Crustal evolution of a continental magmatic arc from subduction to collision

Ze-Ming Zhang[1,2,†], Hui-Xia Ding[1], Richard M. Palin[3], Xin Dong[2], Zuo-Lin Tian[2], Xiao-Wei Li[1]

[1] *School of Earth Sciences and Resources, China University of Geosciences, Beijing, 100083, China*

[2] *Institute of Geology, Chinese Academy of Geological Sciences, Beijing, 100037, China*

[3] *Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, UK*

[†] Correspondence author: Z.M. Zhang, zzm2111@sina.com

ABSTRACT

Magmatic arcs are the main environment where continental crust is created on the post-Archean Earth; however, how juvenile arc crust evolves into mature continental crust is still controversial. In this study, we report new bulk-rock major and trace elements, Sr–Nd isotopes, and zircon U–Pb ages and Hf isotopes from a large suite of granites collected from the eastern segment of the Gangdese arc, southern Tibetan Plateau, which record a complete history of arc crust evolution from Mesozoic subduction to Cenozoic collision. These new data show that Gangdese crust-derived granites generated during the subduction to collisional stages record significant geochemical changes with age, indicating that the bulk composition, lithological makeup, and thicknesses of the arc crust evolved over time. Here, we propose that the Gangdese arc had a thick juvenile crust with a small volume of ancient crustal components during late-stage subduction of the Neo-Tethys Ocean, a thin juvenile crust with heterogeneously distributed ancient crustal materials during early collision, and a thick juvenile crust with minor proportions of ancient rocks during late collision. This implies that the arc experienced episodes of crustal thickening during the Late Cretaceous and Eocene, interspersed by periods of thinning during the Paleocene and Miocene. This implies several discrete episodes of partial melting in the lower arc crust, and cycling or recycling of juvenile and ancient crustal materials within the arc crust and between the crust and mantle. We suggest that shallow subduction of the Neo-Tethys during the Late Cretaceous promoted tectonic thickening of the arc crust, partial melting of lower crust, and formation of high Sr/Y granites. After the onset of Indo-Asian collision, breakoff of the subducted Neo-Tethyan oceanic slab during the Paleocene/Early Eocene allowed thinning of the overlying arc crust, and generation of crust-derived granites derived from juvenile and ancient crustal sources. Continued underthrusting of the Indian continental crust and subsequent delamination of thickened lithospheric mantle led to thickening and thinning of the arc crust, respectively, and partial melting of thickened lower crust and generation of high Sr/Y

granites during the Oligocene and Miocene. Using the Gangdese as an analogue for post-Archean continental margins, we suggest that cycles of repeated thickening and thinning of arc crust, remelting of the lower arc crust, and multistage material cycling or recycling within the crust and between the crust and mantle from subduction to collision is a common process that drives geochemical maturation of juvenile arc crust.

1. INTRODUCTION

It has long been known that magmatic arcs are the main environment where continental crust is created on the post-Archean Earth; however, major questions remain relating to the geological processes that drive the growth and reworking of juvenile arc crusts (e.g., Hacker et al., 2011, 2015; Jagoutz et al., 2014; Ducea et al., 2015; Lee and Anderson, 2015). For example, how do juvenile basaltic mantle-derived melts evolve into mature andesitic continental crust, and over what timescales do these processes operate? What is the contribution of arc-continent collision to the growth and reworking of arc crust? Is the main mechanism for differentiation or stratification of arc crust fractional crystallization of mantle-derived magmas or remelting of the juvenile lower crust? How are the meta-sedimentary rocks and felsic igneous rocks in the upper arc crust transported to the deep crust? Is decarbonation of lower arc crust an important factor in the increase of atmospheric CO_2 concentration? Answers to these questions have wide-reaching implications for understanding the formation and evolution of continental crust, and the regional-scale changes that have characterized accretionary and collisional orogens throughout Earth history.

Continental magmatic arcs, such as the Cordillera and Gangdese arcs, were widely developed on Earth during the Mesozoic (Fig. 1). The Cordilleran arc formed during subduction of the Pacific oceanic plate beneath the North American continental plate, and is still experiencing ongoing subduction and associated juvenile crustal growth. By contrast, the Gangdese arc, southern Tibetan Plateau, preserves a complete magmatic record from Mesozoic oceanic lithosphere subduction to Cenozoic continental collision, and therefore it is an ideal natural laboratory for studying the growth and reworking of arc crust during the final stages of the Wilson Cycle (Fig. 1; Ding et al., 2003; Chu et al., 2006, 2011; Mo et al., 2007, 2008; Ji et al., 2009; Zhu et al., 2011, 2019, 2022; Niu et al., 2013; Hou et al., 2015; Zhang et al., 2020, 2022a; Ma et al., 2022). In this paper, we report new, detailed geochemical and geochronological data from Gangdese arc granites that were mostly derived from partial melting of the lower arc crust during Late Mesozoic closure of the Neo-Tethys Ocean and subsequent Cenozoic continental collision between India and Asia. Our results show that the petrological makeup, composition, and thickness of arc crust continuously vary through time, and together act to refine and process juvenile arc crust into mature continental crust. The formation and evolution of the Gangdese arc, which is typical of post-Archean continental arcs, may therefore represent an analogue for the growth and maturation of juvenile crust in magmatic arcs worldwide since the onset of plate tectonics c. 3 Gyr ago. Understanding the major controls on orogenesis is important for a wide range of fields within geoscience, including the effect on climate systematics by formation of high-elevation landmasses, the influence on ocean chemistry and bio-productivity by providing nutrients to coastal regions via focused erosion, and the controls on the formation of critical minerals and ores that are essential for transitioning to a greener future.

2. GEOLOGICAL SETTING AND SAMPLES

The Tibetan Plateau, located at the eastern end of the Tethyan tectonic domain, formed following the Cenozoic collision between the Indian and Asian continental plates after terminal northward subduction of Neo-Tethyan oceanic lithosphere (Fig. 1). From north to south, the Tibetan Plateau consists of the Kulun, Songpan–Ganze, Northern and Southern Qiangtang, and Lhasa terranes, and Himalayan orogenic belt, which are separated by the Kunlun, Jinsha, Longmu Co–Shuanghu, Bongong–Nujing and Yarlung–Tsangpo suture zones, respectively (Fig. 2A; Yin and Harrison, 2000; Pan et al., 2012). The Gangdese continental magmatic arc is located within the southern Lhasa terrane, and formed during Mesozoic subduction of Neo-Tethyan oceanic lithosphere and Cenozoic collision between the Indian and Asian continents (Figs. 1 and 2). It preserves long-lasting – but episodic – magmatism from the Middle Triassic to the Miocene, with three main magmatic pulses recorded during the Late Mesozoic, Early Eocene, and Middle Miocene (e.g., Ding et al., 2003; Chung et al., 2003, 2005, 2009; Chu et al., 2006, 2011; Mo et al., 2007, 2008; Ji et al., 2009; Guo et al., 2011; Zhu et al., 2011, 2019, 2022; Wang et al., 2016; Ma et al., 2022; Zhang et al., 2022a).

The studied area is located at the eastern Gangdese arc, and includes three tectonic units: the southeastern Lhasa terrane (eastern Gangdese arc) in the north, the Yarlung–Tsangpo suture zone in the center, and the Himalayan belt in the south (Fig. 2B). The Himalayan belt represents the buried and subsequently exhumed Indian continental crust, and includes the Tethyan Himalayan Sequences and Greater Himalayan Sequences. The former underwent greenschist- to amphibolite-facies metamorphism, whereas the latter experienced high-pressure granulite-facies metamorphism and anatexis (Zhang et al., 2020). The Yarlung–Tsangpo suture zone preserves relics of subducted oceanic crust. The eastern Gangdese arc consists mainly of Late Cretaceous gabbroic to granodioritic intrusions and granitic intrusions, Paleocene to Eocene gabbroic and granitic intrusions, Oligocene granites and sedimentary rocks. The pre-Oligocene rocks experienced different degrees of metamorphism and differential exhumation, with metamorphic grade at the level of exposure decreasing from a granulite-facies metamorphic belt in the southeast, to an amphibolite-facies and greenschist-facies metamorphic belts in the northwest, which represent the lower, middle and upper crustal levels of the Gangdese magmatic arc, respectively (Fig. 2B; Zhang et al., 2020). Miocene granites are absent in the most eastern part of Gangdese arc, but are common in other segments of the arc (Chung et al., 2003, 2005; Hou et al., 2004; Guo et al., 2007; Chen et al., 2011; Wang et al., 2018; Ji et al., 2020).

In order to examine temporal patterns in the characteristics of Late Mesozoic and

Cenozoic granites from the eastern segment of Gangdese arc, we collected and analyzed over one hundred samples from various locations throughout the study area (Fig. 2B). Our geochronological and geochemical data comprise 102 samples newly reported in this study, alongside data from 110 samples that have been reported previously. This set of 212 unique samples reliably covers the compositional ranges of granites in the eastern Gangdese arc that formed during late-stage subduction and collision. These data, together with Sr–Nd isotopes of Late Cretaceous gabbros and Miocene granites, and zircon Hf isotopes and whole-rock $(La/Yb)_N$ values of Miocene granites, allow us to establish a complete overview of crustal evolution processes that occur in a continental magmatic arc from subduction to collision.

3. RESULTS

3.1. Zircon U–Pb ages and trace elements

Zircon grains analyzed from 102 granites mostly show euhedral prismatic shapes and oscillatory zoning (Fig. S1), which are typical of a magmatic origin. Grains from some samples have inherited detrital cores, which are anhedral in shape and have variable zonation patterns, and magmatic rims with oscillatory zoning, such as samples CZ20-10-4 and -10, CZ20-22-14, D024-1, D110-1, D112-1, D123-1, and PM1-05 (Fig. S1). All analyzed spots for zircon magmatic domains from these samples yielded concordant or near-concordant U–Pb ages, with weighted mean ^{206}Pb/^{208}U ages ranging from 24 Ma to 81 Ma (Table S1). These spots mostly have relatively high heavy rare earth element (HREE) contents and high Th/U ratios (mostly > 0.1; Table S1), typical of a magmatic origin. These ages thus represent the crystallization ages of the granites. Alongside previously reported age data from 17 other samples, the studied granites can be divided into three groups: those that formed during the terminal stages of subduction (81–77 Ma), early collision (69–47 Ma), and late collision (36–24 Ma) (Figs. 3 and 4). Early and late subduction of the Neo-Tethys Ocean occurred during the Late Triassic to Early Cretaceous (~220–100 Ma) and Late Cretaceous (~90–70 Ma), respectively (Zhang et al., 2022a). The early collision (soft collision or syn-collision) and late collision (hard collision or late- and post-collision) between the Indian and Asian continents occurred during the Paleocene to Middle Eocene (~70–45 Ma), and after Middle Eocene, respectively (Chung et al., 2005, 2009; Mo et al., 2007, 2008; Hou et al., 2015).

