na ratios (most >1, up to 2.76) and A/CNK values (most >1), low MgO (0.01–2.76) and Mg# (<45), total Fe + Mg (<8), Nb/Ta ratios (most <15) and La/Yb ratios with a few extremely high samples. Recently identified mafic intrusions have high MgO (~5.0%) and Mg# (~56), typical of high-potassium to shoshonitic series (Zhu et al., 2021). Their zircon Hf isotopes show predominately negative components that evolved from ancient continental crust; The early-Cenozoic magmatic flare-up of the western Tengchong arc segment has strongly variable major element compositions: SiO_2 (45% to 76%), K/Na (0.1–2.5), Mg# (3–70), total Fe + Mg (1−22) but Nb/Ta > 8.3 and A/CNK < 1.1.

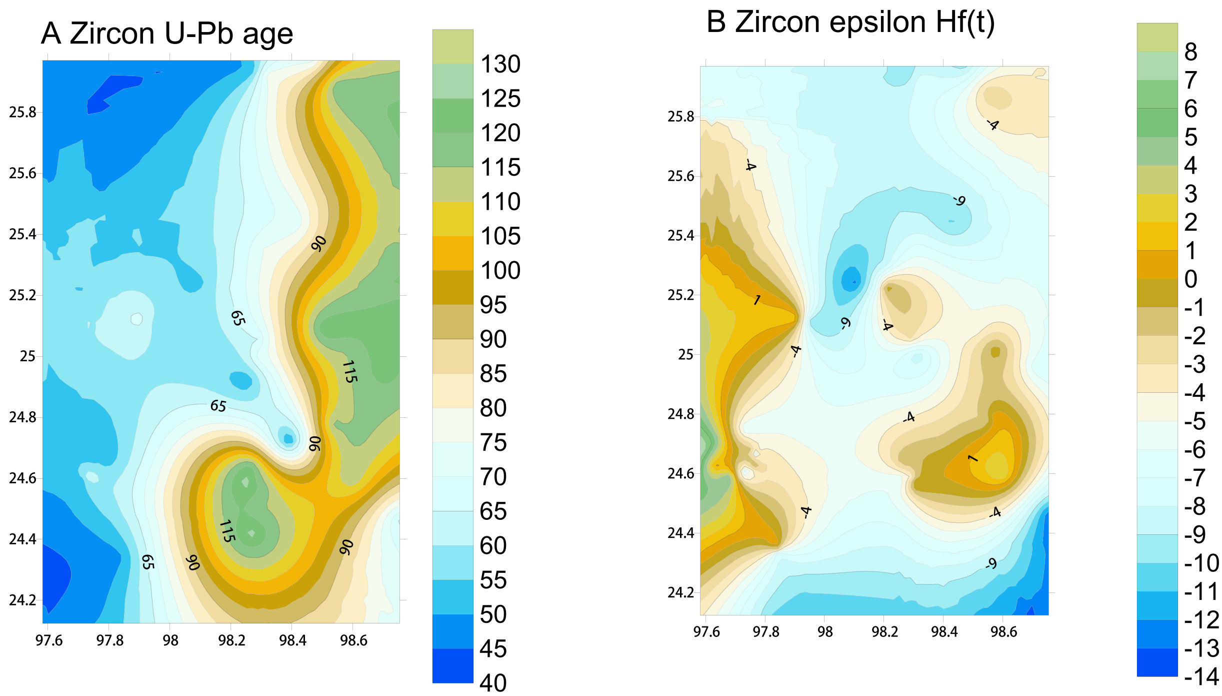

Fig. 4. Mapping of in situ zircon U-Pb age and Hf isotopic composition trend with spatial and temporal evolution of Tengchong arc.

Average values are lower than typical continental crust and arcs, being closer to that of island arcs (Jagoutz and Kelemen, 2015; Ducea et al., 2015). It has higher La/Yb and Sr/Y ratios than the previous two-stage magmatic episode. Zircon Hf composition also displays large variation from +12 to −12, indicating the strong interaction of crust and mantle.

