The Mesozoic magmatic, metamorphic and tectonic evolution of the eastern Gangdese magmatic arc, southern Tibet

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ABSTRACT

Magmatic arcs are natural laboratories for studying the growth of continental crusts. The Gangdese arc, southern Tibet, is an archetypal continental magmatic arc that formed due to Mesozoic subduction of the Neo-Tethyan oceanic lithosphere; however, its formation and evolution remain controversial. In this contribution, we combine newly reported and previously published geochemical and geochronological data for Mesozoic magmatic rocks in the eastern Gangdese arc to reveal its magmatic and metamorphic histories, and review its growth, thickening, fractionation, and mineralization processes. Our results show that (1) the Gangdese arc consists of multiple Mesozoic arc-type magmatic rocks, and records voluminous juvenile crustal growth; (2) The Mesozoic magmatic rocks experienced Late Cretaceous granulite-facies metamorphism and partial melting, thus producing hydrous and metallogenic element-rich migmatites that form a major component of the lower arc crust and are a potential source for the Miocene ore-hosting porphyries; (3) The Gangdese arc witnessed crustal thickening and reworking during the Middle to Late Jurassic and Late Cretaceous; (4) Crystallization-fractionation of mantle-derived magmas and partial melting of thickened juvenile lower crust induced intracrustal chemical differentiation during subduction. We suggest that the Gangdese arc underwent the following main tectonic, magmatic and metamorphic evolution processes: normal subduction and associated mantle-derived magmatism during the Late Triassic to Jurassic; shallow subduction during the Early Cretaceous and an associated magmatic lull; mid-oceanic ridge subduction, high-temperature metamorphism and an associated magmatic flare-up during the early Late Cretaceous , and flat subduction, high-temperature and high-pressure metamorphism, partial melting and associated crust-derived magmatism during the late Late Cretaceous. Key issues for further research include the temporal and spatial distributions of Mesozoic magmatic rocks, the evolution of the components and compositions of arc crust over time, and the metallogenic processes that occur in such environments during subduction.

INTRODUCTION

Magmatic arcs are products of subduction-related magmatism at convergent plate margins, and are ideal natural laboratories for studying plate tectonic processes, crust–mantle interaction, and continental crust growth (Davidson and Arculus, 2006; Miller and Snoke, 2009; Jagoutz and Schmidt, 2012). The formation and evolution of magmatic arcs has been a topic of interest in earth science for many years (e.g., Zandt et al., 2004; Kelemen et al., 2007; Lee et al., 2007, 2012; Jagoutz and Behn, 2013; Ducea et al., 2015; Santosh et al., 2020). The Gangdese magmatic arc, southern Tibet, formed due to Mesozoic subduction of Neo-Tethyan oceanic lithosphere beneath the southern margin of the Asian continent, and preserves widespread arc-related plutonic and volcanic rocks, and therefore been used as a type-example of continental magmatic arcs (Maluski et al., 1982; Xu et al., 1985; Coulon et al., 1986; Debon et al., 1986; Harris et al., 1998a, b; Yin and Harrison, 2000; Ding et al., 2003; Pan et al., 2004, 2012; Chung et al., 2005, 2009; Mo et al., 2005; Zhu et al., 2009a, b; Ji et al., 2009a, b; Zhang et al., 2010a, 2020; Niu et al., 2013; Hou et al., 2015a, b). However, the Gangdese arc experienced intense reworking during the Cenozoic collision between the Indian and Asian continents and subsequent underthrusting of the Indian continent beneath the Asian continent, producing new magmatic and metamorphic lithologies and deformational structures (Molnar et al., 1993; Murphy et al., 1997; Harrison et al., 2000; Yin and Harrison, 2000; Ding and Lai, 2003; Chung et al., 2005; Mo et al., 2005; Mo and Pan, 2006; Dong et al., 2008; Searle et al., 2011; Ji et al., 2012, 2016; Zheng et al., 2012, 2014, 2015; Zhang et al., 2013, 2014a, b, 2015, 2019a; Ding et al., 2014; Palin et al., 2014; Hu et al., 2016; Zhu et al., 2017, 2019; Searle, 2018). As a result, despite focused research, the characteristics of Mesozoic magmatism and metamorphism, and the tectonic evolution of the arc prior to the India–Asia collision remain controversial, and several significantly different models of the Gangdese arc's formation and evolution have been proposed (e.g., Yin and Harrison, 2000; Guo et al., 2011; Pan et al., 2012; Zhu et al., 2019; Kapp and

DeCelles, 2019).

Between longitudes 88° and 95°, the eastern Gangdese arc exposes arc-related magmatic rocks of diverse types and ages, and related polymetallic deposits (Fig. 1). Moreover, rocks from the different crustal levels of the arc have been exposed to the surface due to differential exhumation and erosion during the Late Cenozoic (Burg et al., 1997; Dong et al., 2010a; Zhang et al., 2010b, 2014b, 2020; Searle et al., 2011; Guo et al., 2012, 2020; Xu et al., 2013; Cao et al., 2020). Therefore, the eastern Gangdese arc is a highly favorable area for studying the formation and evolution of the whole arc. In order to reconstruct the magmatic, metamorphic and metallogenic processes of the Gangdese arc, in this contribution, we conduct a detailed study and review of Mesozoic magmatic rocks based on an extensive set of newly reported and previously published geochemical and geochronological data. The key issues addressed by this study are (1) the juvenile crustal growth, thickening, and intracrustal differentiation process, (2) the lithological constitution and nature of lower arc crust, (3) the source and mechanism of porphyry Cu–Au mineralization, and (4) the tectonic evolution of the eastern Gangdese arc during Mesozoic subduction. Our results provide new insight into how the Gangdese arc was built and reworked prior to the arc-continental collision, and the early growth processes of mature magmatic arcs with a complete history from oceanic lithosphere subduction to continental collision.

GEOLOGICAL SETTING AND DATA

The Tibetan Plateau consists of five roughly east-west-trending domains, comprising the Kunlun, Songpan–Ganze, Northern Qiangtang, Southern Qiangtang and Lhasa, terranes, and the Himalayan belt (Fig. 1A). These units are separated by the Kunlun, Jinsha, Longmu Co–Shuanghu, Bangong–Nujiang, and Yarlung–Tsangpo suture zones, representing relicts of the Paleo-Asian, Paleo-, Meso-, and Neo-Tethyan oceans, respectively (e.g., Chang and Zheng, 1973; Dewey et al., 1988; Yin and Harrison, 2000; Ding et al., 2003). The Lhasa terrane, bounded to the south by the Yarlung–Tsangpo suture zone (YTSZ) and to the north by the Bangong–Nujiang suture zone (BNSZ) (Fig. 1), is a micro-continental block that rifted away from the northern margin of the Gondwana supercontinent, and contains Precambrian basement, Paleozoic to Mesozoic sedimentary rocks, and Paleozoic to Cenozoic magmatic rocks (Allègre et al., 1984; Xu et al., 1985; Yin and Harrison, 2000; Ding et al., 2003; Pan et al., 2004, 2006; Chung et al., 2005; Mo et al., 2005; Zhu et al., 2011; Zhang et al., 2012a, b, 2014a, 2020). The Gangdese magmatic arc, with a width of ~100–200 km, is located in the central and southern parts of the Lhasa terrane, and forms the eastern segment of the Trans-Himalayan magmatic arc, which extends E–W for up to 2500 km (Fig. 1A).

The Gangdese arc experienced Mesozoic Andean-type orogeny driven by northward subduction of the Neo-Tethyan oceanic lithosphere beneath the southern margin of the Asian plate (Lhasa terrane), and subsequent Cenozoic Himalayan-type orogeny related to the Indian plate colliding with the Asian plate (Fig. 2; Allègre et al., 1984; Xu et al., 1985; Coulon et al., 1986; Debon et al., 1986; Searle et al., 1987; Pearce and Mei, 1988; Yin and Harrison, 2000; Ding et al., 2003, 2014; Pan et al., 2004; Mo et al., 2005; Mo and Pan, 2006). Thus the region witnessed long-lasting magmatism (~220–10 Ma), with four major pulses of intrusion during the Middle Jurassic, Late Cretaceous, Early Eocene and Early Miocene (Fig. 2; Chu et al., 2006, 2011; Wu et al., 2007, 2010; Ji et al., 2009a, 2014; Guo et al., 2011; Zhu et al., 2011, 2017, 2019; Liu et al., 2014; Zhang et al., 2019a, 2020). The arc magmatic rocks consist mainly of Late Cretaceous and Tertiary intrusive members (the Gangdese batholith), and the Paleogene Linzizong volcanic succession, and minor Triassic and Jurassic intrusives and volcanic (-sedimentary) rocks (Fig. 1B; Chung et al., 2005; Mo et al., 2005, 2007, 2008; Wen et al., 2008a, b; Guo et al., 2011; Zhu et al., 2011, 2019; Lee et al., 2012; Pan et al., 2012; Wang et al., 2016a, b; Li et al., 2018). The Late Cretaceous batholiths form a major component of the eastern Gangdese arc, and include gabbro, diorite, granodiorite and granite, minor hornblendite and other ultramafic rocks (Wen et al., 2008a, b; Zhang et al., 2010a, 2014b; Ma et al., 2013a, b, c; Guo et al., 2020; Tang et al., 2020). The Mesozoic volcanic rocks of the Gangdese arc are the Lower Jurassic Yeba Formation and Upper Jurassic–Lower Cretaceous Sangri Group (Fig. 1B). The Yeba Formation consists mainly of basalt, dacite and rhyolite, with minor andesite (e.g., Zhu et al., 2008; Chen et al., 2014; Liu et al., 2018). The Sangri Group is widespread in the eastern Gangdese arc, and consists of basalt, basaltic andesite, andesite and minor dacite (Dong et al., 2006; Zhu et al., 2009a; Kang et al., 2014; Zhang et al., 2019b).