3.2. Whole-rock major and trace elements

The 119 studied granite samples have variable whole-rock compositions, with SiO_2 of 60.49–77.18 wt. %, Mg# [molar MgO/(MgO+FeO^T)] of 0.22–0.50, A/CNK [molar Al_2O_3/(CaO + Na_2O + K_2O)] of 0.92–1.15, rare earth element (REE) contents of 58–366 ppm, and are mostly calc-alkaline and peraluminous, with some being strongly peraluminous (A/CNK > 1.10; Figs. 3 and 4; Table S2). Geochronological data highlight the clear compositional difference between granites formed during late subduction, early collision, and late collision stages. Granites associated with late subduction have a relatively limited range in SiO_2, Na_2O + K_2O contents, low A/CNK and Mg#, high Sr, and low Y, Zr, Rb, Ni, and REE contents, and high Sr/Y ratios and moderate La/Yb ratios (Figs. 3 and 4A–4D). Early collisional granites have wide compositional ranges, but mostly have relatively low Sr, and high Y and HREE contents, and low Sr/Y and La/Yb ratios (Figs. 3 and 4A–4D). By contrast, the late collisional granites have limited compositional ranges, with relatively high SiO_2, Na_2O+K_2O, and A/CNK, low Mg#, high Sr, and low Y and HREE, and variable but high Sr/Y and La/Yb ratios (Figs. 3 and 4A–4D).

3.3. Whole-rock Sr–Nd isotopic compositions

Whole-rock isotopic analyses of 65 new samples collected for this work and 26 samples previously reported in the literature show that granites formed during late subduction have relatively low ($^{87}Sr/^{86}Sr$)i (0.7042–0.7053) and high $\varepsilon_{Nd}(t)$ values (+3.20 to +0.41), granites related to late collision have relatively high ($^{87}Sr/^{86}Sr$)i (0.7056–0.7106) and low $\varepsilon_{Nd}(t)$ values (–0.93 to –5.78), whereas granites that formed during early collision have widely variable ($^{87}Sr/^{86}Sr$)i (0.7049–0.7192) and $\varepsilon_{Nd}(t)$

values (+2.35 to –9.22) (Figs. 4E, 4F and 5; Table S3).

3.4. Zircon Hf isotopic compositions

Zircon Hf isotopic analyses of the 119 granite samples show that magmatic zircons from late subduction granites have high and positive $\varepsilon_{Hf}(t)$ values ranging from +9.72 to +12.8 (Fig. 6A; Table S4). The magmatic zircons from early collision granites have highly variable, or even negative $\varepsilon_{Hf}(t)$ values of +9.90 to −10.43. By comparison, the late collision Oligocene granite zircons have low and positive $\varepsilon_{Hf}(t)$ values ranging from +0.75 to + 5.39 (Fig. 6A; Table S4).

4. DISCUSSION

4.1. Origin of the eastern Gangdese granites

Voluminous Mesozoic (>85 Ma) magmatic rocks of the Gangdese arc have geochemical features of typical arc magmas, were therefore likely derived from depleted mantle during subduction of the Neo-Tethys ocean, and form juvenile arc crust of the southern Lhasa terrane (Gangdese arc; Chu et al., 2006, 2011; Wu et al., 2007, 2010; Ji et al., 2009; Zhang et al., 2010, 2022a; Zhu et al., 2011, 2019, 2022; Ma et al., 2013, 2022; Zheng et al., 2014; Hou et al., 2015; Meng et al., 2016; Wang et al., 2016). However, the late subduction granites studied here mostly have relatively low A/CNK and Mg# values, high Sr and low Y, Zr, Rb, Ni and REE contents, high Sr/Y and La/Yb ratios, low $(^{87}Sr/^{86}Sr)_i$ and high $\varepsilon_{Nd}(t)$ values, and high zircon $\varepsilon_{Hf}(t)$ values (Figs. 3–6; Tables S2–S4). Therefore, most previous studies have interpreted the granites to have been derived from anatexis of thickened juvenile lower crust (e.g., Wen et al., 2008; Tang et al., 2019; Ding and Zhang, 2019, Ding et al., 2022a, 2022b). Low MgO (<1.88 wt. %), Ni (<5.4 ppm) and Yb (<1 ppm) contents, and low Mg# values (<0.41) are typical features of high-Sr/Y granites derived from thickened mafic lower crust (Wang et al., 2006). The slightly enriched Sr–Nd–Hf isotopic compositions of the granites show that the thickened juvenile lower crust includes a minor proportion of older crustal materials. These interpretations are consistent with previous conclusions that Late Cretaceous lower crust of the eastern Gangdese arc consists of high-pressure (up to 15–17 kbar) and high-temperature (up to 850–880 °C) metamorphosed and partially melted arc-type gabbros (i.e. garnet-rich mafic granulites) and sedimentary rocks (i.e. kyanite- and garnet-bearing schists and gneisses) (Zhang et al., 2014). Further, early melts generated by *in situ* anataxis of these arc-type gabbros represent potential sources of high-Sr/Y granites in the upper arc crust (Ding et al., 2022a; Qin et al., 2022). The late subduction granites are unlikely to be the product of fractional crystallization of mantle-derived magmas, given the absence of coeval intermediate to mafic magmatic rocks in the study region that experienced significantly exhumation during the Last Cenozoic (Cao et al., 2020; Zhang et al., 2020), and zircons in the granites with slightly higher $\delta^{18}O$ values than normal mantle zircon, and inherited cores with Cretaceous and Late Paleozoic U–Pb ages (Tang et al., 2019).

The early collision granites have widely variable major, trace and rare earth element compositions, Sr–Nd–Hf isotopes, and A/CNK and Mg# values, but mostly have lower whole-rock Sr and $\varepsilon_{Nd}(t)$, and zircon $\varepsilon_{Hf}(t)$ values, and higher Y, Zr, Rb, HREE and $(^{87}Sr/^{86}Sr)i$, and lower Sr/Y and La/Yb ratios than the late subduction granites (Figs. 3–6; Tables S2–S4). The relatively more enriched Sr–Nd–Hf isotopic compositions indicate that ancient crustal materials also became incorporated into the melt source region during generation of early collisional granites. As these early collision granites have relatively low A/CNK and $(^{87}Sr/^{86}Sr)i$, high Mg#, $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values, they were likely derived from partial melting of the juvenile lower crust with minor contribution from ancient materials. By contrast, the early collision granites with relatively high A/CNK and $(^{87}Sr/^{86}Sr)i$, low Mg#, low $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values were derived from mixing of melts generated by partial melting of the juvenile and ancient lower crustal materials, or else derived solely from partial melting of ancient materials. In addition, a few granites with relatively high Mg# (>0.4) and Ni (>10 ppm) contents, typical of felsic intrusions evolved from basaltic rocks, probably represent the product of fractional crystallization of mantle-derived magmas, but underwent assimilation of ancient crustal materials. These considerations are consistent with recent conclusions that the eastern Gangdese lower arc crust contains Paleocene high-grade metamorphic and anatectic mafic and felsic granulites, which formed from Late Cretaceous and Early Paleocene arc-type magmatic rocks and ancient sedimentary rocks (Zhang et al., 2013; Palin et al., 2014; Jiang et al., 2022). As such, the Early Cenozoic granites of the Gangdese arc were mostly derived from partial melting of both juvenile and ancient lower crusts (Chung et al., 2005, 2009; Chu et al., 2006, 2011; Guo et al., 2012; Zhang et al., 2013; Jiang et al., 2014, 2022; Wang et al., 2015, 2019; Ma et al., 2017; Li et al., 2019; Tang et al., 2022; Zhu et al., 2022).

Previous studies have shown that the Gangdese arc and Himalayan orogen underwent melting of thickened lower crust during the Oligocene to Miocene (e.g., Chung et al., 2003, 2005; Hou et al., 2004; Zhang et al., 2004, 2022b; Zheng et al., 2012; Ding et al., 2019; Ji et al., 2020; Wu et al., 2020). We also interpret that late collision Oligocene high Sr/Y granites in the eastern Gangdese arc resulted from the partial melting of lower crust based on the following evidence: (1) the granites have relatively high SiO_2, Na_2O, K_2O, Rb and A/CNK, and low Mg#, Zr and Ni (Fig. 3), and relatively enriched Sr–Nd–Hf isotopic compositions, characterized by relatively high $(^{87}Sr/^{86}Sr)i$, and low $\varepsilon_{Nd}(t)$ and zircon $\varepsilon_{Hf}(t)$ values (Figs. 4–6; Tables S2–S4), which are distinct from granites formed by fractionated crystallization of depleted mantle-derived magma. The low MgO (<1.91 wt. %), Ni (<11 ppm) and Yb (mostly < 1 ppm) concentrations, and low Mg# values (<0.47) are typical of high Sr/Y granites that were derived from partial melting of mafic rocks at high pressures representative of the thickened lower crust (Wang et al., 2006); (2) the granites have limited compositional ranges in major and trace elements, and lightly variable Eu/Eu* values, and therefore are unlikely to be products of fractional crystallization of mantle-derived magma. This also is consistent with the lack of coeval intermediate to mafic rocks in the study area; (3) some of the Oligocene granites have relatively high SiO_2, Na_2O+K_2O and A/CNK (>1.10), and contain magmatic zircons with inherited detrital cores (such as samples D024-1, D110-1, D112-1, D123-1, and PM1-05; Fig. S1), and therefore were sourced from the partial melting of ancient sedimentary rocks in the lower arc crust; (4) the exposed lower crustal rocks of the eastern Gangdese arc widely overprinted the Oligocene high-grade metamorphism and partial melting, and the generated melts provide potential sources of the upper crustal granites (Palin et al., 2014; Zhang et al., 2015; Yi et al., 2022). The last two lines of evidence provide direct constraints for the anatexis of lower arc crust during the late stages of collisional orogeny.

4.2. Evolution of components and compositions of the lower arc crust over time

The Gangdese arc experienced intense mantle-derived magmatism and juvenile crustal growth during the Mesozoic. However, our results show that the Late Mesozoic to Cenozoic crust-derived granites are widespread throughout the eastern Gangdese arc (Fig. 2b). Moreover, the granites from different tectonic stages show significantly different major, trace element and isotopic compositions (Figs. 3–6; Tables S2–S4). These show that the juvenile crust of the magmatic arc underwent intense reworking, and its components and compositions evolved over time, through the late subduction and early to late collision stages.

The late subduction granites have depleted mantle-like geochemistry, limited compositional ranges in major and trace elements, and Sr–Nd–Hf isotopes (Figs. 3–6), and lower whole-rock $\varepsilon_{Nd}(t)$ and higher whole-rock $(^{87}Sr/^{86}Sr)_i$ than those of the slightly early gabbros and diorites (Figs. 4e, 4F and 5). These compositional features indicate that juvenile lower arc crust, which formed the source region of the granites, contained a small volume of homogenously distributed ancient crust (Figs. 5 and 7A). This is consistent with the field observations of minor upper amphibolite- and granulite-facies meta-sedimentary rocks that occur throughout the exposed Late Cretaceous lower crust of the eastern Gangdese arc (Qin et al., 2022).

The widespread early collisional granites show highly variable whole-rock chemical compositions (Figs. 3 and 4); some of which have depleted Sr–Nd–Hf isotopic compositions, whereas others have enriched isotopic compositions (Figs. 4e, 4F, 5 and 6A). These characteristics indicate that the juvenile lower crust contains voluminous ancient crustal materials that are likely heterogeneously distributed (Figs. 5, 6A and 7B). This is consistent with previous studies showing that the latest Cretaceous to Eocene (67–44) granites of the Gangdese arc were derived from a remarkably heterogeneous source (Ji et al., 2017), and with field observations showing abundant meta-sedimentary rocks occur in exhumed Early Cenozoic lower crust of the eastern Gangdese arc (Jiang et al., 2022). The mechanisms that allow for incorporation or cycling of silica-rich, surficial sediments into the lower arc crust is still under debate, although in the Gangdese these units were likely transported to such depths via tectonic shortening and underthrusting rather than subduction-related underplating, as has been proposed for other continental arcs worldwide (Fig. 7; Jiang et al., 2022; Li et al., 2022). Moreover, some studies proposed that the Indian continental crust was underthrusted into the Gangdese lower crust during the early collision, and may have formed one of the sources of granites (Chu et al., 2011; Tang et al., 2022; Zhang et al., 2022b; Fig. 7B). In addition, the occurrence of Early Cenozoic mantle-derived and subducted oceanic crust-derived magmatic rocks indicates growth of juvenile crust during the early collision (Mo et al., 2007, 2008; Zhu et al., 2011; Niu et al., 2013; Hou et al., 2015; Fig. 7B).