The spatiotemporal pattern of the three-stage period of intensive magmatism in the Tengchong arc segment progressed from east to west, with both the earliest and latest episodes showing strongly variable compositions from mafic to felsic materials with the central segment in contrast having a notably more evolved composition. Experimental results suggest the Lu-Hf isotopic system is relatively stable when zircon is exposed to metamorphic and/or metasomatized events (Daniel et al., 2013). Both spatial and temporal in situ zircon Lu-Hf isotopic data also display variable patterns from east to west and from early and late Cretaceous to early-Cenozoic (Fig. 6). Both early-Cretaceous and early-Cenozoic magmatic events show extremely variable zircon Hf isotopic compositions from negative to positive indicating the strong interaction of depleted mantle-derived and evolved continental components (Kemp et al., 2007) and a significant mantle contribution (ca. >70%). In contrast, the late-Cretaceous flare-up in the central zone shows a significant crustal and evolved zircon Hf signature (Fig. 3). Recently Zhu et al. (2021) identified the high Mg and K dioritic intrusions that were contacted and coeval with these granitic rocks, the former was produced from the metasomatized lithosphere mantle and played the key role in the extension melting of the overlying crust to produce these crustal signature materials.

The whole-rock geochemical compositions and stable in situ zircon Hf isotopic components can provide robust evidence to understand the nature and mechanisms of the observed episodic magmatism (Jagoutz and Behn, 2013; Jagoutz and Kelemen, 2015; Chapman et al., 2018; Chapman and Ducea, 2019). We compile representative major and trace element variation with SiO_2 and compare them with compositions from typical arc magmatism around the world (Fig. 5), such as the Kohistan arc, Coast Mountains and Sierra Nevada continental arcs, Hidden Bay Kagalaska oceanic arc and the Gangdese continental arc. The data indicates that both the early-Cretaceous and early-Cenozoic flare-ups have close affinity with continental arcs rather than oceanic arcs. Late-Cretaceous magmatism has more enriched compositions than normal continental arcs and displays higher incompatible element compositions than normal continental crust.

4. Discussion

4.1. Driven mechanism of the multi-stage high-MAR events in Tengchong arc segment: external, internal or interaction?

The driving forces of flare-ups are caused by possibly being either upper plate (lithospheric mantle or crust) (Ducea and Barton, 2007; DeCelles et al., 2009; Chapman and Ducea, 2019; Martinez-Ardila et al., 2019; Attia et al., 2020) or lower plate (slab or tectonic) (Schwartz et al., 2017; Shafaii Moghadam et al., 2020). Various mechanisms have been proposed to explain episodic magma flare-ups through space and time. In Cordilleran orogenic systems, Ducea and Barton (2007) suggest crustal/lithospheric thickening during subduction is the key to trigger the high MAR magmatism primarily derived from an upper lithospheric source in Cordilleran arcs. Ducea et al. (2015) and DeCelles et al. (2009) proposed a model that argues that ca. 25–50 Myr episodic high-MAR magmatism events are fueled by cycles of upper-plate processes, where continental crust shortens by thrusting behind the arc triggering intensive magmatism resulting in dense melt residues. These residues eventually sink into the mantle beneath the arc and induce the renewal of the cycle.

Arc migration into regions of increased subduction-related mantle metasomatism may also be important for triggering a high-MAR event (Chapman and Ducea, 2019). The zircon Lu-Hf isotopic and trace element information from Mesozoic magmatism in the central Sierra Nevada (Attia et al., 2020), however, records a dominant juvenile source for magmas throughout MAR episodes showing increasing mantle input in Cordilleran arcs. Most likely, both the upper plate crustal and mantle-derived materials are important to support the generation of MAR episodes in Cordilleran arc systems. In Fiordland, meanwhile, zircon geochronologic, isotopic and associated bulk-rock geochemical data from the Mesozoic Median Batholith shows the flare-up has high Sr/Y magmatism from the underlying mantle and the Zealandia HMA event was triggered by an external dynamic mantle process (Schwartz et al., 2017).