The Early Cretaceous intrusions and Lower Cretaceous volcano-sedimentary rocks are widespread in the central and northern parts of the Lhasa terrane (Fig. 1B). The Early Cretaceous intrusions consist mainly of granitoids (Li et al., 2018). The Lower Cretaceous volcano-sedimentary rocks include the Zenong Group, and Qushenla and Duoni Formations. The Zenong Group contains basaltic andesite, andesite and dacite, the Qushenla Formation consists mainly of basalt, basaltic andesite and andesite, and the Duoni Formation consists mainly of rhyolite, with minor basalt and basaltic andesite (Kang et al., 2008, 2009, 2010).

The eastern Gangdese arc and the Eastern Himalayan Syntaxis includes three tectonic units; from northwest to southeast, these are the Lhasa terrane (eastern Gangdese arc), the YTSZ, and Himalayas (Figs. 1 and 3). The Himalayas include the Tethyan Himalayan and Greater Himalayan Sequences (Fig. 3). The former consists of Paleozoic to Mesozoic sedimentary rocks that formed on the passive continental margin of the Indian plate, and underwent intensive deformation and low-grade metamorphism during the India–Asia collision. The latter consists of Precambrian basement rocks of the Indian continent, and Early Paleozoic and Mesozoic magmatic rocks, and underwent high-grade metamorphism and partial melting during the Cenozoic collisional orogeny (Yin and Harrison, 2000; Zhang et al., 2021 and references therein). The Yarlung–Tsangpo suture zone is a tectonic mélange zone that includes the remnants of Neo-Tethyan oceanic crust and metamorphic rocks from both the Indian and Asian continental margins (Geng et al., 2006).

The eastern Gangdese arc, near the Eastern Himalayan Syntaxis, consists mainly of Late Cretaceous gabbro–granodiorite (Lilong batholith) and granite (Wolong batholith), Paleocene to Eocene granite and gabbro, Late Paleozoic sedimentary rocks, and Jurassic gabbro and granite, and voluminously distributed but unidentified intrusions (Fig. 3; Zhang et al., 2020). These rocks underwent variable degrees of metamorphism during the Mesozoic to Cenozoic, and were intruded by Late Oligocene granites, which show no evidence of deformation and metamorphism (Fig. 3). These metamorphic rocks constitute the crustal section of the eastern Gangdese arc, with the low-grade (greenschist- to epidote amphibolite-facies), middle-grade (amphibolite-facies) and high-grade (granulite-facies) metamorphic rocks (belts) representing the upper, middle, and lower crustal components, respectively (Fig. 3; Zhang et al., 2020). Geological mapping shows that the exposed Oligocene lower arc crust consists of metamorphosed Late Cretaceous, Jurassic, Paleocene to Eocene gabbros, diorites, and granites, and Late Paleozoic sedimentary rocks (Fig. 3; Zhang et al., 2020).

The Jurassic magmatic rocks newly reported here occur as lenses of varying size or as thin sheets within the Late Cretaceous and Paleocene magmatic rocks (Figs. 3 and 4A). These magmatic rocks have been transformed into migmatitic garnet-bearing amphibolites and gneisses during Late Cretaceous, Paleocene and Eocene high-grade metamorphism and partial melting (Dong et al., 2010a; Zhang et al., 2010b, 2013, 2014b, 2019a; Guo et al., 2011, 2013a; Niu et al., 2019). The garnet amphibolites consist mainly of amphibole, garnet, epidote, with minor plagioclase, quartz, biotite, rutile, ilmenite and zircon, and commonly contain garnet-bearing felsic leucosomes parallel to the foliation of the host rocks (Figs. 4A–C). The garnet-bearing gneisses commonly show strong foliation, and consist mainly of plagioclase, quartz, and biotite, with minor amphibole, garnet, epidote, ilmenite, apatite and zircon (Fig. 4D). The felsic leucosomes contain plagioclase, quartz, garnet, amphibole, epidote, biotite and zircon (Fig. 4E). Some garnet amphibolites have transformed into garnet-free amphibolites, consisting of amphibole and epidote, plagioclase, quartz, ilmenite and quartz (Fig. 4F) due to later retrograde metamorphism at lower amphibolite-facies conditions. Sixteen metamorphosed Jurassic magmatic rocks, including the garnet-bearing and -free gneisses and amphibolites, and one garnet-bearing leucosome (T16-77-6) are described here, and their mineral assemblages, protolith and metamorphic ages and sampling locations are summarized in Data Repository Table S1. Zircon U–Pb age data and trace element, Hf isotopic data, and whole-rock chemical compositions are listed in Tables S2, S3 and S4, respectively. The whole-rock major and trace element compositions, and zircon U–Pb ages of Mesozoic magmatic rocks from the eastern Gangdese arc between longitudes 88° and 95° compiled from literatures are listed in Table S5. The newly reported SiO_2 and Cu concentrations of the Late Cretaceous magmatic rocks are listed in Table S6. The Late Cretaceous rocks, now occurring as migmatitic garnet amphibolites and gneisses due to late Late Cretaceous high-grade metamorphism and partial melting, were widely sampled from the exposed lower arc crust section in the Zhaxi, Milin and Bujiu areas (Fig. 3).

ANALYTICAL METHODS

Major element analyses of whole rock were conducted via XRF (Primus Ⅱ, Rigaku, Japan) at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. The detailed sample digestion procedure was as follows: (1) Sample powder (200 mesh) were placed in an oven at 105 ℃ for drying of 12 hours; (2) ~1.0g dried sample was accurately weighted and placed in the ceramic crucible and then heated in a muffle furnace at 1000 ℃ for 2 hours. After cooling to 400 ℃, this sample was placed in the drying vessel and weighted again in order to calculate the loss on ignition (LOI). (3) 0.6 g sample powder was mixed with 6.0 g cosolvent (Li_2B_4O7:$LiBO_2$:LiF = 9:2:1) and 0.3 g oxidant (NH_4NO_3) in a Pt crucible, which was placed in the furnace at 1150 ℃ for 14 min. Then, this melting sample was quenched with air for 1 min to produce flat discs on the fire brick for the XRF analyses.

Trace element analysis of whole rock samples was conducted on an Agilent 7700e ICP-MS at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. The detailed sample digestion procedure was as follows: (1) Sample powder (200 mesh) were placed in an oven at 105 ℃ for drying of 12 hours; (2) 50 mg sample powder was accurately weighed and placed in a Teflon bomb; (3) 1 ml HNO_3 and 1 ml HF were slowly added into the Teflon bomb; (4) Teflon bomb was putted in a stainless steel pressure jacket and heated to 190 ℃ in an oven for >24 hours; (5) After cooling, the Teflon bomb was opened and placed on a hotplate at 140 ℃ and evaporated to incipient dryness, and then 1 ml HNO_3 was added and evaporated to dryness again; (6) 1 ml of HNO_3, 1 ml of MQ water and 1 ml internal standard solution of 1ppm In were added, and the Teflon bomb was resealed and placed in the oven at 190 ℃ for >12 hours; (7) The final solution was transferred to a polyethylene bottle and diluted to 100 g by the addition of 2% HNO_3.

In situ U–Pb dating and trace element analysis of zircon were simultaneously conducted by LA–ICP–MS at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China. Detailed operating conditions for the laser ablation system and the ICP–MS instrument and data reduction are the same as description by Zong et al. (2017). The spot size and frequency of the laser were set to 32 μm and 5 Hz, respectively, in this study. Each analysis incorporated a background acquisition of approximately 20–30 s followed by 50 s of data acquisition from the sample. Zircon 91500 and glass NIST610 were used as external standards for U–Pb dating and trace element calibration, respectively. GJ-1 and Plešovice zircon standards were used as secondary reference materials. An Excel-based software ICPMSDataCal was used to perform off-line selection and integration of background and analyzed signals, time-drift correction and quantitative calibration for trace element analysis and U–Pb dating (Liu et al., 2010). Concordia diagrams and weighted mean calculations were made using Isoplot/Ex_ver4.15 (Ludwig, 2003).