The Oligocene granites have restricted ranges in major and trace elements (Figs. 3 and 4), and similar but relatively enriched isotopic compositions (Figs. 4E, 4F, 5 and 6A), indicating that the lower crust during late collision consisted mainly of juvenile crustal materials with minor amounts of homogenously distributed ancient rocks (Fig. 7C). Rare occurrences of Oligocene mantle-derived magmatic rocks imply that the Gangdese arc underwent limited growth by addition of juvenile crust during that time (Shang et al., 2016).

The Miocene granites show similar Sr–Nd isotopes to the Oligocene granites (Figs. 4E, 4F and 5), but mostly have higher zircon $\varepsilon_{Hf}(t)$ values than the latter (Fig. 6A). We suggest that the lower crustal source region of the Miocene granites contains similar lithological components to the Oligocene one, but is dominated by juvenile crustal materials and only has minor and heterogeneously distributed ancient materials (Figs. 6A and 7D). The Miocene mantle-derived ultrapotassic rocks have more enriched Sr–Nd–Hf isotopic compositions than the Miocene granites, indicating that the Gangdese arc's lithospheric mantle has been enriched due to pervasive metasomatism of the subducted Indian crust (e.g., Zhao et al., 2009; Liu et al., 2014; Yang et al., 2015). Therefore, the depleted Hf isotopic features of the Miocene granites are inherited from pre-existing juvenile crust that generated during subduction and early collision, implying that the arc did not experience significant growth of juvenile crust during the Miocene.

Geochemical characteristics that differ significantly between Mesozoic and Cenozoic magmatic rocks clearly indicate that the lower crust of the eastern Gangdese arc evolved from a depleted juvenile lower crust during the subduction stage into a more fertile lower crust during the collisional stage. Therefore, the lower arc crust has an increasing contribution of mantle-derived juvenile crustal components from early to late subduction (>85 Ma), and an increasing proportion of ancient crustal materials as late subduction transitioned to collision (Figs. 5, 6A and 7). The lower arc crust magma source became progressively more heterogeneous from the late subduction stage to the early collisional period, remained homogeneous between the early and late collisional periods, and then became more heterogeneous from the Oligocene to the Miocene (Figs. 5, 6A and 7). Therefore, the eastern Gangdese arc is characterized by the growth of juvenile crust and associated reworking (i.e., the accretion of mantle-derived magmas and remelting of the juvenile and ancient crustal materials) during the late subduction and early collision stages, but by the reworking of juvenile and ancient lower crusts, and limited growth of juvenile crust during the late collision stage.

4.3. Evolution of the arc crustal thickness over time

The modern Gangdese arc has a crustal thickness of 60-80 km, which is twice as thick as average continental crust, but there is still great controversy about the mechanisms and timing of this crustal thickening (Harrison et al., 1992; Zhao et al., 1993; Willett and Beaumont, 1994; Yakovlev and Clark, 2014; Kapp and DeCelles, 2019). Some studies argued that the Gangdese arc crust underwent thickening during Mesozoic subduction (England and Searle, 1986; Murphy et al., 1997; Ding and Lai, 2003; Ding et al., 2003, 2014; Kapp et al., 2005, 2007a, 2007b; Ji et al., 2012), whereas other workers have proposed that the majority of crustal thickening occurred after around 50 Ma as a direct result of continental collision and ongoing convergence (Molnar et al., 1993; Yin and Harrison, 2000; Williams et al., 2001; Chung et al., 2003, 2005, 2009; Hou et al., 2004, 2015; Mo et al., 2008; Wang et al., 2014a, 2014b; Yang et al., 2015, 2016a, 2016b; Zhu et al., 2017). High Sr/Y granites can form via anatexis of garnet-bearing mafic granulites or eclogites in the thickened lower crust (e.g., Chung et al., 2003; Hou et al., 2004), and therefore their Sr/Y and La/Yb ratios can be used to estimate minimum crustal thicknesses (e.g., Chapman et al., 2015; Profeta et al., 2015; Hu et al., 2017; Zhu et al., 2017; Sundell et al., 2021). Our work indicates that the late subduction granites have high Sr/Y ratios (mostly >50), early collision granites have low Sr/Y ratios (mostly <40), and late collision Oligocene granites have high Sr/Y ratios (mostly >60; Fig. 3g). These suggest that the minimum crustal thickness of the eastern Gangdese arc changed over time. In order to eliminate the effect of fractional crystallization on whole-rock compositions, chondrite-normalized $(La/Yb)_N$ values of high Sr/Y granites with SiO_2 = 60–70 wt.%, MgO < 4 wt.% and Rb/Sr = 0.04–0.2 were used to estimate the minimum crustal thickness. In this case, the $(La/Yb)_N$ values of the late subduction, early and late collision (Oligocene) granites are 12–37, 6–31, and 30–56, respectively (Fig. 6B). According to the calculation method of Hu et al. (2017) and average $(La/Yb)_N$ ratios (23, 14 and 44) of the three stages of granites, the Late Cretaceous, Early Eocene and Oligocene minimum crustal thickness are estimated at ~55 km, ~40 km and ~75 km, respectively (Fig. 6B).

Previous studies have documented that crust-sourced high Sr/Y granites are absent in the Gangdese arc during the Cretaceous (i.e. older than 85 Ma; Zhu et al., 2017; Zhang et al., 2022a), implying that the arc had a normal continental crustal thickness (<40 km) at that time. Widespread Miocene high Sr/Y granites mostly have lower $(La/Yb)_N$ ratios than the Oligocene granites (Fig. 6B), suggesting that the Miocene arc crust was probably thinner than during the Oligocene. Therefore, the Gangdese arc underwent its first phase of crustal thickening during the Late Cretaceous, subsequent crustal thinning during the Late Cretaceous to Early Eocene (~75–50 Ma), a second stage of crustal thickening during the Middle Eocene to Oligocene (~50–25 Ma), and a final stage of crustal thinning during the Late Oligocene to Miocene (Figs. 6B and 7).

Our estimation of the changes of arc crustal thickness over time is supported by previous works: (1) Southern Tibet had a normal crustal thickness during the Paleocene and Early Eocene, and a thickened crust during the Oligocene and Middle Miocene (Chung et al., 2009), (2) the Gangdese arc underwent crustal thickening in the early Late Cretaceous, and thinning in the latest Late Cretaceous (Ji et al., 2014), (3) the eastern Gangdese arc crust experienced the most significant thickening during the Late Eocene (Zhang et al., 2015), (4) the eastern Gangdese arc crust experienced thickening and reworking during the Eocene to Oligocene (Ding and Zhang, 2019). Moreover, the alternate crustal thickening and thinning of the arc crust is temporally consistent with (1) Late Cretaceous and Oligocene high-pressure and high-temperature metamorphism and anatexis of the Gangdese lower arc crust (Zhang et al., 2013, 2015; Palin et al., 2014; Ding et al., 2022a, 2022b; Qin et al., 2022), (2) Late Cretaceous, and Late Eocene to Oligocene contractional deformation and crustal shortening (Murphy et al., 1997; Ding and Lai, 2003; Kapp et al., 2005, 2007a, 2007b; Mo et al., 2007; Chung et al., 2009), and (3) Late Cretaceous to Early Eocene, and Miocene extensional deformation and sedimentation in the Gangdese arc (Meng et al., 2017; Kapp and DeCelles, 2019).

An independent check on these results derived from $(La/Yb)_N$ ratios is provided by the Eu/Eu*-in-zircon crustal thickness proxy. When applying this barometer to detrital zircons separated from modern river sands sourced from the Gangdese granites, Tang et al. (2021) revealed that the Gangdese arc experienced two episodes of crustal thickening (to 60–70 km) since the Cretaceous, with the first thickening event dated at 90–70 Ma, and the second at 50–30 Ma. Our data show that the magmatic zircons with Th/U > 0.1 and La < 1 (spots = 1299) from the granites studied here have highly variable Eu/Eu* values (Fig. 6C). Although zircon grains from late subduction and late collision granites mostly have higher Eu/Eu* values than the early collision granites, and a trend of early crustal thinning and late crustal thickening seems to be visible, the estimated crustal thicknesses are likely all less than 55 km based on average Eu/Eu* values (Fig. 6C). An irresolvable problem when applying the Eu/Eu*-in-zircon crustal thickness proxy to detrital zircons is that the effect of fractional crystallization, assimilation and mixing on chemical compositions of granitic zircons cannot be evaluated, as whole-rock chemical compositions of the detrital zircon-sourced granites are unknown. Nonetheless, the results suggested here for zircon Eu/Eu* values match those suggested from average $(La/Yb)_N$ ratios, which would be unexpected unless both signatures were coherently and independently measuring changes in crustal architecture through time.

4.4. Geodynamics for the arc crustal evolution

The Gangdese arc experienced Mesozoic accretionary orogeny, and overprinted the Cenozoic collisional orogeny, together with the Himalayan Range situated along the northern margin of India (Fig. 1; Yin and Harrison, 2000; Ding et al., 2003; Zhu et al., 2011; Pan et al., 2012). Some studies have suggested that the Gangdese arc underwent the following tectonic evolution: normal subduction of the Neo-Tethyan lithosphere from the Jurassic to the Early Cretaceous, early Late Cretaceous subduction of its mid-oceanic ridge, late Late Cretaceous flat subduction of the young oceanic slab, Early Cenozoic continental collision and breakoff of subducted oceanic lithosphere, Late Eocene to Oligocene underthrusting of Indian continent, and delamination of thickened lithospheric mantle during the Miocene (e.g., Chung et al., 2003, 2005; Hou et al., 2004; Lee et al., 2009; Zhao et al., 2009; Zhang et al., 2010, 2022a; Guo et al., 2011; Ma et al., 2014; Ji et al., 2016; Zhu et al., 2019; Ding et al., 2022a, 2022b). Our new data and key insights into changes in Gangdese arc crustal compositions and thicknesses over time can be combined with this tectonic model to constrain the geodynamic history of the arc's crustal evolution.

The Late Cretaceous (~85–75 Ma) Gangdese arc contains voluminous high Sr/Y granites in the upper arc crust and high-pressure granulite-facies migmatites in the thickened lower crust (Wen et al., 2008; Zhang et al., 2014, 2022a; Tang et al., 2019; Ding et al., 2022a). This metamorphic and magmatic association is probably related to shallow subduction of young oceanic lithosphere following subduction of the Neo-Tethyan mid-oceanic ridge, which occurred at ~100 Ma (Zhang et al., 2010; Guo et al., 2011, 2013; Zheng et al., 2014; Zhu et al., 2019). Low-angle subduction induced compressional deformation and tectonic thickening of the arc crust, and underthrusting of upper crustal rocks (intracrustal material cycling), as shallow-angle subducted slabs are more closely coupled with the overlying continental plate than subducted slabs that descend at high angles. This drove anatexis of thickened juvenile lower crust with minor ancient crustal rocks and formation of dense mafic residues, which were probably recycled into mantle (Fig. 7A). This melting was mostly driven by the breakdown of hydrous minerals (amphibole and biotite) at granulite-facies temperatures of 850–880 °C, catalyzed by the addition of water into the thickened lower crust provided from devolatilizing oceanic lithosphere and subducted sediments (Ding et al., 2022a, 2022b).