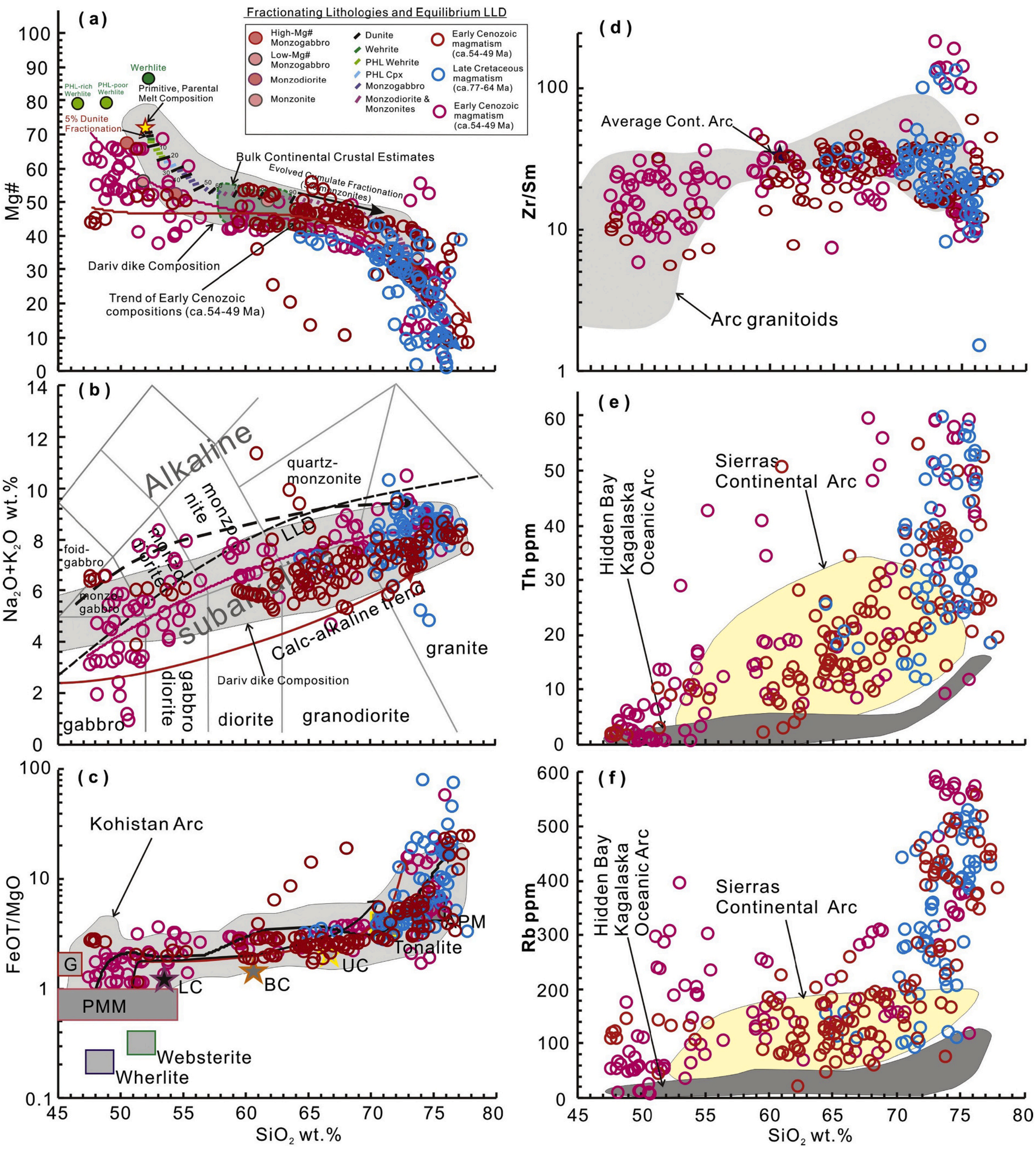

Fig. 5. The major composition of three-stage high-MAR magmatism in the Tengchong terrane of SE Tibet. a-d. referenced Jagoutz (2009, 2010) and Jagoutz and Kelemen (2015); e-f referenced Kay et al. (2019). The data of Nevada, Aleutian, and Gangdese arc from (http://georoc.mpch-mainz.gwdg.de/georoc/).