Experiments of in situ Hf isotope ratio analysis of zircon were conducted in the same or adjacent locations as the in situ U–Pb dating spots using a Neptune Plus MC–ICP–MS (Thermo Fisher Scientific, Germany) in combination with a Geolas HD excimer ArF laser ablation system (Coherent, Göttingen, Germany) that was hosted at the Wuhan Sample Solution Analytical Technology Co., Ltd., Hubei, China. All data were acquired on zircon in single spot ablation mode at a spot size of 44 μm. The energy density of laser ablation that was used in this study was ~7.0 J cm^{-2}. Each measurement consisted of 20 s of acquisition of the background signal followed by 50 s of ablation signal acquisition. Detailed operating conditions for the laser ablation system and the MC–ICP–MS instrument and analytical method are the same as description by Hu et al. (2012).

ZIRCON U–Pb AGES AND HF ISOTOPES OF THE METAMORPHOSED JURASSIC MAGMATIC ROCKS

Petrographic observation shows that zircon grains in the metamorphosed Jurassic magmatic rocks (migmatitic garnet amphibolites and gneisses, and associated leucosome) occur in the matrix and as inclusions within garnet, amphibole, plagioclase and quartz. The zircon grains mostly have stubby prismatic shapes and core–rim textures in cathodoluminescence (CL) images (Fig. 5). Zircon core domains display oscillatory and banded zoning, whilst rim domains show slight patchy zoning or no zoning (Fig. 5). The zircon rims of some samples are too thin to analyze via laser ablation for geochronology and trace element analyses. For all dated grains, zircon cores yielded near-concordant U–Pb ages, with weighted mean ages ranging from 155 Ma to 175 Ma (Table S2; Fig. 6). Zircon rim domains from nine samples yielded similar and concordant U–Pb ages, with weighted mean ages of 82 Ma to 91 Ma (Table S2; Fig. 6). The zircon core domains have higher rare earth element (REE) contents, Th/U ratios, and more significant negative Eu anomalies than those of the rim domains (Table S2; Figs. 7A, B, E and F). The zircon rims from the garnet-rich gneiss (Fig. 7A) and garnet-rich leucosome (Fig. 7B) samples have relatively low REE contents, and weakly fractionated and even flat heavy rare earth element (HREE) patterns.

The Lu–Hf isotopic analyses of eleven samples of gneiss, amphibolite and leucosome show that the zircon core and rim domains have similar and low $^{176}Lu/^{177}Hf$ (<0.0031), and with $^{176}Hf/^{177}Hf$ isotopic ratios ranging from 0.28297 to 0.28315 (Table

S3), and therefore have relatively high $\varepsilon_{Hf}(t)$ values of +10.7 to +16.3, and young two-stage Hf model ages from 171 Ma to 551 Ma (Table S3; Fig. 8).

GEOCHEMISTRY OF THE JURASSIC MAGMATIC ROCKS

The Jurassic magmatic rocks reported in this study have variable major and trace element compositions, with SiO_2 of 43.94–75.60 wt. % (Fig. 9A), Al_2O_3 of 11.29–18.98 wt. %, total FeO (FeO^T) of 1.61–12.45 wt. %, MgO of 0.53–5.43 wt. %, CaO of 2.97–11.16 wt. %, Na_2O of 0.56–6.24 wt. %, K_2O of 0.14–3.11 wt. %, Sr of 46–896 ppm, and Y of 4.2–125 ppm (Table S4), and varying Sr/Y ratios of 0.4–156 (Fig. 9B). These rocks are calc-alkalic or calcic, except for sample T16-91-34 being alkalic, and plot in the compositional fields of gabbro, diorite, granodiorite, and granite in the igneous rock classification diagram of Middlemost (1994). These rocks are mostly metaluminous with A/CNK values of 0.72–1.02, and have varying Mg# values of 0.32–0.52, except for the garnet-rich leucosome sample (T16-77-6), which is peraluminous and has a high A/CNK value of 1.40 (Table S4; Fig. 10).

The Jurassic rocks mostly show weakly fractionated REE patterns with light rare earth element (LREE) enrichment and HREE depletion, and a negative Eu anomaly (Fig. 11A). Some samples show flat REE patterns or positive Eu anomalies. The garnet-rich leucosome (T16-77-6) shows a HREE enrichment (Fig. 11A). On a primitive mantle-normalized trace element spider diagram, the Jurassic rocks mostly show enrichment of large ionic lithophilic elements (LILE), and negative anomaly for Nb, Ta and Ti (Fig. 11B).

GEOCHEMISTRY OF THE MESOZOIC MAGMATIC ROCKS

The compiled whole-rock geochemical data indicate that the Late Triassic and Jurassic magmatic rocks of the eastern Gangdese arc have highly variable chemical compositions, ranging from ultramafic to granitic, with SiO_2 contents of 40.90–79.11 wt. % (Table S5; Fig. 9A). These rocks also have variable A/CKN values of 0.53–

1.49, and Mg# values of 0.21–0.65 (Table S5; Fig. 10). The Jurassic rocks display fractionated REE patterns, characterized by LREE enrichment and HREE depletion (Fig. 11C), and LILE enrichment, and Nb, Ta and Ti depletion (Fig. 11D). The magmatic zircons from these Late Triassic and Jurassic magmatic rocks have similar, positive and high $\varepsilon_{Hf}(t)$ values (mostly > +10), and young two-stage Hf model ages (< 0.6 Ga; Fig. 8). Notably, the Middle Jurassic (~150–165 Ma) granitic rocks mostly have relatively high Sr/Y ratios (>50; Table S5; Fig. 9B). Except for components compatible with feldspar (Na_2O and K_2O), other major oxides that favor partitioning into pyroxene, amphibole and biotite (Al_2O_3, FeO^T, MgO, CaO, TiO_2 and MnO) exhibit a strong negative correlation with increasing silica of the Jurassic rocks (Fig. 12).

The early Late Cretaceous (90–100 Ma) magmatic rocks are mostly gabbroic and dioritic in composition, with minor granitic members (Table S5; Fig. 9A), and have low A/CNK values (<1.0) and high Mg# values (>0.40; Table S5; Fig. 10). By contrast, the late Late Cretaceous (<90 Ma) magmatic rocks have evolved SiO_2 contents (Table S5; Fig. 9A) and are dominated by granitic rocks, with high A/CNK values (mostly >0.8) and low Mg# values (mostly <0.50; Table S5; Fig. 10). These Late Cretaceous rocks display fractionated REE patterns, characterized by LREE enrichment and HREE depletion (Fig. 11E), and LILE enrichment, and Nb, Ta and Ti depletion (Fig. 11F). The magmatic zircons from these Late Cretaceous rocks have positive but varying $\varepsilon_{Hf}(t)$ values (+5 to +20) and relatively old two-stage Hf model ages (Fig. 8). It is noted that the late Late Cretaceous (~70–85 Ma) granitoids have high Sr/Y ratios (mostly >50; Table S5; Fig. 9B), high A/CNK values (>1.0; Fig. 10A) and low Mg# values (mostly <0.35; Fig. 10B), more fractionated REE patterns (Fig. 11G), and more significant LILE enrichment and negative Ti anomaly (Fig. 11H).

The granulite-facies metamorphosed Late Cretaceous and Jurassic magmatic rocks are major components of the Oligocene lower crust of the eastern Gangdese arc (Fig. 3). The whole-rock SiO_2 and Cu contents reported here show that the Late Cretaceous mafic and intermediate rocks (119 samples) have variable Cu contents, but mostly with relatively high Cu (100–1100 ppm; Table S6; Fig. 13), while the seven Jurassic rock samples have relatively low Cu contents (13.6–114 ppm; Table S4; Fig. 13).