Following continental collision at ~65 Ma, the Indian plate crustal rocks were progressively underthrusted below the Gangdese arc crust (Chung et al., 2009; Chu et al., 2011; Tang et al., 2022; Zhang et al., 2022b). This addition of older crustal material increased the isotopic and geochemical heterogeneity of the lower arc crust, and caused crustal thickening of the Himalayan orogen (Fig. 7B). Rollback and breakoff of subducted oceanic lithosphere induced the upwelling of asthenosphere, and extension and thinning of arc crust during the early stage of collision (Figs. 6B and 7B). The lower arc crust and lithospheric mantle were intensely heated and partially melted to generate mantle-sourced rocks, juvenile and ancient crust-derived granites in the Gangdese arc and Himalayan orogen (Fig. 7B; Aikman et al., 2008; Zeng et al., 2011; Hou et al., 2012; Zhang et al., 2013, 2022b; Ma et al., 2017; Wu et al., 2020). These granites have notably different petrological and geochemical signatures to pre-collision intrusions (see above), given the differences in pressure (depth) and the mixture of protoliths that experienced anatexis.

With continued underthrusting of the Indian continent, the arc crust and lithospheric mantle underwent strong contraction and thickening, and intracrustal material cycling from the Eocene to the Oligocene (Figs. 6B and 7C). High-grade metamorphism and anatexis of the strongly thickened lower crust produced Oligocene high Sr/Y granites in the Gangdese arc, and leucogranites in the Himalayan orogen, and dense mafic residues that were probably foundered (recycled) into the mantle (Fig. 7C). Miocene magmatism in the Gangdese arc and Himalayan orogen, and the thinning of thickened arc crust are probably related to the convective removal or delamination of thickened lithospheric mantle and induced upwelling of asthenosphere (Chung et al., 2005; Zhao et al., 2009; Fig. 7D). Roll-back, break-off or tearing of the subducted Indian lithosphere are also plausible models that have been proposed for Miocene magmatism (Guo et al., 2011, 2015; Zhu et al., 2019; Ji et al., 2020; Wang et al., 2022). The partial melting of enriched lithospheric mantle that was metasomatized by dewatering subducted Indian crust generated potassic to ultrapotassic magmas; the remelting of thickened lower crust generated the high Sr/Y granites in the Gangdese arc (Fig. 7D; Chung et al., 2003; Hou et al., 2004; Zhao et al., 2009). Finally, the anatexis of ancient crust produced leucogranites that are now exposed within the Himalayan orogen.

4.5. Implications for the evolution of continental arc crust

Juvenile arc magmas extracted from the mantle have a basaltic bulk composition, whereas mature Phanerozoic continental crust has an overall andesitic composition

(Rudnick and Gao, 2003; Hacker et al., 2011; Jagoutz and Kelemen, 2015). Proposed mechanisms of transforming juvenile arc crust into continental crust include foundering of dense mafic rocks of lower arc crust (Arndt and Goldstein, 1989; Kay and Kay, 1991), crustal formation from primary mantle-derived or subducted oceanic crust-derived andesitic magmas (Kelemen, 1995; Niu et al., 2013), or mixing of basaltic rock with silicic magma derived by partial melting of mafic, subducting crust (Martin, 1986), or relamination of buoyant, subducted silica-rich sediments that can increase the bulk-SiO_2 content of the lower crust as a whole (Hacker et al., 2011, 2015; Kelemen and Behn, 2016). Fractional crystallization of mafic magma is commonly suggested to be a key mechanism of intracrustal differentiation and foundering of dense lower arc crustal rocks (Jagoutz, 2014; Keller et al., 2015; Jagoutz and Klein, 2018). However, partial melting within lower arc crust is likely necessary for juvenile arc crust to vertically differentiate and be refined into chemically mature continental crust (Kay and Kay, 1993; Brown and Rushmer, 2006; Garrido et al., 2006; Brown, 2007, 2010; Stern and Scholl, 2010; Jagoutz and Behn, 2013; Ducea et al., 2015).

As described above, the Gangdese arc consists mainly of Mesozoic and Early Cenozoic arc-type magmatic rocks with the depleted mantle-like Sr, Nd and Hf isotopic compositions, and therefore represents a juvenile crust that extracted from the mantle (Chu et al., 2006; Zhu et al., 2011; Zhang et al., 20114; Hou et al., 2015). However, the Oligocene lower crust of the eastern Gangdese arc contains not only mafic granulites, but also voluminous felsic granulites, with minor meta-sedimentary and meta-ultramafic rocks, and has an overall intermediate composition (Zhang et al., 2020). Moreover, as the upper crust of the Gangdese arc contains voluminous granitic and andesitic rocks and minor mafic magmatic rocks (Chung et al., 2005; Mo et al., 2007, 2008; Zhu et al., 2011, 2019; Niu et al., 2013), we speculate that the whole crust of eastern Gangdese arc has an overall andesitic composition, and therefore resembles mature continental crust, rather than juvenile mafic arc crust.

Previous studies have argued that Late Cretaceous granites (e.g. the Lilong batholith) represent a product of fractional crystallization of mantle-derived rocks, and thus forms a juvenile arc crustal section (Zhang et al., 2014; Guo et al., 2020). This implies that the Gangdese arc underwent intracrustal differentiation via fractional crystallization during late subduction. The present study, as well as the occurrence of multistage high-grade metamorphic and anatectic rocks in the exposed arc root, indicate that the lower crust of the eastern Gangdese arc underwent at least four stages of high-temperature metamorphism and partial melting to generate the widespread Late Cretaceous, Paleocene to Early Eocene, Oligocene and Miocene granites in the upper crust. In addition, we speculate that the dense residues of garnet-rich mafic granulite or eclogite produced by the anatexis of the thickened lower crust have partly foundered into the less-dense underlying mantle, suggesting multistage of recycling of juvenile and ancient crustal materials into mantle (Fig. 7). Therefore, we suggest that repeated partial melting within the thickened lower crust is one of key mechanisms for refining mafic arc crust into andesitic continental crust for magmatic arcs with a complete evolutionary history from subduction to collision.

Early collisional granites in the eastern Gangdese arc mostly display significant enrichment of Sr–Nd–Hf isotopic compositions, indicating an addition of ancient continental crustal materials to the juvenile lower crust. This isotopic enrichment event is temporally consistent with the early stages of the Indo-Asian collision. Therefore, it is likely that the Indian continental crust was underthrusted into the Gangdese arc juvenile crust to form fertile material source for the early collision granites (Fig. 7B; Chu et al., 2011; Zhang et al., 2022b). The subducted and subsequently exhumed Indian continental crust contains voluminous felsic rocks, including high-grade metamorphosed granites, pelites and graywackes (Kohn, 2014; Zhang et al., 2022b). In addition, the felsic intrusive rocks and supracrustal rocks from the Gangdese upper crust were transported to the lower crust by subduction erosion and arc crustal underthrusting during the late subduction and collisional orogeny, indicating multiple periods of intracrustal material cycling (Zhang et al., 2013, 2020; Jiang et al., 2022; Li et al., 2022; Qin et al., 2022). Transporting these felsic rocks to the lower arc crust can significantly modify the components and compositions of juvenile lower arc crust and even the whole arc crust, and therefore is an additional mechanism for compositionally modifying arc crust. These processes are similar to relamination of buoyant, subducted rocks to the lower crust of magmatic arcs, which is considered to be a key mechanism for refining arc crust into continental crust (Hacker et al., 2011, 2015; Kelemen and Behn, 2016).

The above-described Gangdese magmatic arc crust preserves a complex evolutionary history from subduction to collision, and an overall andesitic composition that resembles mature continental crust; therefore, the temporal changes in magmatism, crustal component, thickness, and architecture are proposed here to be common processes for arc crustal evolution since the onset of plate tectonics.

5. CONCLUSIONS

1. The eastern Gangdese magmatic arc contains widespread crust-sourced granites, which formed during Late Cretaceous subduction, and Early and Late Cenozoic collision, and show significantly different major, trace element, and isotopic compositions, indicating that the components, compositions, thicknesses and architecture of the arc crust have changed over time.
2. The eastern Gangdese arc had a thick juvenile crust with a small volume of homogenously distributed ancient crust during the late subduction stage, a thin crust consisting of heterogeneously distributed juvenile and ancient crustal materials during the early collision stage, a thick juvenile crust with minor amounts of homogenously distributed ancient rocks during the late collision (Oligocene), and a thick juvenile crust with minor and heterogeneously distributed ancient materials during the late collision (Miocene).
3. The eastern Gangdese arc crust experienced the Late Cretaceous and Eocene crustal thickening, Paleocene and Miocene thinning, and at least four stages of anatexis of the lower arc crust, and associated cycling or recycling of juvenile and ancient crustal materials within the arc crust and between the crust and mantle.

4. Shallow subduction of Neo-Tethys oceanic lithosphere promoted tectonic thickening of the Gangdese arc crust and led to anatexis of lower crust and formation of high Sr/Y granites during the Late Cretaceous. Immediately after the onset of Indo-Asian collision, the deeply subducted oceanic slab breakoff and rollback-driven extension temporarily allowed thinning of the arc crust, and generation of juvenile and ancient crust-derived granites during the Early Cenozoic. Continued underthrusting of the Indian continent crust and subsequent delamination of thickened lithospheric mantle led to thickening and thinning of the arc crust, respectively, and anatexis of thickened lower crust and generation of high Sr/Y granites during the Oligocene and Miocene.
5. The eastern Gangdese arc is characterized by the growth of juvenile crust and associated reworking during the late subduction and early collision stages, but by the reworking of juvenile and ancient lower crusts, and limited growth of juvenile crust during the late collision stage. The prolonged and alternate growth and reworking processes that were related to changing dynamics of subduction and collision are considered to be a common mechanism for maturation of juvenile crust of continental magmatic arcs.

ACKNOWLEDGEMENTS

This study is co-supported by the National Natural Science Foundation of China (U2244203 and 91855210), and the China Geological Survey (DD20221630). Ph.D. and master students Wentan Li, Zhongrao Li, Wentao An, Weirui Lu, Mingming Guo, Shuangpeng Wu, Di Wang, Hongfei Ren, Zhaoge Hao, Tong Feng, Zhongtao Shi and Yuilong Bai took part in this study.

REFERENCES CITED

Aikman, A.B., Harrison, T.M., and Ding, L., 2008, Evidence for early (>44 Ma) Himalayan crustal thickening, Tethyan Himalaya, southeastern Tibet: Earth and Planetary Science Letters, v. 274, p. 14–23, https://doi.org/10.1016/j.epsl.2008.06.038.

Arndt, N.T., and Goldstein, S.L., 1989, An open boundary between lower continental crust and mantle: its role in crust formation and crustal recycling: Tectonophysics, v. 161, no. 3–4, p. 201–212, https://doi.org/10.1016/0040-1951(89)90154-6.

Brown, M., 2007, Crustal melting and melt extraction, ascent and emplacement in orogens: mechanisms and consequences: Journal of the Geological Society, London, v. 164, no. 4, p. 709–730, https://doi.org/10.1144/0016-76492006-171.