Major flare-ups along the southern margin of Asia plate during the subduction of Neo-Tethys, from west to east, major arcs including Iran, Kohistan, Lhasa (Gangdese), Tengchong, and Sumatra arcs. 1. Iran arc, major episodes occurred at 110–80, 75–50, 50–35, 35–20 and 15–10 Ma, but the 35–20 and 15–10 Ma episodes show notably less volume than others, so the major pulses focused on first to third pulses, The data indicated that the first to second episodic magmas dominated by the underlying mantle, and third episodic magmas show increasing contributions from the crust with highest contribution from continental crust (Shafaii Moghadam et al., 2020). These episodes mainly accompanied changes from extension, collision to extension in subduction zone dynamics (Shafaii Moghadam et al., 2020); 2. Kohistan arc, an ongoing 120 Ma of magmatic evolution, with 150–80 and 80–50 Ma main episodes of distinct geochemical signatures involving the slab and the sub-arc mantle components that are controlled by overall geodynamic of the Neo-Tethyan slab from subduction to continental arc collision (Jagoutz et al., 2019). At ca. 50 Ma, there is notably continental crust contributions due to collision with India (Bouilhol et al., 2013; Jagoutz et al., 2019); 3. The Lhasa magmatic arc, it can be divided into two parts, including northern-central and southern Lhasa (Gangdese arc). The Gangdese arc has three high flux events that peak at ca. 93, 50 and 15 Ma (Chapman and Kapp, 2017), each of them is characterized by northward migration of magmatism and more evolved isotopic compositions of magmatism located farther north from the Indus-Yarlung suture zone and mainly related to the subduction of Neo-Tethys and the collision of India -Asia. The northern-central Lhasa shows three major

