The timing, origin and T-fO2 crystallization conditions of long-lived magmatism at the Yangla copper deposit, Sanjiang Tethyan orogenic belt: Implications for post-collisional magmatic-hydrothermal ore formation

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An integrated study involving zircon geochronology, Hf isotopic characteristics and trace elements combined with detailed field investigation was carried out for the felsic magmatic system in the Yangla skarn copper deposit area in the Sanjiang orogenic belt, southwestern China. The intrusive units are composed of syn-mineralized dioritic enclaves, granodiorite, quartz monzonite porphyry (238–230 Ma), and granite stocks and monzogranite dikes (~223 Ma), bracketing a time span of ca. 15 Myr. The uniform Hf isotope characteristics during an ~15 Myr period suggest a primary control of the isotopic signature by a stable, long-lived, hot reservoir in the deep lithosphere. The occurrence of mafic enclaves and the identical intermediate initial εHf values (~5.9 to 1.7) of granodiorite, granite, and monzogranite, suggest that the felsic magmatic system was produced by remelting of Neoproterozoic lower crustal rocks that mixed with minor amounts of mantle-derived melts. Application of comprehensive indices of zircons, such as Th/U, Zr/Hf, T(Ti in zircon), and Ce/Nd, implies that (1) mafic melt injected into felsic magma during the early stage, from which the granodiorite and dioritic enclaves formed; (2) progressive evolution from granodiorite to quartz monzonite porphyry with addition of crustal components, as revealed by the positive correlation between εHf and Th/U; (3) the incorporation of the crustal component into the residual magma from which quartz monzonite porphyry formed, reduced the fO2 of the mineralized and barren quartz monzonite porphyry and settled much of dense sulfides out at depth; and (4) another discrete reduced magma pulse, from which the granite and monzogranite dikes crystallized at slightly higher Ti-in-zircon model temperatures, suggesting a slightly more reduced condition of the hidden intrusive portion of magma chamber. In general, the magmatic system is interpreted to be related to post-collisional lithospheric extension after slab break-off. The Cu, S, and water of the felsic magmas were mainly derived from the recycling of Neoproterozoic hydrous arc lower crustal rocks triggered by asthenospheric upwelling.

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1. Introduction

The genetic linkage between the hydrous, oxidized, metalliferous felsic magma and the intrusion-related Cu mineralization has been well established (Mathur et al., 2000; Richards, 2003; Bi et al., 2009; Jugo, 2009; Hou et al., 2011; Richards, 2011; Han et al., 2013; Sun et al., 2013; Zajac et al., 2013; Zhang et al., 2013). Subduction process exercise primary controls on ultimate enrichment of metals (Cu, Au) and S (Griffin et al., 2013) and the relatively high fO2, H2O contents in arc magmas (Kelley and Cottrell, 2009), whereas the metal-fertile felsic magmas with those characteristics generated in post-collisional environments are thought to be the products of remelting of subduction-modified arc lithosphere (Richards, 2009). At deposit scale, the occurrence of both barren and mineralized stocks or dikes with similar age and rock type is mainly ascribed to differences of magma fO2 (Ballard et al., 2002). Decreasing fO2 would induce sulfide saturation (Jenner et al., 2010) and settle much of dense sulfides out at depth prior to hydrothermal fluid exsolution (Richards, 2009, 2014). In practice, at least two factors can reduce fO2, i.e., magnetite fractionation (Jenner et al., 2010) and crust-magma interaction process (Ripley and Li, 2013), but it remains unclear as to which is the dominant factor leading to such distinct fO2 conditions of the barren and mineralized stocks or dikes in a deposit area. In the upper crust, the underlying
precursor pluton (5–15 km) supplies magmas and fluids for the shallow vertically elongate stocks or dike swarms (>3 km). Understanding the relationship in fO2 between the precursor pluton and the porphyry stocks or dikes probably contributes to explore the difference of fO2 between the barren and mineralized porphyries in a deposit area.

The Sanjiang orogenic belt, within the Tethyan collisional regime of Yunnan Province, southwestern China, is one of the premier polymetallic belts in China, hosting various types of ore deposits that are dominated by magmatic–hydrothermal deposits (Deng et al., 2014; Mao et al., 2014a, 2014b). Porphyry–skarn Cu ± Au deposits can be recognized in both the southern Yidun arc and the Jinshanjian–Ailaoshan belt of the Sanjiang orogenic belts. The complex tectonic history of the area, with overprinting metamorphism and deformation, resulted in the offset of igneous units in the Jinshajiang belt (Wang et al., 2000), where deep-seated plutons and the associated relatively shallow porphyry stocks or dikes are no longer preserved in spatial association with each other. As a rare Triassic intrusion-related Cu deposit along the Jinshajiang belt, the Yangla magmatic system advantageously preserves both a deep-seated pluton (i.e., Jiaren granodiorite pluton) and stocks (e.g., Linong, Lunong and Jiangbian stocks), and associated barren and mineralized porphyry dikes.