Brown, M., 2010, Melting of the continental crust during orogenesis: the thermal, reheological, and compositional consequences of melt transport from lower to upper continental crust: Canadian Journal of Earth Sciences, v. 47, p. 655–694, https://doi.org/10.1139/E09-057.

Brown, M., and Rushmer, T., 2006, Evolution and differentiation of the continental crust. Cambridge University Press, New York, 332–384.

Cao, W., Yang, J., Zuza, A. V., Ji, W.Q., Ma, X.X., Chu, X., and Burgess, Q. P., 2020, Crustal tilting and differential exhumation of Gangdese batholith in southern Tibet revealed by bedrock pressures: Earth and Planetary Science Letters, v. 543, p. 116–347, https://doi .org/10.1016/ j.epsl.2020.116347.

Chapman, J.B., Ducea, M.N., DeCelles, P.G., and Profeta, L., 2015, Tracking changes in crustal thickness during orogenic evolution with Sr/Y: An example from the North American Cordillera: Geology, v. 43, no.10, p. 919–922, https://doi .org/10.1130/G36996.1.

Chen, J.L., Xu, J.F., Zhao, W.X., Dong, Y.H., Wang, B.D., and Kang, Z.Q., 2011, Geochemical variations in Miocene adakitic rocks from the western and eastern Lhasa terrane: Implications for lower crustal flow beneath the Southern Tibetan Plateau: Lithos, v. 125, no. 3–4, p. 928–939, https://doi.org/10.1016/ j.lithos.2011.05.006.

Chu, M.F., Chung, S.L., Song, B., Liu, D., O'Reilly, S.Y., and Pearson, N.J., 2006, Zircon U–Pb and Hf isotope constraints on the Mesozoic tectonics and crustal evolution of southern Tibet: Geology, v. 34, no. 9, p. 745–748, https://doi.org/10.1130/G22725.1.

Chu, M.F., Chung, S.L., O'Relly, S. Y., Pearson, N.J., Wu, F.Y., Liu, X.H., Liu, D.Y., Ji, J.Q., Chu, C.H., and Lee, H.Y., 2011, India's hidden inputs to Tibetan orogeny revealed by Hf isotopes of Transhimalayan zircons and host rocks: Earth and Planetary Science Letters, v. 307, no. 3–4, p. 479–486, https://doi.org/10.1016/j.epsl.2011.05.020.

Chung, S. L., Liu, D., Ji, J., Chu, M. F., Lee, H. Y, Wen, D. J., Lo, C.H., Lee, T.Y., Qian, Q., and Zhang, Q., 2003, Adakites from continental collision zones: melting of thickened lower crust beneath southern Tibet: Geology, v. 31, no. 11, p. 1021–1024, https://doi.org/10.1130/G19796.1.

Chung, S.L., Chu, M.F., Zhang, Y., Xie, Y., Lo, C.H., Lee, T.Y., Lan, C.Y., Li, X.H., Zhang, Q., and Yang, Y.Z., 2005, Tibetan tectonic evolution inferred from spatial and temporal variations in post-collisional magmatism: Earth-Science Reviews, v. 68, no. 3–4, p. 173–196, https://doi.org/10.1016/j.earscirev.2004.05.001.

Chung, S.L., Chu, M.F., Ji, J., O'Reilly, S.Y., Pearson, N. J., Liu, D., Lee, T.Y., and Lo, C.H., 2009, The nature and timing of crustal thickening in Southern Tibet: geochemical and zircon Hf isotopic constraints from postcollisional adakites: Tectonophysics, v. 477, no. 1–2, p. 36–48, https://doi.org/10.1016/j.tecto.2009.08.008.

Ding, L., and Lai, Q.Z., 2003, New geological evidence of crustal thickening in the Gangdese block prior to the Indo-Asian collision: Chinese Science Bulletin, v. 48, p. 1604–1610, https://doi .org/10.1007/BF03183969.

Ding, L., Kapp, P., Zhong, D.L., and Deng, W.M., 2003, Cenozoic volcanism in Tibet: evidence for a transition from oceanic to continental subduction: Journal of Petrology, v. 44, no. 10, p. 1833–1865, https://doi.org/10.1093/petrology/egg061.

Ding, L., Xu, Q., Yue, Y.H., Wang, H.Q., Cai, F.L., and Li, S., 2014, The Andean-type Gangdese Mountains: Paleoelevation record from the Paleocene–Eocene Linzhou Basin: Earth and Planetary Science Letters, v. 392, p. 250–264, https://doi.org/10.1016/ j.epsl.2014.01.045.

Ding, H.X., and Zhang, Z.M., 2019, Early Cenozoic thickening and reworking of the eastern Gangdese arc, south Tibet: Constraints from the Oligocene granitoids: Geological Society London Special Publication, v. 474, no. 1, p. 291–308, https://doi.org/10.1144/SP474.

Ding, H.X., Zhang, Z.M., Palin, R.M., Kohn, M.J., Niu, Z.X., Chen, Y.F., Qin, S.K., Jiang, Y.Y., and Li, W.T., 2022a, Late Cretaceous metamorphism and anatexis of the Gangdese magmatic arc, South Tibet: Implications for thickening and differentiation of juvenile crust: Journal of Petrology, v. 63, no. 3, p. 1–26, https://doi.org/10.1093/petrology/egac017.

Ding, H.X., Zhang, Z.M., and Kohn, M.J., 2022b, Late Cretaceous hydrous melting and reworking of juvenile lower crust of the eastern Gangdese magmatic arc, southern Tibet: Gondwana Research, v. 104, p. 112–125, https://doi.org/10.1016/j.gr.2021.07.017.

Ducea, M.N., Saleeby, J.B., and Bergantz, G., 2015, The architecture, chemistry, and evolution of continental magmatic arcs: Annual Review of Earth and Planetary Sciences, v. 43, p. 299–331, https://doi.org/10.1146/annurev-earth-060614-105049.

England, P., and Searle, M., 1986, The Cretaceous–Tertiary deformation of the Lhasa block and its implications for crustal thickening in Tibet: Tectonics, v. 5, no. 1, p. 1–14, https://doi.org/10.1029/TC005i001p00001.

Garrido, C.J., Bodinier, J.L., Burg, J.P., Zeilinger, G., Hussain, S.S., Dawood, H., Chaudhry, M.N., and Gervilla, F., 2006, Petrogenesis of mafic garnet granulite in the lower crust of the Kohistan paleo-arc complex (northern Pakistan): implications for intra-crustal differentiation of island arcs and generation of continental crust: Journal of Petrology, v. 47, no. 10, p. 1873–1914, https://doi.org/10.1093/petrology/egl030.

Guo, Z.F., Wilson, M., and Liu, J.Q., 2007, Post-collisional adakites in south Tibet: Products of partial melting of subduction-modified lower crust: Lithos, v. 96, no.1–2, p. 205– 224, https://doi.org/10.1016/j.lithos.2006.09.011.

Guo, L., Zhang, H.F., Harris, N., Pan, F.B., and Xu, W.C., 2011, Origin and evolution of multi-stage felsic melts in eastern Gangdese belt: constraints from U–Pb zircon dating and Hf isotopic composition: Lithos, v. 127, no. 1–2, p. 54–67, https://doi.org/10.1016/j.lithos.2011.08.005.

Guo, L., Zhang, H.F., Harris, N., Parrish, R., Xu, W.C., and Shi, Z.L., 2012, Paleogene crustal anatexis and metamorphism in Lhasa terrane, eastern Himalayan syntaxis: Evidence from U–Pb zircon ages and Hf isotopic compositions of the Nyingchi Complex: Gondwana Research, v. 21, no. 1, p. 100–111, doi:10.1016/j.gr.2011.03.002.

Guo, L., Zhang, H.F., Harris, N., Pan, F.B., and Xu, W.C., 2013, Late Cretaceous (~81 Ma) high-temperature metamorphism in the southeastern Lhasa terrane: Implication for the Neo-Tethys ocean ridge subduction: Tectonophysics, v. 608, p. 112–126, https://doi.org/10.1016/j.tecto.2013.10.007.

Guo, Z.F., Wilson, M., Zhang, M.L., Cheng, Z.H., and Zhang, L.H., 2015, Post-collisional ultrapotassic mafic magmatism in south Tibet: Products of partial melting of pyroxenite in the mantle wedge induced by roll-back and delamination of the subducted Indian continental lithosphere slab: Journal of Petrology, v. 56, no. 7, p. 1365–1405, https://doi.org/10.1093/petrology/egv040.

Guo, L., Jagoutz, O., Shinevar, W.J., and Zhang, H.F., 2020, Formation and composition of the Late Cretaceous Gangdese arc lower crust in southern Tibet: Contributions to Mineralogy and Petrology, v. 175, no. 6, p. 58, https://doi.org/10.1007/s00410-020-01696-y.

Hacker, B.R., Kelemen, P.B., and Behn, M.D., 2011, Differentiation of the continental crust by relamination: Earth and Planetary Science Letters, v. 307, no. 3–4, p. 501–516, https://doi.org/10.1016/j.epsl.2011.05.024.

Hacker, B.R., Kelemen, P.B., and Behn, M.D., 2015, Continental lower crust: Annual Review of Earth and Planetary Sciences, v. 43, p. 167–205, https://doi.org/10.1146/annurev-earth-050212-124117.

Harrison, T.M., Copeland, p., Kidd, W.S.F., and Yin, A., 1992, Raising Tibet:

Science, v. 255, no. 5052, p. 1663–1670, doi:10.1126/science.255.5052.1663.

Hou, Z.Q., Gao, Y.F., Qu, X.M., Rui, Z.Y., and Mo, X.X., 2004, Origin of adakitic intrusives generated during mid-Miocene east–west extension in southern Tibet: Earth and Planetary Science Letters, v. 220, no. 1–2, p. 139–155, https://doi.org/10.1016/S0012-821X(04)00007-X.

Hou, Z.Q., Zheng, Y.C., Zeng, L.S., Gao, L.E., Huang, K.X., Li, W., Li, Q.Y., Fu, Q., Liang, W., and Sun, Q.Z., 2012, Eocene-Oligocene granitoids in southern Tibet: constraints on crustal anatexis and tectonic evolution of the Himalayan orogen: Earth and Planetary Science Letters, v. 349, p. 38–52, https://doi.org/10.1016/j.epsl.2012.06.030.

Hou, Z.Q., Duan, L., Lu, Y.J., Zheng, Y.C., Zhu, D.C., Yang, Z.M., Yang, Z.S., Wang, B.D., Pei, Y.G., Zhao, Z.D., and McCuaig, T.C., 2015, Lithospheric architecture of the Lhasa terrane and its control on ore deposits in the Himalayan–Tibetan orogeny: Economic Geology, v. 110, no. 6, p. 1541–1575, https://doi.org/10.2113/econgeo.110.6.1541.

Hu, F., Ducea, M.N., Liu, S., and Chapman, J.B., 2017, Quantifying Crustal Thickness in Continental Collisional Belts: Global Perspective and a Geologic Application: Scientific Reports, v. 7, 7058, https://doi.org/10.1038/s41598-017-07849-7.

Jagoutz, O., and Behn, M.D., 2013, Foundering of lower arc crust as an explanation for the origin of the continental Moho: Nature, v. 504, p. 131–134, https://doi.org/10.1038/nature12758.