DISCUSSION

Juvenile Crustal Growth of the Gangdese Arc

Magmatic arcs are generally characterized by the widespread occurrence of mantle- and subducted oceanic crust-derived magmatic rocks, and therefore represent sites of significant juvenile crust growth (Davidson and Arculus, 2006; Niu et al., 2013; Ducea et al., 2015; Jagoutz and Kelemen, 2015). Mesozoic magmatic rocks – both plutonic and volcanic rocks – widely occur throughout the Lhasa terrane, comprising nearly half of the exposed lithologies (Fig. 1B). These magmatic units are mostly metaluminous and calc-alkalic mafic to felsic rocks (Figs. 9A and 10A; Table S5), and characterized by significant enrichment of LILEs, negative anomaly of Nb, Ta and Ti, and fractionated REE patterns (Fig. 11). Therefore, the Mesozoic magmatic rocks show typical arc-like geochemical signatures, and mostly have depleted mantle-like Hf isotopic compositions (Fig. 8), which are comparable with the mafic rocks of Neo-Tethyan oceanic crust (Xu and Castillo, 2004; Zhang et al., 2005). In addition, some magmatic rocks also display adakite-like compositional features, characterized by high Sr/Y ratios and more fractionated REE patterns with strong HREE depletion (Figs. 9B and 11). In this case, it is widely accepted that the Mesozoic magmatic rocks were derived from the partial melting of mantle-wedge that was metasomatized by subducted slab-related fluids and/or melts, and the remelting of Mesozoic mantle-derived rocks in the thickened lower arc crust (e.g., Chu et al., 2006, 2011; Wen et al., 2008a, b; Ji et al., 2009a, 2014; Zhang et al., 2010a, 2014a, 2019a, 2020; Guo et al., 2011; Zhu et al., 2011, 2017, 2019; Zheng et al., 2012, 2014; Ma et al., 2013a, b, c; Wang et al., 2016a, b; Tang et al., 2020).

The widespread occurrence of Mesozoic mantle-derived magmatic rocks indicates that the Gangdese arc experienced substantial crustal growth driven by addition of large volumes of juvenile crust, as also proposed by previous studies (Chu et al., 2006, 2011; Mo et al., 2007, 2008; Ji et al., 2009a; Wu et al., 2010; Zhu et al., 2011; Hou et al., 2015a; Zhang et al., 2019a). In addition, some workers suggest that the entire Gangdese arc (southern Lhasa terrane) consists of juvenile crust (e.g., Zhu et al., 2011; Hou et al., 2013, 2015a); however, Paleozoic magmatic rocks and sedimentary rocks, and minor Precambrian rocks do occur (e.g., Dong et al., 2009, 2010a, b; Ma et al., 2019; Zhang et al., 2020), refuting this interpretation. Moreover, previous studies have shown that the thickened lower crust of Gangdese arc contains sedimentary rocks that have been deeply buried (Dong et al., 2010a, b; Qin et al., 2019; Guo et al., 2020; Zhang et al., 2020), and the partial melting of the meta-sedimentary rocks led to emplacement of Early Cenozoic S-type granites (Zhang et al., 2013; Ji et al., 2017; Ma et al., 2017; Ding and Zhang, 2018).

Early Cenozoic intrusions and the Linzizong volcanic succession are also widespread in the Gangdese arc (Fig. 1B). These rocks show geochemical characteristics of arc-related magmatic rocks (e.g., Ding et al., 2003; Chung et al., 2005; Mo et al., 2007, 2008; Lee et al., 2012; Zhu et al., 2017, 2019). In this case, many studies argued that juvenile crustal growth of the Gangdese arc continued into the Early Cenozoic, driven by partial melting of mantle-derived magmatism related to the breakoff of subducted Neo-Tethyan oceanic lithosphere, and remaining Neo-Tethyan oceanic crust (e.g., Mo et al., 2007, 2008; Zhu et al., 2011; Niu et al., 2013; Hou et al., 2015a). However, some Early Cenozoic granitoids have high Sr/Y ratios and more fractionated REE patterns, and therefore were considered as products of partial melting of the thickened juvenile lower crust (Guo et al., 2011; Guan et al., 2012; Ji et al., 2012; Zhang et al., 2013; Yakovlev and Clark, 2014; Zheng et al., 2014; Zhu et al., 2017; Ding and Zhang, 2018). Overall, we consider that the most significant additions of juvenile crust to the Gangdese arc occurred during the Middle Jurassic, Late Cretaceous and Early Cenozoic, corresponding with the three significant magmatic pulses shown in Fig. 2.

Crustal Thickening and Differentiation of the Gangdese Arc

The present crust of the Gangdese arc is twice as thick as average continental crust (up to 60–80 km; Hirn et al., 1984; Molnar, 1988; Zhao et al., 1993; Yakovlev and Clark, 2014). Because the Gangdese arc experienced Mesozoic accretionary and Cenozoic collisional orogenesis, the timing and mechanisms of crustal thickening remain controversial. Most workers proposed that Gangdese crustal thickening occurred after ~60 Ma, representing the onset of continental collision and subsequent convergence (Molnar et al., 1993; Yin and Harrison, 2000; Chung et al., 2003, 2005; Hou et al., 2004, 2015a; Guo et al., 2007; Mo et al., 2008; Zhu et al., 2017). By contrast, some studies based on investigations of magmatism and structural deformation in the region have argued that the Gangdese arc had a thick crust during the Late Cretaceous prior to India–Asia collision (Murphy et al., 1997; Ding and Lai, 2003; Ding et al., 2003, 2014; Kapp et al., 2003, 2005a, b, 2007a, b; Ji et al., 2012; Cao et al., 2020; Tang et al., 2021).

Our zircon geochronology indicates that the inherited cores of zircon in the garnet-rich migmatites and hosting leucosome from the Gangdese lower arc crust display oscillatory and banded zoning (Fig. 5), have relatively high REE contents and Th/U ratios, fractionated REE patterns with significant negative Eu anomalies (Table S2; Fig. 7). These features indicate that the inherited cores of zircon have a magmatic origin, and therefore the obtained ages of 155–175 Ma represent the protolith ages of the metamorphosed magmatic rocks. By contrast, the zircon overgrowth rims show patchy zoning or no zoning (Fig. 5), have relatively low Th/U ratios, low REE contents, and weakly fractionated and even flat HREE patterns (Table S2; Fig. 7), indicating that the zircon rim domains are typical of metamorphic origin from high-grade metamorphic mafic and felsic rocks containing garnet (Schaltegger et al., 1999; Vavra et al., 1999; Corfu et al., 2003; Harley et al., 2007). The ages of 82–91 Ma obtained from the zircon rims represent the high-grade metamorphic and anatectic ages of the garnet-bearing migmatites. Therefore, our study shows that Jurassic magmatic rocks underwent Late Cretaceous high-grade metamorphism and partial melting.

Recent studies demonstrated that the Late Cretaceous (90–100 Ma) magmatic rocks and associated Paleozoic sedimentary rocks from the eastern Gangdese arc underwent Late Cretaceous (~68–90 Ma) upper amphibolite- to granulite-facies metamorphism and partial melting under conditions of up to 800–900 °C and 1.3–1.7 GPa (Zhang et al., 2010a, b, 2014a, b; Guo et al., 2013a; Niu et al., 2019; Qin et al., 2019). The data from this study and those from previous works thus indicate that the Mesozoic arc-type magmatic rocks and their host sedimentary rocks have been transported into the lower arc crust, and the crust has been thickened to at least 50–55 km during the late stage of subduction of the Neo-Tethyan oceanic lithosphere. This conclusion is generally consistent with previous propositions that the Gangdese arc underwent crustal thickening during the Late Cretaceous (Ji et al., 2014), and had achieved a crustal thickness of 50–60 km by 70–90 Ma (Tang et al., 2021), which were obtained by the geochemical evidence of magmatic rocks.

Although underplating and accretion of mantle-derived magmatic rocks lead to growth of the continental crust, the bulk continental crust has an andesitic composition and so is not in equilibrium with the upper mantle (Jagoutz & Kelemen, 2015). Therefore, net continental crustal growth probably involves the early extraction of basaltic magma from the mantle and later intracrustal differentiation of mantle-derived mafic rocks (Taylor and McLennan, 1985; Rudnick, 1995; Rudnick and Gao, 2003; Hawkesworth and Kemp, 2006). The intracrustal differentiation mechanisms mainly include fractional crystallization (Davidson and Arculus, 2006; Hawkesworth and Kemp, 2006; Keller et al., 2015; Chapman et al., 2016; Jagoutz and Klein, 2018), and remelting of juvenile crust (Brown and Rushmer, 2006; Brown, 2010; Brown and Ryan, 2011).