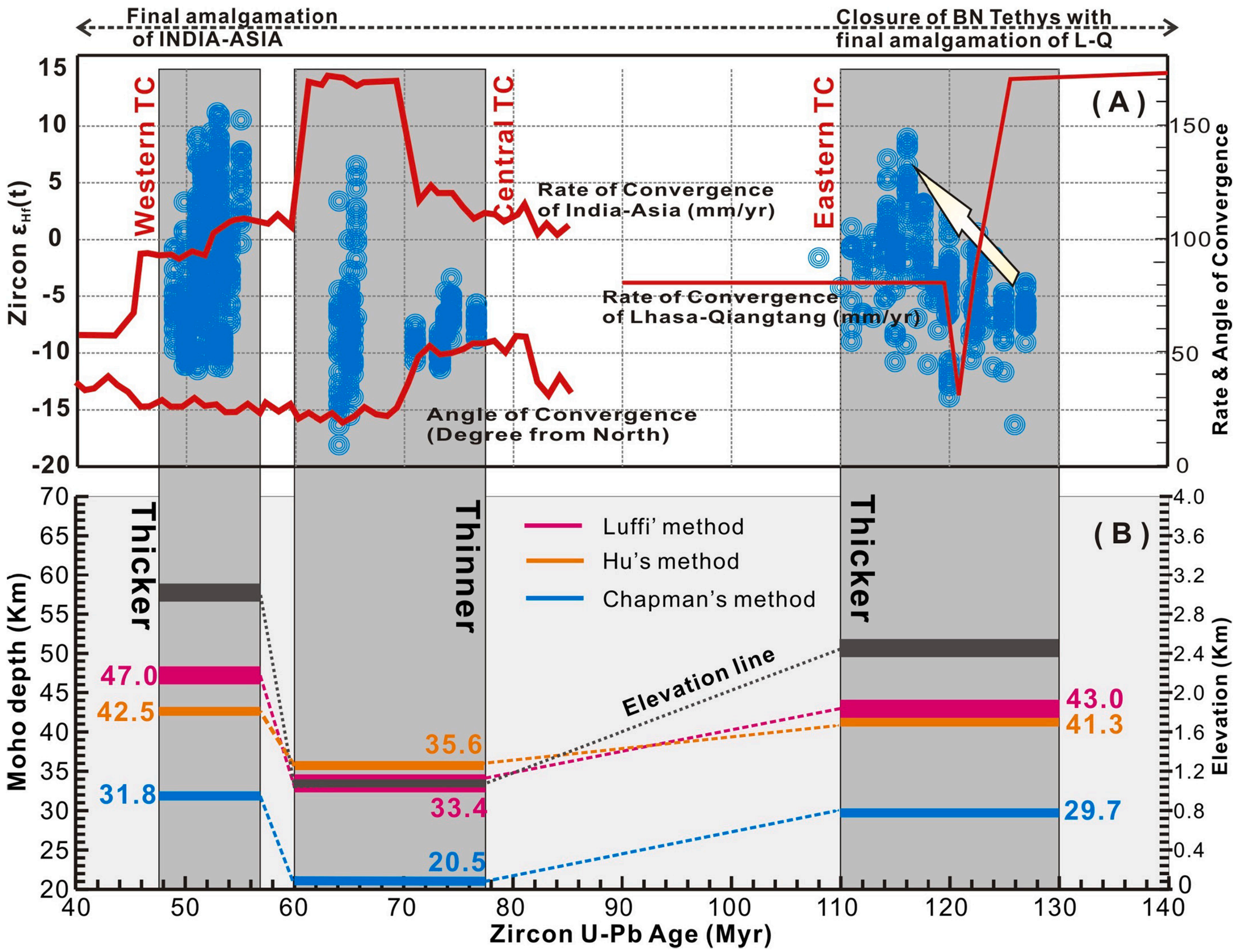

Fig. 6. A. Zircon U-Pb age vs zircon $\varepsilon_{Hf}(t)$ value of Tengchong arc magmatism, convergence rate of Neo-Tethys and angle, the convergence data of India-Asia from Lee and Lawver (1995) and Lhasa-Qiangtang block referenced from Young et al. (2019). *Bombylius zircon* U-Pb age of Tengchong arc magmatism vs Mohodepth and elevation of Tengchong arc segment (Chapman et al., 2015; Hu et al., 2016; Luffi, 2019).

episodes at ca. 150–110 Ma, 90–85 Ma, and 52 Ma, with major continental crust contributions and related mantle melting inputs in the late-stage, which resulted from the dynamic process of slab break-off following the Qiangtang-Lhasa and India-Asia collision (Zhu et al., 2011). 4. The Sumatra arc that exhibits major magmatic pulses during ca. 102–85 and 52 Ma, similar to both tempos and isotopic compositions of magmatism in Gangdese arc, these magmatic events most likely correlated with repeated steepening and shallowing of the slab dip, rather than India-Asian convergence rates (Zhang et al., 2019).

The Tengchong arc segment displays a well coupled spatio-temporal evolution (Fig. 3), where younger high-MAR events are to the west (Figs. 1–2). The oldest (east) and youngest (west) high MAR events could be driven by a similar mechanism due to that they have similar petrochemical and isotopic features. Similar to most arcs in the southern margin of Asia plate, such as Iran, Kohistan, Gangdese and Sumatra arcs, both show similar high MAR events during the early Cenozoic at ca. 55–50 Ma, these early Cenozoic pulses display very closely correlation with the final initial collision of India-Eurasia plate (Zhu et al., 2011; Chapman et al., 2017; Jagoutz et al., 2019). Both are closely involved with the Neo-Tethyan subduction and final welding of the India-Asia continent. The coeval pulses in the Iran and Sumatra arcs may relate to the steepening and extension of Neo-Tethyan slab dip (Zhang et al., 2019; Shafaii Moghadam et al., 2020). But, as for the trend of geochemical and isotopic compositions, the ca. 55–49 Ma magmatic pulse in the Tengchong arc segment show similar character to those of Kohistan and Gangdese arcs: both have highly geochemical and isotopic variations such as highly variable Si content and Mg# and zircon εHf(t) values (most samples from ca. +10 to −10, even more variable) (Zhu et al., 2011; Bouilhol et al., 2013; Jagoutz et al., 2019, and this study) (Fig. 3). Chapman and Kapp (2017) suggested that this high flux events in the Gangdese arc is characterized by northward migration of magmatism and more evolved isotopic compositions of magmatism located farther north from the suture zone. Undoubtedly, both Kohistan, Gangdese and Tengchong arc rocks at ca. 55–50 Ma recorded a broader range of geochemical and radiogenic isotopic composition, which were reflective of the wider arc and the age of the lithospheric provinces encountered (Chapman et al., 2021 reference therein). During the initial collision of India-Asia, crustal thickening was achieved through both magmatic and tectonic activities, where more evolved continental crust merged into the ca. 55–50 Ma magmatic pulse, which resulted into an enhanced evolved isotopic shift in both Kohistan and Gangdese arcs. The phenomenon that the flare ups shifts to more evolved isotopic ratios has been proposed elsewhere, including some crustal materials, but also plenty of mantle-derived materials, such as Cretaceous Sierra Nevada batholith, Cretaceous Peninsular Ranges batholith, Cretaceous Median batholith, Jurassic and Triassic arcs in the Korean Peninsula, Paleogene