Jagoutz, O., 2014, Arc crustal differentiation mechanisms: Earth and Planetary Science Letters, v. 396, p. 267–277, https://doi.org/10.1016/j.epsl.2014.03.060.

Jagoutz, O., and Kelemen, P.B., 2015, Role of arc processes in the formation of continental crust: Annual Review of Earth and Planetary Sciences, v. 43, p. 363–404, https://doi.org/10.1146/annurev-earth-040809-152345.

Jagoutz, O., and Klein, B., 2018, On the importance of crystallization-differentiation for the generation of SiO_2-rich melts and the compositional build-up of arc, and continental) crust: American Journal of Science, v. 318, no. 1, p. 29–63, https://doi.org/10.2475/01.2018.03.

Ji, W.Q., Wu, F.Y., Chung, S.L., Li, J.X., and Liu, Z.C., 2009, Zircon U–Pb geochronology and Hf isotopic constraints on petrogenesis of the Gangdese batholith, southern Tibet: Chemical Geology, v. 262, no. 3–4, p. 229–245, https://doi.org/10.1016/j.chemgeo.2009.01.020.

Ji, W.Q., Wu, F.Y., Liu, C.Z., and Chung, S.L., 2012, Early Eocene crustal thickening in southern Tibet: New age and geochemical constraints from the Gangdese batholith: Journal of Asian Earth Sciences, v. 53, p. 82–95, https://doi.org/10.1016/j.jseaes.2011.08.020.

Ji, W.Q., Wu, F.Y., Chung, S.L., and Liu, Z.C., 2014, The Gangdese magmatic constraints on a latest Cretaceous lithospheric delamination of the Lhasa terrane, southern Tibet: Lithos, v. 210–211, p. 168–180, https://doi.org/10.1016/j.lithos.2014.10.001.

Ji, W. Q., Wu, F.Y., Chung, S.L., Wang, X.C., Liu, C.Z., Li, Q.L., Liu, Z.C., Liu, X.C., and Wang, J.G., 2016, Eocene Neo-Tethyan slab breakoff constrained by 45 Ma oceanic island basalt-type magmatism in southern Tibet: Geology, v. 44, no. 4, p. 283–286, https://doi.org/10.1130/G37612.1.

Ji, W.Q., Wu, F.Y., Liu, C.Z., and Zhang, H., 2017, Zircon U–Pb geochronology and Hf isotopes of granitic rocks and river sands in the Nyingchi region, Tibet: Constraints on evolution of the deep crust beneath the southeast Lhasa terrane: Journal of Asian Earth Sciences, v. 145, p. 613–625, https://doi.org/10.1016/j.jseaes.2017.07.006.

Ji, W.Q., Wu, F.Y., Liu, X.C., Liu, Z.C., Zhang, C., Liu, T., Wang, J.G., and Peterson, S.R., 2020, Pervasive Miocene melting of thickened crust from the Lhasa terrane to Himalaya, southern Tibet and its constraint on generation of Himalayan leucogranite: Geochimica et Cosmochimica Acta, v. 278, p. 137–156, https://doi.org/10.1016/j.gca.2019.07.048.

Jiang, Z.Q., Wang, Q., Wyman, D.A., Li, Z.X., Yang, J.H., Shi, X.B., Ma, L., Tang, G.J., Gou, G.N., Jia, X.H., and Guo, H.F., 2014, Transition from oceanic to continental lithosphere subduction in southern Tibet: Evidence from the Late Cretaceous–Early Oligocene (~91–30Ma) intrusive rocks in the Chanang–Zedong area, southern Gangdese: Lithos, v. 196–197, p. 213–231, https://doi.org/10.1016/j.lithos.2014.03.001.

Jiang, Y.Y., Zhang, Z.M., Palin, R.M., Ding, H.X., and Mo, X.X., 2022, Early Cenozoic partial melting of meta-sedimentary rocks of the eastern Gangdese arc, southern Tibet, and its contribution to syn-collisional magmatism: Geological Society of America Bulletin, v. 134, no. 1–2, p. 179–200, https://doi.org/10.1130/B35763.1.

Kapp, P., Yin, A., Harrison, T.M., and Ding, L., 2005, Cretaceous–Tertiary shortening, basin development, and volcanism in central Tibet: Geological Society of America Bulletin, v. 117, no. 7–8, p. 865–878, https://doi.org/10.1130/B25595.1.

Kapp, P., DeCelles, P.G., Gehrels, G.E., Heizler, M., and Ding. L., 2007a, Geological records of the Lhasa–Qiangtang and Indo-Asian collisions in the Nima area of central Tibet: Geological Society of America Bulletin, v. 119, no. 7–8, p. 917–933, https://doi.org/10.1130/B26033.1.

Kapp, P., Decelles, P.G., Leier, A., Fabijanic, J.M., He, S., Pullen, A., Gehrels, G.E., and Ding, L., 2007b, The Gangdese retroarc thrust belt revealed: Geological Society of America Today, v. 17, no. 7, p. 4–9, https://doi.org/10.1130/GSAT01707A.1.

Kapp, P., and DeCelles, P.G., 2019, Mesozoic–Cenozoic geological evolution of the Himalayan–Tibetan orogen and working tectonic hypotheses: American Journal of Science, v. 319, no. 3, p. 159–254, https://doi .org/10.2475/03.2019.01.

Kay, R.W., and Kay, S.M., 1991, Creation and destruction of lower continental crust: Geologische Rundschau, v. 80, p. 259–278, https://doi.org/10.1007/BF01829365.

Kay, R.W., and Kay, S.M., 1993, Delamination and delamination magmatism: Tectonophysics, v. 219, no. 1–3, p. 177–189, https://doi.org/10.1016/0040-1951(93)90295-U.

Kelemen, P., 1995, Genesis of high Mg# andesites and the continental crust: Contributions to Mineralogy and Petrology, v. 120, p. 1–19, https://doi.org/10.1007/BF00311004.

Kelemen, P.B., and Behn, M.D., 2016, Formation of lower continental crust by relamination of buoyant arc lavas and plutons: Nature Geoscience, v. 9, p. 197–205, https://doi.org/10.1038/ngeo2662.

Keller, C.B., Schoene, B., Barboni, M., Samperton, K.M., and Husson, J.M., 2015, Volcanic-plutonic parity and the differentiation of the continental crust: Nature, v. 523, p. 301–307, https://doi.org/10.1038/nature14584.

Kohn, M.J., 2014, Himalayan metamorphism and its tectonic implications: Annual Review of Earth and Planetary Sciences, v. 42, p. 381–419, https://doi.org/10.1146/annurev-earth-060313-055005.

Lee, C.T.A., and Anderson, D.L., 2015, Continental crust formation at arcs, the arclogite “delamination” cycle, and one origin for fertile melting anomalies in the mantle: Science Bulletin, v. 60, no. 13, p. 1141–1156, https://doi.org/10.1007/s11434-015-0828-6.

Lee, H.Y., Chung, S.L., Lo, C.H., Ji, J., Lee, T.Y., Qian, Q., and Zhang, Q., 2009, Eocene Neotethyan slab breakoff in southern Tibet inferred from the Linzizong volcanic record: Tectonophysics, v. 477, no. 1–2, p. 20–35, https://doi.org/10.1016/j.tecto.2009.02.031.

Li, Q.W., Nebel, O., Nebel-Jacobsen, Y., Richter, M., Wang, R., Weinberg, R., Zhao, J.H., and Cawood, P.A., 2019, Crustal reworking at convergent margins traced by Fe isotopes in I-type intrusions from the Gangdese arc, Tibetan Plateau: Chemical Geology, v. 510, p. 47–55, https://doi.org/10.1016/j.chemgeo.2019.02.007.

Li, W.T., Ding, H.X., Zhang, Z.M., and Larson, K.P., 2022, Petrogenesis of meta-sedimentary rocks in the deep crust of the eastern Gangdese arc: Lithos, p.430–431, 106884, https://doi.org/10.1016/j.lithos.2022.106884.

Liu, D., Zhao, Z.D., Zhu, D.C., Niu, Y.L., and Harrison, T.M., 2014, Zircon xenocrysts in Tibetan ultrapotassic magmas: Imaging the deep crust through time:

Geology, v. 42, no. 1, p. 43–46, https://doi.org/10.1130/G34902.1.

Ma, L., Wang, Q., Wyman, D.A., Jiang, Z.Q., Yang, J.H., Li, Q.L., Guo, G.N., and Guo, H.F., 2013, Late Cretaceous crustal growth in the Gangdese area, southern Tibet: petrological and Sr–Nd–Hf–O isotopic evidence from Zhengga diorite–gabbro: Chemical Geology, v. 349–350, p. 54–70, https://doi.org/10.1016/j.chemgeo.2013.04.005.

Ma, L., Wang, B.D., Jiang, Z.Q., Wang, Q., Li, Z.X., Wyman, D.A., Zhao, S.R., Yang, J.H., Gou, G.N., and Guo, H.F., 2014, Petrogenesis of the Early Eocene adakitic rocks in the Napuri area, southern Lhasa: partial melting of thickened lower crust during slab break-off and implications for crustal thickening in southern Tibet: Lithos, v. 196–197, p. 321–338, https://doi.org/10.1016/j.lithos.2014.02.011.

Ma, L., Wang, Q., Kerr, A., Yang, J.H., Xia, X.P., Ou, Q., Yang, Z.Y., and Sun, P., 2017, Paleocene (ca. 62 Ma) leucogranites in southern Lhasa, Tibet: products of syn-collisional crustal anatexis during slab roll-back: Journal of Petrology, v. 58, no. 11, p. 2089–2114, https://doi.org/10.1093/petrology/egy001.

Ma, X.X., Attia, S., Cawood, T., Cao, W.R., Xu, Z.Q., and Li, H.B., 2022, Arc tempos of the Gangdese batholith, southern Tibet: Journal of Geodynamics, v. 149, 101897, https://doi.org/10.1016/j.jog.2022.101897.

Martin, H., 1986, Effect of steeper Archean geothermal gradient on geochemistry of subduction-zone magmas: Geology, v. 14, no. 9, p. 753–756, https://doi.org/10.1130/0091-7613(1986)14<753:EOSAGG>2.0.CO;2.

Meng, Y.K., Xu, Z.Q., Santosh, M., Ma, X.X., Chen, Z.J., Guo, G.L., and Liu, F., 2016, Late Triassic crustal growth in southern Tibet: Evidence from the Gangdese magmatic belt: Gondwana Research, v. 37, p. 449–464, https://doi.org/10.1016/j.gr.2015.10.007.

Meng, J., Coe, R.S., Wang, C., Gilder, S.A., Zhao, X., Liu, H., Li, Y.L., Ma, P.F., Shi, K., and Li, S., 2017, Reduced convergence within the Tibetan Plateau by 26 Ma: Geophysical Research Letters, v. 44, no. 13, p. 6624–6632, https://doi.org/10.1002/2017GL074219.

Mo, X.X., Hou, Z.Q., Niu, Y., Dong, G.C., Qu, X.M., Zhao, Z.D., and Yang, Z.M., 2007, Mantle contributions to crustal thickening during continental collision: evidence from Cenozoic igneous rocks in southern Tibet: Lithos, v. 96, no. 1–2, p. 225–242, https://doi.org/10.1016/j.lithos.2006.10.005.

Mo, X.X., Niu, Y.L., Dong, G.C., Zhao, Z.C., Hou, Z.Q., Zhou, S., and Ke, S., 2008, Contribution of syncollisional felsic magmatism to continental crust growth: A case study of the Paleogene Linzizong volcanic succession in southern Tibet: Chemical Geology, v. 250, no. 1–4, p. 49–67, https://doi.org/10.1016/j.chemgeo.2008.02.003.