Various crystallization differentiation processes have been proposed for the Mesozoic Gangdese arc. For example, Zhang et al. (2014b) argued that the Late Cretaceous Lilong batholith, forming the main component of the eastern Gangdese arc crust, shows an original magmatic differentiation trend, where gabbro represents cumulates and diorite is the crystalline products of evolved magmas. Subsequently, Guo et al. (2020) proposed that mafic-intermediate rocks of the Lilong batholith represent a 'damp' (i.e. water-rich) igneous differentiation sequence, and Xu et al. (2019) indicated that the hornblende-dominated fractional crystallization of Cuijiu igneous complex generated the Gangdese arc crust during the Early Mesozoic (~200 Ma). In fact, the Mesozoic magmatic rocks of the eastern Gangdese arc have highly variable SiO_2 contents (Fig. 9A), A/CNK and Mg# values (Fig. 10), indicating that these rocks probably underwent significant fractional crystallization. The data presented here also show that the Jurassic magmatic rocks from the eastern Gangdese arc have variations in major and trace element compositions, REE patterns and Eu anomalies, and the whole-rock SiO_2 contents exhibit strong negative correlations with Al_2O_3, FeO^T, MgO, CaO, TiO_2 and MnO contents (Table S4; Figs. 9A, 11A-D and 12). Such compositional variations are typical for an evolving calc-alkaline magmatic suite that originated from a mantle-derived magma source. These results suggest that fractional crystallization drove intracrustal chemical differentiation of the Gangdese arc crust during Mesozoic subduction.

The widespread occurrence of Cenozoic high Sr/Y granitoids in the eastern Gangdese arc indicate that the arc crust underwent intense intracrustal chemical differentiation via the remelting of thickened juvenile lower crust during the Cenozoic collisional orogeny. This study and previous works demonstrate that the eastern Gangdese arc lower crust underwent Late Cretaceous (~68–90 Ma) granulite-facies metamorphism and associated partial melting. Moreover, the Late Cretaceous anatectic rocks are widespread in the Lilong, Zhaxi, Milin and Bujiu areas, and form major component of the exposed lower crust section of the Gangdese arc (Fig. 3). Therefore, we suggest that the eastern Gangdese arc crust underwent intracrustal chemical differentiation in the Late Cretaceous (<90 Ma) that was induced by remelting of thickened juvenile lower crust, which consisted mainly of the Late Cretaceous (90–100 Ma) and Jurassic mantle-derived magmatic rocks. Voluminous melts generated by this process represent a potential source for the late stage of Late

Cretaceous granitoids (~70–85 Ma), such as the Wolong batholith (Fig. 3). The granitoids have chemical features of arc-type magmatic rocks, but higher Sr/Y ratios (Fig. 9B) and A/CNK values (Fig. 10A), lower Mg# values (Fig. 10B), more fractionated REE patterns (Fig. 11G), more significant enrichment of LILEs and negative anomalies of Nb, Ta and Ti (Fig. 11H) than other Late Cretaceous arc rocks. Therefore, previous studies mostly proposed that the Wolong granitoids were derived from partial melting of thickened juvenile lower crust (e.g., Wen et al., 2008a; Ji et al., 2014; Tang et al., 2020). However, Guo et al. (2020) argued that the Wolong granitoids were formed by factional crystallization of wet magma and intracrustal assimilation. In fact, the early Late Cretaceous (>90 Ma) arc magmatic rocks are dominated by gabbro and diorite, with minor granite, whereas the late Late Cretaceous (<90 Ma) magmatic rocks are mostly granitic (Fig. 9A; Zhang et al., 2019a; Zhu et al., 2019). This may imply that the high Sr/Y granitoids were not products of crystallization differentiation of mafic magma. In addition, some Jurassic (~160 Ma) arc-type granites have high Sr/Y ratios (Fig. 9B), and were considered to be products of remelting of thickened juvenile lower crust (Wang et al., 2012; Zhang et al., 2014c). This indicates that the thickening of juvenile crust and intracrustal chemical differentiation have occurred in the early stage of subduction of oceanic lithosphere. We therefore suggest that the partial melting of thickened lower crust plays an important role in the differentiation and reworking of Gangdese juvenile crust before arc-continent collision. Importantly, this is inconsistent with previous conclusions that differentiation via fractional crystallization is a dominant mechanism for chemically differentiating arc crust (Taylor, 1967; Davidson and Arculus, 2006; Hawkesworth and Kemp, 2006; Keller et al., 2015; Chapman et al., 2016; Jagoutz and Klein, 2018).

The Component and Nature of the Gangdese Lower Arc Crust

The lower crust (arc root) of continental magmatic arcs is characterized by underplating of mantle-derived magmatic rocks, assimilation and remelting of juvenile and ancient crustal materials, and mixing, storage and homogenization of mantle- and crust-derived melts, and therefore is the key site of building and reworking of arc crusts (e.g., Hildreth and Moorbath, 1988; Daczko et al., 2001; Miller and Snoke, 2009). The architecture, lithological constitution, and geochemistry of the lower levels of continental arc crust – and how each have changed through time – are poorly constrained. The Gangdese arc offers a rare opportunity to constrain these variables through various stages of the Wilson Cycle. Based on the presence of adakitic (high Sr/Y) rocks, Chung et al. (2003) and Hou et al. (2004) considered that the Miocene thickened lower crust consists of garnet amphibolites and/or eclogites. Zhang et al. (2014b) and Niu et al. (2019) indicated that the garnet amphibolites, derived from the high-pressure granulite-facies metamorphism and partial melting of gabbros of the Late Cretaceous Lilong batholith root, are a major component of the Gangdese arc lower crust. Based on detailed geological mapping, Zhang et al. (2020) further revealed that the lower crust of the eastern Gangdese arc is composed of voluminous migmatitic garnet amphibolite (meta-gabbro) and migmatitic orthogneiss (meta-diorites and meta-granites), and with minor meta-sedimentary rocks (Fig. 3). Guo et al. (2020) also showed that the Gangdese arc lower crust contains Late Cretaceous garnet-bearing meta-gabbros (garnet amphibolites). Here, we show that the Jurassic magmatic rocks, together with the Lilong batholith gabbros and diorites, were buried and metamorphosed during the Late Cretaceous to form migmatitic garnet amphibolites and gneisses in the lower crust at high-temperature (800–900 °C) and high-pressure (1.3–1.7 GPa) granulite-facies conditions. The occurrence of voluminous amphibole-rich rocks of this age in this region indicates that the Gangdese arc had a hydrous lower crust both during Mesozoic subduction and Cenozoic collision, and that partial melting occurred at water-saturated conditions. This provides robust evidence for the Gangdese arc having a water-rich thickened lower crust before the arc-continent collision, as also suggested by Xu et al. (2019).

Experimental study and phase equilibrium modeling has demonstrated that clinopyroxene-free garnet amphibolite could be stable at *P*–*T* conditions of 800–900

°C and 1.0–1.7 GPa in the presence of melt (López and Castro, 2001; Palin et al., 2016a, 2016b). Melting experiments conducted on high-Al basalt and tholeiite with variable amounts of H_2O show that garnet and amphibole may co-exist with felsic melt in the presence of excess H_2O at 1.0–2.0 GPa and 800–900 °C (Winther and Nowton, 1991). Water-saturated melting experiments performed on gabbro at 1.25–1.5 GPa and 800–950 °C show that the melts produced are tonalitic in composition, and the residues contain amphibole, garnet, zoisite, plagioclase, titanite and ilmenite (Selbekk and Skjerlie, 2002). These results provide support for the thickened lower crust of the Gangdese arc containing voluminous hydrated garnet amphibolite. It is possible that the component and nature of the Gangdese lower arc crust evolved over time. For example, the lower arc crust was relative dry during Late Cretaceous (90–100 Ma) ridge subduction, and then became wet due to hydration during the flat subduction of oceanic slab (see the following section).

Porphyry Cu–Au Mineralization of the Gangdese Arc

Porphyry Cu–Au ore deposits in magmatic arcs usually formed during subduction of oceanic lithosphere (e.g., Skewes and Stern, 1995; Kay et al., 1999; Richards et al., 2001; Perello et al., 2003; Sillitoe, 2010). The mantle-derived calc-alkaline basaltic magmas undergo a MASH process (melting, assimilation, storage, and homogenization) in the lower arc crust, which produces ore-bearing magmas with intermediate to felsic compositions (Richards, 2003; Sillitoe, 2010). The continuous oceanic slab subduction provides the water, metals, and S required for porphyry Cu–Au deposit formation (Audétát and Simon, 2012; Wang et al., 2017). However, the porphyry Cu–Au deposits form only during specific, temporally-constrained magmatic periods in the evolution of a long-lived arc. Jurassic arc-type magmatic rocks are widespread within the eastern Gangdese arc between longitudes 88° and 95°, however the Jurassic arc magma-related large and giant porphyry Cu-Au deposits occur only at the Xietongmen area of the western segment of eastern Gangdese arc (Fig. 1B). The ore-hosting diorite and granodiorite porphyries formed in the Middle

Jurassic (161–185 Ma), and have depleted mantle-like isotopic compositions (Tang et al., 2010, 2015; Hou et al., 2015b; Lang et al., 2017; Xu et al., 2017). By contrast, the ore-barren Jurassic magmatic rocks from the eastern Gangdese arc are isotopically less juvenile. Hou et al. (2015b) argued that incorporation of crustal components during underplating of Jurassic magma induced copper sulfide accumulation at the arc base, inhibiting porphyry Cu–Au deposits forming at this time. In addition, whether this Jurassic arc is an island arc or a continental arc remains controversial (Aitchison et al., 2007; Wang et al., 2012; Zhu et al., 2013; Zhang et al., 2014c; Tang et al., 2015). Wang et al. (2017) argued that the Xietongmen porphyry Cu–Au district is located close to the front of continental arc, where arc magmas show a larger contribution from slab fluids that carried volatile, fluid-mobile elements, and were more oxidized, as such fertile magmas provide ideal conditions for generating porphyry deposits. Xu et al. (2017) proposed that the Xietongmen mineralised diorites were derived from a Jurassic hydrous mantle wedge induced by slab dehydration. These magmas contain higher contents of water and other volatiles and have higher oxidation states, which favored the transfer of metals (such as Cu, Au) to the upper crust, and then formed the porphyry Cu–Au deposits.