Coast Mountains batholith (Chapman et al., 2021 reference therein). The presence of significant high positive zircon $\varepsilon_{Hf}(t)$ values (up to +12.0), low SiO_2 content, and high-Mg# (up to 70) imply significant contributions from juvenile mantle-derived materials. The upwelling mantle materials could be a key control process to induce the melting of overlying mafic crust to generate the extensive granitic magmatism (Zhu et al., 2017a). Isotopic shifts can well imply the variable contributions from mantle and/or crustal materials (Chapman and Ducea, 2019; Chapman et al., 2021). Evolved isotopic shift may result from retroarc understrusting and introduction of isotopically evolved, melt-fertile continental crust or lithosphere into the arc source (DeCelles et al., 2009, 2015; DePaolo et al., 2019; Ducea, 2002; Ducea and Barton, 2007; Chapman et al., 2021 reference). Arcs constructed on juvenile lithosphere would not show the same shift (e.g. Coast Mountain batholith, Cecil et al., 2019). Similarly, we argue that the ca. 55–49 Ma pulse in the central to western Tengchong arc segment may correlate with the initial collision of India-Asia, and source lithospheric mantle, continental arc materials and slab-derived fluids/melts (Wang et al., 2014; Zhao et al., 2016). These melt-fertile crustal materials increased the range of isotopic ratios in both Kohistan, Gangdese and Tengchong arcs (Zhu et al., 2011; Bouilhol et al., 2013; Jagoutz et al., 2019, and this study), where the slab break-off following the initial collision played a key role in this flare-up (Zhu et al., 2011).

The pulses at ca. 130–110 Ma (Figs. 2–3), are different from any arcs in the southern margin of Asia plate, but similar to those magmatic pulses in the central and northern Lhasa that could be associated with the southward subduction of Bangong-Nujiang Tethys (Zhu et al., 2011; Zhu et al., 2017a). Both show similar temporal and evolutionary trend of geochemical and isotopic composition. In the initial stage of the early Cretaceous flare-up events, evolved isotopic compositions with negative zircon εHf(t) values predominated, which indicate major contributions from evolved crustal materials. Arc migration may be induced by steepening of slab dip, and in this setting, subducted recycled sediments and metasomatized mantle wedge may result in the production of high Mg-K dioritic and granodioritic magmas (Zhu et al., 2019; Ma et al., 2021). Subsequently, with slab rollback and break-off, more mantle-derived magmas may upwell ca. 122–120 Ma (Zhu et al., 2017a) and result in the magmatism with higher MgO and Mg#, enhanced positive zircon εHf(t) values (up to +10) (Figs. 3 & 6), and a broader range of composition and isotopes than before. The early-Cretaceous high MAR events has increasing zircon $\varepsilon_{Hf}(t)$ values up to +10.0 implying increasing mantle contributions during this "flare-up", suggesting possible upwelling mantle materials induced this flare-up, and evolving from dominated fertile crustal isotopic signatures to significant mantle isotopic controls. This could be interpreted as related to the tectonic processes upon closure of Qiangtang-Baoshan and Lhasa-Tengchong, from soft-collision to slab break-off of Bangong-Nujiang Tethyan ocean (Zhu et al., 2015). During slab break-off, a slab window may result in the partial melting of various sources region including upwelling asthenospheric mantle, enriched lithospheric mantle, and overlying crust (Ferrari, 2004). The sub-arc mantle wedge could possibly contain melts from both sub-slab asthenosphere enriched in HFSE and normal sub-arc mantle depleted in HFSE as supported by more primitive isotopic compositions (Ferrari, 2004). In which case arc magmatism shifts to greater contributions of mantle and/or juvenile source. These signatures also indicated the varied sources involved in the magmatism following the collision and thicken crust (Fig. 6).