Molnar, P., England, P., and Martinod, J., 1993, Mantle dynamics, uplift of the Tibetan Plateau, and the Indian monsoon: Reviews of Geophysics, v. 31, no. 4, p. 357–396, https://doi.org/10.1029/93RG02030.

Murphy, M.A., Yin, A., Harrison, T.M., Dürr, S.B., Chen, Z., Ryerson, F.J., Kidd, W.S.F., Wang, X., and Zhou, Z., 1997, Did the Indo-Asian collision alone create the Tibetan Plateau: Geology, v. 25, no. 8, p. 719–722, https://doi.org/10.1130/0091-7613(1997)025<0719:DTIACA>2.3.CO;2.

Niu, Y.L., Zhao, Z.D., Zhu, D.C., and Mo, X.X., 2013, Continental collision zones are primary sites for net continental crust growth—A testable hypothesis: Earth-Science Reviews, v. 127, p. 96–110, https://doi.org/10.1016/j.earscirev.2013.09.004.

Palin, R.M., Searle, M.P., St-Onge, M.R., Waters, D.J., Roberts, N.M.W., Horstwood, M.S.A., Parrish, R.R., Weller, O.M., Chen, S., and Yang, J., 2014, Monazite geochronology and petrology of kyanite- and sillimanite-grade migmatites from the northwestern flank of the eastern Himalayan syntaxis: Gondwana Research, v. 26, no. 1, p. 323–347, https://doi.org/10.1016/j.gr.2013.06.022.

Pan, G.T., Wang, L.Q., Li, R.S., Yuan, S.H., Ji, W.H., Yin, F.G., Zhang, W.P., and Wang, B.D., 2012, Tectonic evolution of the Qinghai–Tibet plateau: Journal of Asian Earth Sciences, v. 53, p. 3–14, https://doi.org/10.1016/j.jseaes.2011.12.018.

Profeta, L., Ducea, M.N., Chapman, J.B., Paterson, S.R., Gonzales, S.M.H., Kirsch, M., Petrescu, L., and DeCelles, P.G., 2015, Quantifying crustal thickness over time in magmatic arcs: Scientific reports, v. 5, 17786, https://doi.org/10.1038/srep17786.

Qin, S.K., Zhang, Z.M., Palin, R.M., Ding, H.X., Dong, X., and Tian, Z.L., 2022, Tectonic burial of sedimentary rocks drives the building of juvenile crust of magmatic arc: Geological Society of America Bulletin, v. 134, no. 11–12, p. 3064–30778, https://doi.org/10.1130/B36271.1.

Rudnick, R.L., and Gao, S., 2003, Composition of the continental crust: Treatise on Geochemistry, v. 3, p. 1–64, https://doi.org/10.1016/B0-08-043751-6/03016-4.

Shang, Z., Zeng, L.S., Gao, L.E., Gao, J.H., Chen, F.K., Hou, K.J., Wang, Q., and Guo, C.L., 2016, Formation mechanism of the Chengba high Sr/Y granodiorite and enclaves in southern Gangdise region, southern Tibet: Geological Bulletin of China, v. 35, no. 1, p. 71–90, (in Chinese with English abstract), http://dzhtb.cgs.cn/gbc/ch/reader/view_abstract.aspx?file_no=20160107andflag=1.

Stern, R.J., and Scholl, D.W., 2010, Yin and yang of continental crust creation and destruction by plate tectonic processes: International Geology Review, v. 52, no. 1, p. 1–31, https://doi.org/10.1080/00206810903332322.

Sundell, K.E., Laskowski, A.K., Kapp, P.A., Ducea, M.N., and Chapman, J.B., 2021, Jurassic to Neogene quantitative crustal thickness estimates in southern Tibet: Geological Society of America Today, v. 31, no. 6, p. 4–10, https://doi.org/10.1130/GSATG461A.1.

Tang, Y.W., Chen, L., Zhao, Z.F., and Zheng, Y.F., 2019, Geochemical evidence for the production of granitoids through reworking of the juvenile mafic arc crust in the Gangdese orogen, southern Tibet: Geological Society of America Bulletin, v. 132, no. 7–8, p. 1347–1364, https://doi.org/10.1130/B35304.1.

Tang, M., Ji, W.Q., Chu, X., Wu, A., and Chen, C., 2021, Reconstructing crustal thickness evolution from europium anomalies in detrital zircons: Geology, v. 49, no. 1, p. 76–80, https://doi.org/10.1130/G47745.1.

Tang, Y.W., Chen, L., Zhao, Z.F., and Zheng, Y.F., 2022, Origin of syn-collisional granitoids in the Gangdese orogen: Reworking of the juvenile arc crust and the ancient continental crust: Geological Society of America Bulletin, v. 134, no. 3–4, p. 577–598, https://doi.org/10.1130/B35928.1.

Wang, Q., Xu, J.F., Jiang, P., Bao, Z.W., Zhao, Z.H., Li, C.F., Xiong, X.L., and Ma, J.L., 2006, Petrogenesis of adakitic porphyries in an extensional tectonic setting, Dexing, South China: Implications for the Genesis of Porphyry Copper Mineralization: Journal of Petrology, v. 47, no. 1, p. 119–144, https://doi.org/10.1093/petrology/egi070.

Wang, R., Richards, J.P., Hou, Z.Q., Yang, Z.M., and DuFrane, S.A., 2014a, Increased magmatic water content — the key to Oligo-Miocene porphyry Cu–Mo±Au formation in the eastern Gangdese belt, Tibet: Economic Geology, v. 109, no. 5, p. 1315–1339, https://doi.org/10.2113/econgeo.109.5.1315.

Wang, R., Richards, J.P., Hou, Z.Q., Yang, Z.M., Gou, Z.B., and DuFrane, S.A., 2014b, Increasing magmatic oxidation state from Paleocene to Miocene in the eastern Gangdese belt, Tibet: implication for collision-related porphyry Cu–Mo ± Au mineralization: Economic Geology, v. 109, no. 7, p. 1943–1965, https://doi.org/10.2113/econgeo.109.7.1943.

Wang, R., Richards, J.P., Hou, Z.Q., An, F., and Creaser, R.A., 2015, Zircon U–Pb age and Sr–Nd–Hf–O isotope geochemistry of the Paleocene–Eocene igneous rocks in western Gangdese: Evidence for the timing of Neo-Tethyan slab breakoff: Lithos, v. 224–225, p. 179–194, https://doi.org/10.1016/j.lithos.2015.03.003.

Wang, C., Ding, L., Zhang, L.Y., Kapp, P., Pullen, A., and Yue, Y.H., 2016, Petrogenesis of Middle–Late Triassic volcanic rocks from the Gangdese belt, southern Lhasa terrane: Implications for early subduction of Neo-Tethyan oceanic lithosphere: Lithos, v. 262, p. 320– 333, https://doi.org/10.1016/j.lithos.2016.07.021.

Wang, R., Weinberg, R.F., Collins, W.J., Richards, J.P., and Zhu, D.C., 2018, Origin of post-collisional magmas and formation of porphyry Cu deposits in southern

Tibet: Earth-Science Reviews, v. 181, p. 122–143, https://doi.org/10.1016/j.earscirev.2018.02.019.

Wang, R.Q., Qiu, J.S., Yu, S.B., Lin, L., and Xu, H., 2019, Magma mixing origin for the Quxu intrusive complex in southern Tibet: Insights into the early Eocene magmatism and geodynamics of the southern Lhasa subterrane: Lithos, v. 328–329, p. 14–32, https://doi.org/10.1016/j.lithos.2019.01.019.

Wang, R., Weinberg, R.F., Zhu, D.C., Hou, Z.Q., and Yang, Z.M., 2022, The impact of a tear in the subducted Indian plate on the Miocene geology of the Himalayan-Tibetan orogen: Geological Society of America Bulletin, v. 134, no. 3–4, p. 681–690, https://doi.org/10.1130/B36023.1.

Wen, D.R., Chung, S.L., Song, B., Iizuka, Y.Y., Yang, H.J., Ji, J.Q., Liu, D.Y., and Gallet, S., 2008, Late Cretaceous Gangdese intrusions of adakitic geochemical characteristics, SE Tibet: petrogenesis and tectonic implications: Lithos, v. 105, no.1–2, p. 1–11, https://doi.org/10.1016/j.lithos.2008.02.005.

Willett, S.D., and Beaumont, C., 1994, Subduction of Asian lithospheric mantle beneath Tibet inferred from models of continental collision: Nature, v. 369, no. 6482, p. 642–645, doi:10.1038/369642a0.

Williams, H., Turner, S., Kelley, S., and Harris, N., 2001, Age and composition of dikes in Southern Tibet: new constraints on the timing of east–west extension and its relationship to post-collisional volcanism: Geology, v. 29, no. 4, p. 339–342, https://doi.org/10.1130/0091-7613(2001)029<0339:AACODI>2.0.CO;2.

Wu, F.Y., Clift, P.D., and Yang, J.H., 2007, Zircon Hf isotopic constraints on the sources of the Indus Molasse, Ladakh Himalaya, India: Tectonics, v. 26, no. 2, TC2014, https://doi.org/10.1029/2006TC002051.

Wu, F.Y., Ji, W.Q., Liu, C.Z., and Chung, S.L., 2010, Detrital zircon U–Pb and Hf isotopic data from the Xigaze fore-arc basin: Constraints on Transhimalayan magmatic evolution in southern Tibet: Chemical Geology, v. 271, no. 1–2, p. 13–25, https://doi.org/10.1016/j.chemgeo.2009.12.007.

Wu, F.Y., Liu, X.C., Liu, Z.C., Wang, R.C., Xie, L., Wang, J.M., Ji, W.Q., Yang, L., Liu, C., Khanal, G.P., and He, S.X., 2020, Highly fractionated Himalayan leucogranites and associated rare-metal mineralization: Lithos, v. 352–353, 105319, https://doi.org/10.1016/j.lithos.2019.105319.

Yakovlev, P.V., and Clark, M.K., 2014, Conservation and redistribution of crust during the Indo-Asian collision: Tectonics, v. 33, p. 1016–1027, https://doi.org/10.1002/2013TC003469.

Yang, Z.M., Lu, Y.J., Hou, Z.Q., and Chang, Z.S., 2015, High-Mg diorite from Qulong in Southern Tibet: Implications for the genesis of adakite-like intrusions and associated porphyry Cu deposits in collisional orogens: Journal of Petrology, v. 56, no. 2, p. 227–254, https://doi.org/10.1093/petrology/egu076.

Yang, Z.M., Goldfarb, R., and Chang, Z.S., 2016a, Generation of post-collisional porphyry copper deposits in southern Tibet triggered by subduction of the Indian continental plate: Society of Economic Geologists Special Publication, v. 19, p. 279–300, https://doi.org/10.5382/SP.19.11.

Yang, Z.M., Hou, Z.Q., Chang, Z.S., Li, Q.Y., Liu, Y.F., Qu, H.C., Sun, M.Y., and Xu, B., 2016b, Cospatial Eocene and Miocene granitoids from the Jiru Cu deposit in Tibet: Petrogenesis and implications for the formation of collisional and postcollisional porphyry Cu systems in continental collision zones: Lithos, v. 245, p. 243–257, https://doi.org/10.1016/j.lithos.2015.04.002.