An important finding from the Gangdese arc is that many large and giant porphyry Cu–Au deposits formed during the Miocene post-collisional orogeny (Fig. 1B; Hou et al., 2009, 2011, 2015a, b; Tafti et al., 2009; Tang et al., 2010; Chen et al., 2011; Liang et al., 2014; Yang et al., 2015; Xu et al., 2017; Wang et al., 2018). Because the Miocene ore-hosting porphyries have an affinity to adakitic rocks and geochemical features characteristic of the depleted mantle, previous studies considered that the ore-hosting rocks were derived from partial melting of thickened juvenile lower crust (Hou et al., 2009, 2011, 2013, 2015a, b; Yang et al., 2015; Wang et al., 2018; Zheng et al., 2018). Possible source rocks of the ore-hosting porphyries are considered to be the Jurassic arc magmatic rocks that underplated into the lower arc crust before the collision, based on the Miocene and Jurassic rocks having similar Sr–Nd–Hf isotopic compositions (e.g., Hou et al., 2015a, b; Hou and Wang, 2019).

That is, the remelting of the pre-existing Jurassic mantle-derived mafic rocks in the thickened lower crust during the post-collision orogeny generated the Miocene ore-hosting porphyries.

The new data reported here suggest that the metamorphosed Late Cretaceous gabbros and diorites (migmatitic garnet amphibolites), broadly distributed in the lower crust of the eastern Gangdese arc, mostly have higher Cu concentrations (mostly > 60–100 ppm) than the Jurassic magmatic rocks outlined here (Cu < 114 ppm; Tables S4 and S6; Fig. 13), and normal arc magmatic rocks (Cu < 60 ppm; Hou et al., 2015a). Therefore, we propose that the voluminous garnet amphibolites may also be one of the potential source rocks of the Miocene ore-hosting porphyries. Moreover, experimental studies (e.g., Selbekk and Skjerlie, 2002) have shown that the partial melting of water-rich garnet amphibolites can generate magma with very high H_2O content (up to 10–16 wt. %), which is one of the necessary conditions to allow porphyry Cu mineralization (e.g., Hou et al., 2009, 2011; Wang et al., 2014b, 2018; Lu et al., 2015; Yang et al., 2015, 2016a, b). The water- and metal elements-rich nature of the Late Cretaceous juvenile lower crust of the Gangdese arc are probably an essential prerequisite for the formation of Miocene ore-hosting porphyries.

Although porphyry Cu–Au ore deposits in the Andean arcs formed during subduction of oceanic lithosphere, some studies argued that some large and giant ore-hosting porphyries were derived from remelting of garnet amphibolites, representing products of high-pressure metamorphism of mantle-derived gabbros, in the presence of water during juvenile crustal thickening, which itself was induced by shallow subduction of the Neo-Tethyan oceanic slab (e.g., Kay and Mpodozis, 2001; Bissig et al., 2003). Therefore, we propose that some subduction- and collision-related porphyry Cu–Au deposits have a similar metallogenic mechanism, i.e. the ore-hosting porphyries originated from the remelting of hydrated and thickened juvenile lower crust, although they formed during different stages of the continental magmatic arc's tectonic evolution.

Mesozoic Tectonic Evolution of the eastern Gangdese Arc

The Gangdese magmatic arc documents a complete growth process spanning Mesozoic oceanic lithospheric subduction to Cenozoic continental collision. As the India-Asian continental collision initiated at the Early Cenozoic, around ~65–55 Ma (e.g., Rowley, 1996; Yin and Harrison, 2000; Mo et al., 2003; Leech et al., 2005; Guillot et al., 2008; Najman et al., 2010; Wu et al., 2014a; Zhu et al., 2015; Hu et al., 2016; Ding et al., 2017), the formation and evolutionary history of the Gangdese arc can be divided into two stages: Mesozoic (pre-collisional) subduction and Cenozoic collision (Fig. 2). The latter stage includes the syn-collisional (65–40 Ma) and post-collisional (<40 Ma) periods (e.g., Mo et al., 2005; Zhu et al., 2017, 2019; Zhang et al., 2019a). It is widely accepted that rifting of the Lhasa terrane from the southern margin of Gondwana supercontinent and the opening of Neo-Tethyan Ocean occurred during the Carboniferous–Early Permian (e.g., Dewey et al., 1988; Sciunnach and Garzanti, 2012; Li et al., 2016b). However, the age of onset of subduction of Neo-Tethyan oceanic lithosphere beneath the Lhasa terrane remains a matter of discussion. Coulon et al. (1986) suggested that the Neo-Tethyan subduction began in the Early Cretaceous time since the remnant ophiolites in the Yarlung–Tsangpo suture zone have Late Jurassic ages. But, the Yarlung–Tsangpo ophiolite does not likely represent a remnant of the Neo-Tethyan oceanic crust between the Indian and Asian continents (Wu et al., 2014b), and the Neo-Tethyan oceanic crust had already disappeared owing to the long duration of subduction and/or erosion during the Mesozoic and Cenozoic (Wang et al., 2016b).

Late Triassic–Jurassic arc-type magmatic rocks have been increasingly reported in the Lhasa terrane (e.g., Kapp et al., 2005a; Chu et al., 2006; Dong et al., 2006; Qu et al., 2007; Zhang et al., 2007; Pullen et al., 2008; Zhu et al., 2008, 2009a, b; Ji et al., 2009a; Guo et al., 2011; Dong and Zhang, 2013; Kang et al., 2014; Song et al., 2014; Li et al., 2016a; Wang et al., 2016a). Three tectonic models have been proposed to explain the origin of these magmatic rocks: (1) northward subduction of Neo-Tethyan oceanic lithosphere (e.g., Chu et al., 2006; Dong et al., 2006; Zhang et al., 2007; Zhu et al., 2008; Guo et al., 2013b; Kang et al., 2014; Ma et al., 2018), (2) southward subduction of the Meso-Tethyan (Bangong–Nujiang) oceanic lithosphere (e.g., Pan et al., 2012; Zhu et al., 2013; Li et al., 2016b, 2018), and (3) roll-back or breakoff of the Sumdo oceanic lithosphere between the southern and northern Lhasa subterranes (Dong and Zhang, 2013). However, most studies inferred that these Early Mesozoic magmatic rocks were related to arc magmatism induced by the northward subduction of Neo-Tethys (e.g., Ding et al., 2003; Chu et al., 2006; Dong et al., 2006; Geng et al., 2006; Qu et al., 2007; Zhang et al., 2007, 2012b; Yang, 2008; Zhu et al., 2008; Ji et al., 2009a, b; Pan et al., 2012; Guo et al., 2013b; Kang et al., 2014; Meng et al., 2016a, b; Ma et al., 2017, 2018; Xu et al., 2019). Considering the temporal and spatial distribution of the Early Mesozoic arc-type magmatic rocks, Wang et al. (2016a) proposed that the northward subduction of Neo-Tethys had begun by the Middle Triassic (~237 Ma). Our study shows that Middle and Late Jurassic magmatic rocks from the eastern Gangdese arc have geochemical signatures typical of arc-related rocks. Therefore, we suggest that the Jurassic arc-type magmatic rocks formed during a period of normal (steep) subduction of Neo-Tethys (Fig. 14A). In addition, the underplating and accretion of voluminous mantle-derived rocks probably resulted in the initial thickening of arc crust, and remelting of thickened juvenile lower crust, which resulted in the formation of Late Jurassic high Sr/Y granitoids.