The pulse at ca. 76–64 Ma can be compared with the coeval pulse of back arc magmatism in the Iran arc (Shafaii Moghadam et al., 2020), the difference is the distinct isotopic composition. In the Iran case, the magmatic rocks show mantle-like signatures not affected by AFC processes (Shafaii Moghadam et al., 2020). But in the Tengchong case, the late-Cretaceous magmatism shows notably crustal signatures (Zhu et al., 2021; Fig. 3). Two possible model could be considered, the melting of evolved continental crust and/or a metasomatized and fertile lithospheric mantle source combining with overlying crust. Zhu et al. (2021) identified the coeval high Mg and K dioritic magmas with have notable crustal signatures including negative εHf(t) values and high K and Th from nearby, coeval intrusions. The high Mg and K diorites can be compared with sanukitoids produced from the mantle wedge metasomatized by water-rich subducted sediments during steepening subduction (Zhu et al., 2021). Therefore, we infer that the late-Cretaceous pulse could be formed through the change from shallow to steep subduction (Zhu et al., 2021), resulting in the fertile lithospheric mantle and the fertile mantle-derived magmas underplating the base of the continental crust and inducing melting of overlying evolved continental crust. Therefore, sediments subduction/accretion may play a role in enhancing the flare-up (Clift and Vannucchi, 2004; Ducea et al., 2015).

This case is similar to the situation in Cordilleran arcs where subduction-related metasomatism is an important element in enhancing a high MAR event (Chapman and Ducea, 2019). Both the Gangdese and Tengchong have late-Cretaceous intensive magmatism with crustal signatures (Zhu et al., 2011; Zhu et al., 2021), prior to the early-Cenozoic flare-up. Increasing subduction-related metasomatism was identified (Zhu et al., 2021), therefore, these cumulatively metasomatized-related magmatism in the southern margin of the Asian continent could be important fuel for refertilization and hydration in the deep lithosphere to enhance the largest flare-up after 55 Ma following the final closure of Neo-Tethys.

Various lines of evidence have helped to establish correlations between intensive magmatic episodes and various processes, such as cycle of closely linked upper-plate shortening by thrusting (DeCelles et al., 2009), dynamic mantle process (Schwartz et al., 2017), dynamic transformation in the orogen (Guo et al., 2022), and arc migration (Chapman and Ducea, 2019). In Iran and Sumatra arcs, there is no clear relationship between the subduction velocity, convergence rates and magmatic pulses. Similarly, the multi-stage intensive magmatism in the Tengchong case also lacks good correlation with these geophysical parameters. The evolution of early Cretaceous magmatism shows no relationship with the rate of convergence of Lhasa-Qiangtang (Fig. 6A), which changes at the flare-up peak, not flare-up initiation. For the late Cretaceous flare-up, major shifts in rate and angle of convergence of India-Asia plate (Fig. 6A), occur well after flare-up initiation. The early Cenozoic magmatic pulse occurred ca 5 m.y. after the decreasing rate of convergence and shows no correlation to angle of convergence of the India-Asia plate (Fig. 6A).

Both the latest results by Luffi (2019) and others (e.g. Chapman et al., 2015; Hu et al., 2016) confirm thickening during the early-Cretaceous, thinning in the late-Cretaceous followed by thickening again in the early-Cenozoic high MAR events. The two crustal thickening events correlate with the amalgamation of Lhasa-Tengchong and Qiangtang-Baoshan and the final welding of the India-Asia plate, but also likely reflect magma additions to the crust in the high MAR events during the early-Cretaceous and early Cenozoic (Cao and Paterson, 2016).

4.2. The role of multi-stage "high MAR events" in continental formation and growth

Mature continental arcs share similar major element compositions with those of the continental crust (Rudnick and Gao, 2003), producing on average upper crustal materials similar to the bulk continental crust (Ducea et al., 2015). Most scholars consider continental arcs to be the primary factory in making new continental crust, with significant input of juvenile contributions from the mantle via basaltic melts (Ducea et al., 2015; Jagoutz and Schmidt, 2012) after removal of mafic to ultramafic roots, for example the Kohistan arc.