Yi, J.K., Zhu, D.C., Weinberg, R.F., Wang, Q., Xie, J.C., Zhang, L.L., and Zhao, Z.D., 2022, Origin of Tibetan post-collisional high-K adakitic granites: Anatexis of intermediate to felsic arc rocks: Geology, v. 50, p. 771–775, https://doi.org/10.1130/G49818.1

Yin, A., and Harrison, T.M., 2000, Geologic evolution of the Himalayan–Tibetan orogen: Annual Review of Earth and Planetary Sciences, v. 28, p. 211–280, https://doi.org/10.1146/annurev.earth.28.1.211.

Zeng, L.S., Gao, L.E., Xie, K.J., and Liu, J., 2011, Mid-Eocene high Sr/Y granites in the Northern Himalayan Gneiss Domes: Melting thickened lower continental crust: Earth and Planetary Science Letters, v. 303, no. 3–4, p. 251–266, https://doi.org/10.1016/j.epsl.2011.01.005.

Zhang, H.F., Harris, N.B.W., Parrish, R.R., Kelley, S., Zhang, L., Rogers, N., Argles, T., and King, J., 2004, Causes and consequences of protracted melting of the mid-crust exposed in the North Himalayan antiform: Earth and Planetary Science Letters, v. 228, no. 1–2, p. 195–212, https://doi.org/10.1016/j.epsl.2004.09.031.

Zhang, Z.M., Zhao, G.C., Santosh, M., Wang, J.L., Dong, X., and Shen, K., 2010, Late Cretaceous charnockite with adakitic affinities from the Gangdese batholith, southeastern Tibet: Evidence for Neo-Tethyan mid-oceanic ridge subduction: Gondwana Research, v. 17, no. 4, p. 615–631, https://doi.org/10.1016/j.gr.2009.10.007.

Zhang, Z.M., Dong, X., Xiang, H., Liou, J.G., and Santosh, M., 2013, Building of the deep Gangdese arc, south Tibet: Paleocene plutonism and granulite-facies metamorphism: Journal of Petrology, v. 54, no. 12, p. 2547–2508. https://doi.org/10.1093/petrology/egt056.

Zhang, Z.M., Dong, X., Xiang, H., He, Z.Y., and Liou, J.G., 2014, Metagabbros of the Gangdese arc root, south Tibet: implications for the growth of continental crust: Geochimica et Cosmochimica Acta, v. 143, p. 268–284, https://doi.org/10.1016/j.gca.2014.01.045.

Zhang, Z.M., Dong, X., Xiang, H., Ding, H.X., He, Z.Y., and Liou, J.G., 2015, Reworking of the Gangdese magmatic arc, southeastern Tibet: post-collisional metamorphism and anatexis: Journal of Metamorphic Geology, v. 33, no. 1, p. 1–21, https://doi.org/10.1111/jmg.12107.

Zhang, Z.M., Ding, H.X., Palin, R.M., Dong, X., Tian, Z.L., and Chen, Y.F., 2020, The lower crust of the Gangdese magmatic arc, southern Tibet: Gondwana Research, v. 77, p. 136–146, https://doi.org/10.1016/j.gr.2019.07.010.

Zhang, Z.M., Ding, H.X., Dong, X., Tian, Z.L., Palin, R.M., Santosh, M., Chen, Y.F., Jiang, Y.Y., Qin, S.K., Kang, D.Y., and Li, W.T., 2022a, The Mesozoic magmatic, metamorphic, and tectonic evolution of the eastern Gangdese magmatic arc, southern Tibet: Geological Society of America Bulletin, v. 134, no. 7–8, p. 1721–

1740, https://doi.org/10.1130/B36134.1.

Zhang, Z.M., Ding, H.X., Palin, R.M., Dong, X., Tian, Z.L., Kang, D.Y., Jiang, Y.Y., Qin, S.K., and Li, W.T., 2022b, On the origin of high-pressure mafic granulite in the Eastern Himalayan Syntaxis: Implications for the tectonic evolution of the Himalayan orogen: Gondwana Research, v. 104, p. 4–22, https://doi.org/10.1016/j.gr.2021.05.011.

Zhao, W.J., Nelson, K.D., and Project INDEPTH Team, 1993, Deep seismic reflection evidence for continental underthrusting beneath southern Tibet: Nature, v. 366, 557–559, doi:10.1038/366557a0.

Zhao, Z.D., Mo, X.X., Dilek, Y., Niu, Y.L., DePaolo, D.J., Robinson, P., Zhu, D.C., Sun, C.G., Dong, G.C., Zhou, S., Luo, Z.H., and Hou, Z.Q., 2009, Geochemical and Sr–Nd–Pb–O isotopic compositions of the post-collisional ultrapotassic magmatism in SW Tibet: petrogenesis and implications for India intra-continental subduction beneath southern Tibet: Lithos, v. 113, no. 1–2, p. 190–212, https://doi.org/10.1016/j.lithos.2009.02.004.

Zheng, Y.C., Hou, Z.Q., Li, Q.Y., Sun, Q.Z., Liang, W., Fu, Q., Li, W., and Huang, K.X., 2012, Origin of Late Oligocene adakitic intrusives in the southeastern Lhasa terrane: Evidence from in situ zircon U–Pb dating, Hf–O isotopes, and whole-rock geochemistry: Lithos, v. 148, p. 296–311, https://doi.org/10.1016/j.lithos.2012.05.026.

Zheng, Y.C., Hou, Z.Q., Gong, Y.L., Liang, W., Sun, Q.Z., Zhang, S., Fu, Q., Huang, K.X., Li, Q.Y., and Li, W., 2014, Petrogenesis of Cretaceous adakite-like intrusions of the Gangdese Plutonic Belt, southern Tibet: Implications for mid-ocean ridge subduction and crustal growth: Lithos, v. 190–191, p. 240–263, https://doi.org/10.1016/j.lithos.2013.12.013.

Zhu, D.C., Zhao, Z.D., Niu, Y.L., Mo, X.X., Chung, S. L., Hou, Z.Q., Wang, L.Q., and Wu, F.Y., 2011, The Lhasa terrane: record of a microcontinent and its histories of drift and growth: Earth and Planetary Science Letters, v. 301, no. 1–2, p. 241–255, https://doi.org/10.1016/j.epsl.2010.11.005.

Zhu, D.C., Wang, Q., Cawood, P.A., Zhao, Z.D., and Mo, X.X., 2017, Raising the Gangdese Mountains in southern Tibet: Journal of Geophysics Research: Solid Earth, v. 122, no. 1, p. 214–223, https://doi.org/10.1002/2016JB013508.

Zhu, D.C., Wang, Q., Chung, S.L., Cawood, P.A., and Zhao, Z.D., 2019, Gangdese magmatism in southern Tibet and India–Asia convergence since 120 Ma: Geological Society London Special Publications, v. 483, p. 583–604. https://doi.org/10.1144/SP483.14.

Zhu, D.C., Wang, Q, Weinberg, R.F., Cawood, P.A., Chung, S.L., Zheng, Y.F., Zhao, Z.D., Hou, Z.Q., and Mo, X.X., 2022, Interplay between oceanic subduction and continental collision in building continental crust: Nature Communications, v. 13, 7141, https://doi.org/10.1038/s41467-022-34826-0.

Figure captions:

Figure 1. Paleogeographic reconstruction of the Gangdese magmatic arc during the Late Mesozoic and Cenozoic. (A) Gangdese crustal growth during the Late Cretaceous subduction of Neo-Tethys Ocean beneath the Asian continent. (B) Gangdese crustal growth and reworking during the Early Eocene collision between India and Asia. (C) Formation of the Tibetan Plateau and reworking of Gangdese arc crust during the Late Oligocene ongoing continental convergence. The paleogeographic map is after Scotese (2014).

Figure 2. Geological map of the Tibetan Plateau (A) and the eastern Gangdese magmatic arc (B), showing the distribution of metamorphic belts, and locations of some of the studied granite samples.

Figure 3. Plots of zircon U–Pb ages versus whole-rock major (A, B), A/CNK (C), Mg# (D) and trace elements (E-J) of the granites, with a division of tectonic stages.

Data sources are listed in Table S2.

Figure 4. Plots of zircon U–Pb ages versus whole-rock REE (A), HREE (B), La/Yb (C), Eu/Eu*(D), ($^{87}Sr/^{86}Sr)_i$ (E) and $\varepsilon_{Nd}(t)$ values (F) of the granites and gabbros, with a division of tectonic stages. Data sources are listed in Tables S1 and S3.

Figure 5. Plot of ($^{87}Sr/^{86}Sr)_i$ versus $\varepsilon_{Nd}(t)$ values of the granites and gabbros, with descriptions of components and natures of the lower arc crust in different tectonic stages. Data sources are listed in Table S3.

Figure 6. Plots of zircon U–Pb ages versus zircon $\varepsilon_{Hf}(t)$ values (A), whole-rock $(La/Yb)_N$ (crustal thickness; B) and zircon Eu/Eu* (crustal thickness, C) of the granites, with descriptions of components and natures of the arc crust (A), and thickening and thinning processes of the arc crust (B, C) in different tectonic stages. Data sources are listed in Tables S1, S2 and S4, except for the Miocene granites from Chu et al. (2011).

Figure 7. Geodynamic model of crustal evolution of the Gangdese magmatic arc. (A) Shallow subduction of the Neo-Tethyan lithosphere during the Late Cretaceous resulted in the thickening of arc crust, and partial melting of thickened juvenile lower crust with minor and homogenously distributed ancient crustal rocks to generate high Sr/Y granites and dense mafic residues. (B) Rollback and breakoff of the subducted Neo-Tethyan lithosphere, underthrusting of ancient Indian crust beneath the Gangdese arc crust, and thinning of the thickened arc crust during the Late Cretaceous to Paleocene. Upwelling of asthenosphere induced the intense partial melting of mantle and heterogeneously distributed juvenile and ancient lower crustal rocks to generate the mafic magmatic rocks, and granites in the Gangdese arc and Himalayan orogen. (C) Underthrusting of Indian lithosphere beneath the Asian lithosphere induced significant crustal thickening, and partial melting of thickened juvenile lower crust

with minor and homogenously distributed ancient crustal rocks to generate high Sr/Y granites and dense mafic residues in the Gangdese arc, and leucogranites in the Himalayan orogen during the Late Eocene to Oligocene. (D) Delamination of thickened lithospheric mantle and associated upwelling of asthenosphere induced the thinning of thickened crust, and partial melting of the lithospheric mantle and juvenile lower crust with minor and heterogeneously distributed ancient rocks to generate ultrapotassic magmatic rocks, high Sr/Y granites and dense mafic residues in the Gangdese arc, and leucogranites in the Himalayan orogen during the Miocene.

Supplemental Material:

Supplemental Text S1: Analytical Methods.

Figure S1. Zircon cathodoluminescence images of the granites from the eastern Gangdese arc, with U-Pb dating locations and ages (in Ma).

Table S1. Zircon U-Pb dating and trace element data of the Late Mesozoic and Cenozoic granites of the eastern Gangdese arc.

Table S2. Whole-rock chemical compositions of the Late Mesozoic and Cenozoic granites of the eastern Gangdese arc.

Table S3. Whole-rock Sr and Nd isotopic compositions of the Late Mesozoic and Cenozoic magmatic rocks of the eastern Gangdese arc.

Table S4. Zircon Hf isotopic data of the Late Mesozoic and Cenozoic granites of the eastern Gangdese arc.