Early Cretaceous arc-type magmatic rocks (~140–100 Ma) are widespread in the central and northern parts of Lhasa terrane, but rare in the southern part of the terrane (Fig. 1B), which represents a period when the southern Gangdese arc was in a magmatic lull (Figs. 2, 9 and 14B). The geodynamic setting of Early Cretaceous arc-type rocks has been ascribed to (1) the northward subduction of the Neo-Tethys (e.g., Allègre et al., 1984; Coulon et al., 1986; Ding and Lai, 2003; Ding et al., 2003; Kapp et al., 2003, 2005a, 2007a) or (2) bidirectional subduction beneath both flanks of the Lhasa terrane; that is, northward subduction of the Neo-Tethys and southward subduction of the Meso-Tethys (Zhu et al., 2009b, 2011, 2016). Based on the spatial and temporal distribution of Early Cretaceous arc magmatic rocks – which mainly occur in the central and northern Lhasa terrane, and the ages of magmatic rocks become younger northward (Li et al., 2018), we propose that the subduction angle of Neo-Tethyan oceanic slab may have gradually flattened between the Late Jurassic and Early Cretaceous, since the subducted oceanic lithosphere becomes younger and less dense as the Neo-Tethyan mid-oceanic ridge gradually approached the trench (subduction zone; Fig. 14B). Young (<20 Ma) oceanic lithosphere is thin, hot and buoyant, and is not easy to subduct, therefore a low-angle subduction zone will preferentially form during subduction of young oceanic lithosphere (e.g., Stern, 2002; Weller et al., 2019). Shallow subduction of the oceanic lithosphere is expected to remove asthenospheric mantle and cause a magmatic lull within the southern Lhasa terrane, as well as drive northward migration of arc magmatism into the central and northern Lhasa terrane (Fig. 13B). This is consistent with the observation that the rare Early Cretaceous magmatic rocks in the southern Gangdese arc show adakitic signatures, and are probably derived from partial melting of the thickened juvenile lower crust or subducted slab (Zhu et al., 2009a; Hernández-Uribe et al., 2020). The Early Cretaceous magmatic lull recorded in the southern Gangdese arc has been previously ascribed to either shallow subduction of the Neo-Tethys oceanic slab (Kapp et al., 2007; Zhang et al., 2019c) or retreat and rollback of the Neo-Tethys subduction zone (Maffione et al., 2015; Xiong et al., 2016; Dai et al., 2021). The Early Cretaceous arc magmatic rocks in the northern Lhasa terrane may have formed from the southward subduction of the Bangong–Nujiang Tethys, as argued by previous studies (e.g., Zhu et al., 2009b, 2013, 2016; Sui et al., 2013; Chen et al., 2014; Li et al., 2018).

Widespread early Late Cretaceous (~90–100 Ma) arc magmatic rocks record a magmatic "flare-up" event within the Gangdese arc (Figs. 1B and 2; Wen et al., 2008a, b; Zhang et al., 2010a, 2014b; Guo et al., 2013a; Ma et al., 2013a, b, 2015; Jiang et al., 2014; Zheng et al., 2014; Dai et al., 2015; Zhu et al., 2017; Zhang et al., 2019a). Although this magmatic pulse has been widely related to the northward subduction of the Neo-Tethys, three distinct geodynamical models have been proposed: a) normal-angle subduction (Ji et al., 2009a), b) subducted slab roll-back (Ma et al., 2013a, b; Meng et al., 2020), and c) spreading mid-oceanic ridge subduction (Zhang et al., 2010a).

Active mid-oceanic ridge subduction is a natural consequence of the gradual consumption and final closure of oceanic basin, and is occurring in the eastern margin of Pacific plate (e.g., DeLong et al., 1979; Cole and Stewart, 2009). Subduction-related magmatism can change markedly due to upwelling of asthenosphere through a slab window when spreading mid-oceanic ridges enter a subduction zone (Fig. 14C; Dickinson and Snyder, 1979; Aguillon-Robles et al., 2001; Thorkelson and Breitsprecher, 2005; Cole and Stewart, 2009). In this case, high heat flow from the asthenosphere can induce partial melting of overlying arc crust, subducting oceanic crust at slab window edges, mantle wedge material, and even asthenosphere to generate intermediate to acidic rocks, adakitic rocks, and mafic rocks, respectively (DeLong et al., 1979; Yogodzinski et al., 2001; Thorkelson and Breitsprecher, 2005). In addition, spreading ridge subduction along active continental margins can induce high temperature and ultrahigh-temperature metamorphism of overlying arc crustal rocks (Sisson et al., 1989; Underwood et al., 1999; Iwamori, 2000; Santosh and Kusky, 2010).

Zhang et al. (2010a, 2011) showed that the early Late Cretaceous magmatic rocks of the eastern Gangdese arc include calc-alkaline rocks, adakites, high temperature and anhydrous charnockites, and that the country rocks of the charnockite experienced syn-intrusive high-temperature metamorphism. Therefore, they suggested that these magmatic components formed during subduction of the Neo-Tethyan mid-oceanic ridge (Fig. 14C). The same geodynamic setting was also proposed for the early Late Cretaceous magmatic event of the Gangdese arc by later studies (e.g., Guan et al., 2010; Guo et al., 2011, 2013a; Zhu et al., 2013, 2019; Meng et al., 2014; Zheng et al., 2014; Kapp and DeCelles, 2019). In addition, Zhang et al. (2019b) further revealed that the early Late Cretaceous volcanic rocks of the Gangdese arc include two distinct volcanic successions: asthenosphere-derived basalts and slab-derived adakitic dacites. They attributed this event to Neo-Tethyan mid-oceanic ridge subduction that allowed for contributions from both upwelling asthenosphere and melting of subducted slab crust, which differs from the typical scenario of normal-angle subduction or low-angle/flat subduction and subsequent slab rollback.

The late Late Cretaceous (~70–90 Ma) Gangdese arc contains high-pressure granulite-facies metamorphic and anatectic migmatites in the lower crust, and voluminous high Sr/Y granites in the upper crust (Fig. 3). This metamorphic and magmatic association is probably related to flat subduction of young oceanic lithosphere following subduction of the Neo-Tethyan mid-oceanic ridge (Fig. 14D). This is consistent with previous conclusions that the Neo-Tethys underwent flat subduction, and the Gangdese arc crust was notably thick during the Late Cretaceous (~ 75–80 Ma), as constrained by evidence from deformation, sedimentary strata and magmatism (e.g., Ding et al., 2003; Chung et al., 2005; Leier et al., 2007; Pullen et al., 2008; Ji et al., 2014; Kapp and DeCelles, 2019; Tang et al., 2021). Low-angle subduction of young oceanic lithosphere would generate intense compressional stresses in the overlying magmatic arc, and cause intense thickening of arc crust (Fig. 14D; e.g., Stern, 2002). The Late Cretaceous (~70–85 Ma) adakitic granites were thus probably derived from partial melting of high-pressure mafic granulites in the thickened juvenile lower crust that was hydrated by slab-derived aqueous fluids (Fig. 14D). In addition, with the continued subduction of oceanic lithosphere, the ridge slab gap and associated asthenosphere upwelling probably migrated below the lithosphere of central Lhasa terrane, which accounts for extension and back-arc magmatism in the Gangdese arc, as represented by Late Cretaceous bimodal igneous rocks, adakites and K-rich magmatic rocks (Fig. 14D; Li et al., 2013; Meng et al., 2014; Ma et al., 2015; Zhang et al., 2019b).

While our new data shed important light on the geological evolution of the Gangdese arc and adjacent regions, the Mesozoic tectonic model proposed here is highly simplified. The Gangdese arc probably underwent a more complex evolution process, including multiple and alternating advance and retreat of the Neo-Tethyan slab and subduction zone (trench), and alternating contraction and extension, and resultant thickening and thinning of the arc crust (Kapp and DeCelles, 2019). Revealing the temporal and spatial distributions of Mesozoic magmatic rocks, the petrogenesis of large batholiths, the evolving of component and composition of arc crust over time, the contributions of ancient crustal materials to the juvenile crustal building, and the metallogenic processes during subduction remain key issues for further research.

CONCLUDING REMARKS

(1) The Gangdese magmatic arc underwent intense Mesozoic arc-type magmatism, with two main magmatic pulses in the Middle Jurassic and Late Cretaceous. The widespread occurrence of depleted mantle-like magmatic rocks indicate that the arc experienced voluminous growth of juvenile continental crust during the Mesozoic, driven by subduction of the Neo Tethys oceanic lithosphere.

(2) The Mesozoic magmatic rocks of the eastern Gangdese arc have been buried into the lower arc crust, and transformed to migmatitic garnet amphibolites during Late Cretaceous (~68–90 Ma) high-grade metamorphism and partial melting. The voluminous hydrous and metal element-rich granulitic migmatites are main component of the lower arc crust, and probably potential source rocks of Miocene ore-hosting porphyries.

(3) The Gangdese arc experienced crustal thickening during the Middle to Late Jurassic, and Late Cretaceous. The remelting of the thickened juvenile lower crust produced high Sr/Y granitoids in the upper crust, and is probably a main mechanism for intracrustal chemical differentiation of the arc crust during the subduction of Neo-Tethys.