These high MAR events, emplaced as plutons and volcanism (most has been removed during uplift and erosion due to the tectonic activity), forming a major component of the Tengchong arc segment making up 50–70% of the area exposed in this region. From a view of both area and volume of these high MAR events, it is a significant component in the formation of the Tengchong arc segment. The residue of these arcs is granulitic at pressures below ca. 15 kbar, and could become a dense (3.6 g/cm^{-3}, bi-mineralic garnet pyroxenite (eclogite) at higher pressures (deeper levels) (Ducea, 2002). The high La/Yb and Sr/Y ratios (Fig. 3) precluded the formation of cyclic garnet-bearing "arclogites", instead resulting in amphibolite to granulite facies and garnet-free residues in the thin arcs (Ducea et al., 2020). Therefore, it is less likely that foundering-prone, sizable roots (Ducea, 2002) were generated by high-MAR magmatism in the Tengchong, as readily observed in the modern Andes. The multi-stage high MAR events record the multi-stage crustal thickness through the formation of the Tengchong arc segment, and this Tengchong case resembles continental arcs that have not experienced delamination and instead preserve thicker sections of mafic lower crust (Chapman et al., 2021).

The three-stage high-MAR events in the Tengchong arc have average andesite to dacite compositions. Al-in-Hbl calculated results from diorite-tonalite-granodiorite-monzogranite-granites of early-Cretaceous and gabbro-diorite-granodiorite-monzogranite of early-Cenozoic high-MAR events have a depth range from ~22 to 5 km for early Cretaceous pluton, and 24 to 9 km for early Cenozoic pluton, respectively (Zhu et al., 2017a; Zhao et al., 2016, 2019), indicating these high-MAR rocks were mainly emplaced in the middle crust. Ducea et al. (2015) has suggested that high MAR events in the subduction systems can involve ~50% recycled upper plate crust and mantle lithosphere, and the remaining ~50% comes from the mantle wedge. Similarly, in the Tengchong case, although the tonalite-granodiorite-monzogranites dominate, early Cretaceous high-Mg diorites to quartz diorites (Zhu et al., 2017a, 2017b; Ma et al., 2021), late Cretaceous high-Mg monzodiorites (Zhu et al., 2021), and early Cenozoic gabbro-diorites (Wang et al., 2014, 2015; Ma et al., 2021; Zhao et al., 2019), are closely associated with these intermediate to felsic rocks and represent the significant mantle contributions. According to Hf isotopic calculation (Zhu et al., 2018a), at least, the mantle contributions can reach up to 50% for early Cretaceous and early Cenozoic flare-up. Therefore, these high MAR events produced plutons that accumulated within the continental crust, representing growth of the continental arc segment from various contributions, including various continental crust materials, slab-derived melts/fluids, and significant materials from both juvenile and metasomatized mantle materials, resulting in a significant contribution to the growth of the continental crust.

5. Conclusions

Three high-MAR events in the east (ca. 131–111 Ma), middle (ca. 76–64 Ma), to the west (ca. 55–49 Ma) took place in the westward migrating Tengchong arc segment of southeastern Tibet. Both the early-Cretaceous and Cenozoic magmatic episodes have variable compositions and significant mantle contributions, similar to typical continental arcs. These pulses are closely correlated with the changes of crustal thickness, but no correlation with angle and rates of convergence of the plates.

The multistage high MAR events have typical low isotopic characteristics that closely correlate to the interaction of crust-mantle driven by collision-related crustal thickening, but the subsequent increasing isotope trend indicates the increasing contribution from juvenile mantle-derived materials, potentially driven by slab roll-back and break-off. The central magmatic flare-up was produced by an increase in subduction-related metasomatism, which provided enough fuel to trigger the following early-Cenozoic flare-up in the Himalayan-Tibetan orogenic system.

The flare-up produced plutons and batholiths located within the middle continental crust and constitute an area of ~5000 km^2, greater than 50% of the entire segment, with a granulite facies residue in the deep lithosphere. This has played a major role in the formation and growth of the Tengchong arc segment in the SE Tibetan Plateau.

Credit author statement

The authors statement that we have no any credit issue for any author and any papers that we have published, we have kept and will keep very good credit.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Dataset of whole geochronology, geochemistry and in situ zircon Hf isotopes for Cretaceous-Cenozoic magmatism in the Tengchong arc, SE Tibet. Supplementary data to this article can be found online at https://doi.org/10.1016/j.tecto.2022.229308.

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