(4) Major tectonic and magmatic processes of the Gangdese arc include the Late Triassic to Jurassic normal subduction of Neo-Tethys and associated mantle-derived magmatism, the Early Cretaceous shallow subduction and magmatic lull, the early Late Cretaceous mid-oceanic ridge subduction and magmatic flare-up,

and the late Late Cretaceous flat subduction and resultant crust-derived magmatism.

(5) The Gangdese arc records a complex process of crustal growth, thickening and differentiation that occurred before arc-continent collision, and therefore provides insights into the early building of mature continental magmatic arcs that form and evolve through all stages of oceanic lithospheric subduction to continental collision.

SUPPLEMENTARY TABLES

Table S1. Major features of the metamorphosed Jurassic magmatic rocks

Table S2. Zircon U–Pb dating and trace element data of the metamorphosed Jurassic migmatitic rocks

Table S3. Zircon Hf isotopic data of the metamorphosed Jurassic magmatic rocks

Table S4. Whole-rock chemical compositions of the metamorphosed Jurassic magmatic rocks

Table S5. Whole-rock chemical compositions and zircon U–Pb ages of the Mesozoic magmatic rocks of the eastern Gangdese arc

Table S6. Whole-rock SiO_2 and Cu concentrations of the Late Cretaceous mafic and intermediate magmatic rocks of the eastern Gangdese arc lower crust.

ACKNOWLEDGEMENTS

We thank two anonymous reviewers for meticulous and insightful reviews, and Profs. Rob Strachan and Jean H. Bédard for helpful suggestions and editorial handing. This study is co-supported by the National Natural Science Foundation of China (91855210, 41941016-2 and 41872064), the National Key Research and Development Project of China (2016YFC0600310), the Fundamental Research Funds for the Central Universities of China (649911026), and the China Geological Survey (DD20190059). Master students Hongchen Mu, Zhixiang Niu, Ning Zhang, Mengmei

Li and Chengyuan Zhang took part in this study.

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Figure captions:

Figure 1. (A) Sketch geological map of the Tibetan Plateau. (B) Distribution of Mesozoic and Cenozoic magmatic rocks of the Lhasa terrane, showing the locations of giant and large porphyry Cu–Au deposits of Jurassic and Miocene in the Gangdese arc (modified after Zhu et al., 2011, 2019; Chen et al., 2014; Wang et al., 2014a, 2017, 2018; Li et al., 2018; Zhang et al., 2019b). BNSZ: Bangong–Nujiang (Meso-Tethyan) Suture zone, JSSZ: Jinsha (Paleo-Tethyan) Suture Zone, KLSZ: Kunlun Suture Zone, LCSZ: Longmu Co-Shuanghu (Meso-Tethyan) Suture Zone, and YTSZ: Yarlung–Tsangpo (Neo-Tethyan) Suture Zone.

Figure 2. Histogram of zircon U–Pb ages of magmatic rocks in the eastern Gangdese arc, showing four intense pulses of magmatic activity at ~170, ~95, ~50 and ~15 Ma, and durations of Neo-Tethyan oceanic lithosphere subduction and Indo-Asian collision, and the approximate durations of the spreading mid-oceanic ridge

subduction, syn- and post-continental collisions. Data sources: zircon U–Pb ages of <100 Ma are from Zhu et al. (2018) and Zhang et al. (2020), and ages of >100 Ma from this study (Tables S4) and previous literatures (Table S5).

Figure 3. Geological map of the eastern Gangdese arc near the Eastern Himalayan Syntaxis (modified after Zhang et al., 2020), showing the distribution of different degrees of metamorphic rocks (belts), and locations of the studied Jurassic rock samples.

Figure 4. Field photos (A, B) and photomicrographs (C–F) of the metamorphosed Jurassic magmatic rocks. (A) Migmatitic amphibolite, occurring as a thick layer within migmatitic gneiss, shows the banded structure, defined by alternating felsic leucosome and amphibolitic melanosome. (B) Migmatitic garnet amphibolite contains concordant veins or bands of garnet-rich felsic leucosome. (C) Garnet amphibolite (TM8-20-2), containing amphibole, plagioclase, garnet, epidote, quartz, rutile and ilmenite. (D) Garnet-bearing gneiss (TM7-50-2), consisting of plagioclase, quartz, garnet, amphibole, biotite, muscovite, chlorite and ilmenite, and showing a strong foliation. (E) Garnet-rich leucosome (T16-77-6), consisting of plagioclase, quartz, garnet, amphibole, biotite and epidote. (F) Amphibolite (D120302), containing amphibole, epidote, plagioclase, ilmenite and rutile, showing strong foliation. Mineral abbreviations: Amp = amphibole, Bt = biotite, Ep = epidote, Grt = garnet, Pl = plagioclase, and Qtz = quartz.

Figure 5. Cathodoluminescence (CL) images of zircon of the metamorphosed Jurassic magmatic rocks, showing the analyzed spot locations and relevant ages (in Ma). The scale bars are 100 μm. (A) TM07-50-2, garnet-bearing gneiss; (B) T16-77-6, garnet-rich leucosome; (C) T17-1-25, gneiss; (D) T17-1-26, gneiss; (E) D120302, amphibolite; (F) D120303, gneiss; (G) D350612, amphibolite; (H) D350613, gneiss.

Figure 6. Zircon U–Pb concordia diagram of the metamorphosed Jurassic magmatic rocks, showing the mean ages obtained from magmatic cores of zircon, and the mean ages from metamorphic rims of zircon.

Figure 7. Chondrite-normalized REE patterns of magmatic cores (red lines) and metamorphic rims (green lines) of zircon of the metamorphosed Jurassic magmatic rocks, showing the mean Th/U ratios of magmatic cores and metamorphic rims of zircon.

Figure 8. Zircon U–Pb ages versus $\varepsilon_{Hf}(t)$ values of the Mesozoic magmatic rocks of the eastern Gangdese arc. Data sources of the Late Cretaceous rocks are from Guan et al. (2011), Zhu et al. (2011); Ma et al. (2013a, b), Ji et al. (2014), Zheng et al. (2014), Xu et al. (2015), Tang et al. (2020) and Zhang et al. (2020). The data for the zircon magmatic cores and metamorphic rims of Jurassic magmatic rocks are listed in Table S3.

Figure 9. Zircon U–Pb ages versus whole-rock SiO_2 contents (A) and Sr/Y (B) of the Mesozoic magmatic rocks of the eastern Gangdese arc. The data are listed in Tables S4 and S5. The diagram shows the approximate durations of normal, shallow, spreading ridge and flat subduction processes of the Neo-Tethyan oceanic lithosphere, and two stages of arc crustal thickening.

Figure 10. Zircon U–Pb ages versus whole-rock A/CNK (A) and Mg# (B) of the Mesozoic magmatic rocks of the eastern Gangdese arc. The data are listed in Tables S4 and S5.

Figure 11. Chondrite-normalized REE (A, C) and primitive mantle-normalized trace element (B, D) patterns of the Jurassic and Late Cretaceous magmatic rocks of the eastern Gangdese arc. The newly reported Jurassic rocks are shown by the thick lines in (A, B). The Late Cretaceous (~70–85 Ma) high Sr/Y granitoids are shown by the

thick red lines in (C, D). The related data see Tables S4 and S5.

Figure 12. Harker diagrams of SiO_2 versus other oxides (in wt. %) of the Jurassic migmatitic rocks of the eastern Gangdese arc

Figure 13. Diagram of whole-rock SiO_2 versus Cu contents of the metamorphosed Jurassic and Late Cretaceous magmatic rocks from the eastern Gangdese arc lower crust. The related data see Tables S4 and S6.

Figure 14. Mesozoic tectonic model of the eastern Gangdese arc. (A) Normal (steep) subduction of the Neo-Tethyan oceanic lithosphere, and normal calc-alkaline arc magmatic rocks during the Jurassic (180–145 Ma). (B) Shallow subduction of the oceanic lithosphere and attenuation of mantle-wedge, magmatic lull in the southern Lhasa terrane, and enhanced arc magmatism in the central and northern Lhasa terrane during the Early Cretaceous (145–100 Ma). (C) Subduction of the mid-oceanic ridge and upwelling of asthenosphere in slab window, intense magmatic activity with variable compositions and distinct sources during the Late Cretaceous (100–90 Ma). (D) Flat subduction and dehydration of the young oceanic slab during the Late Cretaceous (90–70 Ma), thickening, hydration and partial melting of the juvenile arc crust, and formation of high Sr/Y granitoids. The continued subduction of a mid-oceanic spreading ridge and upwelling of asthenosphere probably resulted in extension and bimodal magmatism in the central Lhasa terrane.