The Yangla copper deposit has been debated to be either a submarine volcanic-hosted massive sulfide (VMS) or a skarn deposit since the late 1990s (Zhan et al., 1999; Qu et al., 2004; Li et al., 2013). Most recent evidences demonstrate that it is a typical intrusion-related Cu skarn deposit (Zhu et al., 2015). Previous studies at the deposit have revealed that the Cu mineralization was specifically related to Middle–Late Triassic high-K calc-alkaline granodiorite (Zhu et al., 2011; X.A. Yang et al., 2012; Zhu et al., 2015), but opinions on the tectonic setting of the Yangla magmatic system are controversial, varying from subduction-related (X.A. Yang et al., 2012; Yang et al., 2013b) to post-collisional (Zhu et al., 2011). Recently, Liu (2014) examined the characteristics of quartz monzonite porphyry dikes and viewed them as another magmatic bodies related to the Cu mineralization. The quartz monzonite porphyry is considered to be crystallized from residual magma that was emplaced at a shallow level above other intrusive bodies in the area (Li et al., 2013). Importantly, the crystallization age and genesis of the various igneous units are poorly constrained and are contentious. Dating of the mafic microgranular enclaves (MMEs), monzogranite dikes and weathered granite in the deposit area is lacking. In this contribution, our research includes detailed trace element geochemistry, U–Pb geochronology, and Lu–Hf isotopic investigations of zircon populations in diverse types of felsic rocks from the targeted magmatic system. The new comprehensive dataset allows us to identify the tectonic setting, and magma source and T–fO2 conditions, as well as the dynamics of construction of magma system. The evaluation is valuable to confirm the sources of ore metals in the Yangla deposit, and the relationship of precursor pluton and porphyry intrusions and to explain the possible trigger for the distinct magma fO2 at the deposit scale.

2. Geological framework

2.1. Regional geology

Recent study has divided Jinshajiang suture into a western segment and southern segment (Fig. 1a), whereas the western Jinshajiang suture extends eastward and connects with the Garze–Litang suture based on present coordinates, which represents a southward subduction of western Jinsha–Garze–Litang Ocean during the Triassic (Reid et al., 2007; T.N. Yang et al., 2012). The southern Jinshajiang (Jinshajiang–Ailaoshan) orogenic belt is composed of the ophiolitic Paleo–Tethyan suture zone, fringing arc, and collisional magmatic and sedimentary sequences of the Yangtze block passive margin (Fig. 1b). The southern Jinshajiang suture is situated in the transitional area between the Tibetan Plateau and the Yangtze block, spanning the boundary between the Changdu–Simao micro-continental block to the west and Zhongzha–Zhongdian block to the east (Fig. 1b). It is thought to be contiguous with the Ailaoshan suture to the southeast, and both are considered to close branches of the Paleo–Tethyan Ocean and are aligned with the Song Ma suture to the south in Vietnam (Wang et al., 2000; Metcalfe, 2013). The basement of the Qamdo–Simao terrane is buried beneath thick Paleozoic–Mesozoic sequences and only exposed locally (Zhang, 2000), and was possibly separated from South China block during opening of the southern Jinshajiang Ocean in the Late Devonian or early Carboniferous (Mo et al., 1993; Zhang, 2000; Metcalfe, 2002; Z.Q. Hou et al., 2007). Migmatites in the Precambrian crystalline basement, which outcrop along the Ailaoshan belt are 843–833 Ma zircon SHRIMP U–Pb ages (J.L. Liu et al., 2008). The pre–Paleozoic metamorphosed crystalline basement of the Qamdo–Simao terrane along the southern Jinshajiang suture is represented by the Eaqing Complex, which yields an upper intercept zircon U–Pb age of 1627 ± 192 Ma for plagioclase–amphibolite, indicating the presence of a Mesoproterozoic remnant metamorphic basement or microcontinental fragment (Wang et al., 2000).

The southern Jinshajiang orogenic belt experienced a complex history, including subduction of an oceanic plate, collision, post-collisional extension, intracontinental convergence, and a late Paleozoic to Tertiary lengthy period of strike-slip events (Wang et al., 2000). Initial spreading of south Jinshajiang ocean in early Carboniferous is indicated by the SHRIMP U–Pb zircon age of 343.5 ± 2.7 Ma for pegmatoid cumulate gabbro from the ophiolite fragment (Jian et al., 2009b) and 347 ± 7 Ma for Dongzhulin trondhjemite (Zi et al., 2012b), whereas the westward subduction had begun by the Early Permian (Jian et al., 2008; Z et al., 2012b). Voluminous felsic plutons intruded along the southern Jinshajiang suture zone during Late Permian to Triassic are products of different orogenic events. Based on Jian et al. (2009a), Zi et al. (2013) and Wang et al. (2014), the Late Permian–Triassic tectonic evolution includes: (a) Late Permian–earliest Triassic marginal arc margin formation during subduction and closure of an ocean basin; (b) Early–Middle Triassic collision, local extension, and syntectonic volcanism; and (c) Late Middle–Late Triassic magmatism, exhumation, and development of thrust belts across the southern Jinshajiang orogenic belt. The onset of India–Asia collision occurred at ca. 60–55 Ma, which resulted in the formation of the Himalayan orogenic belt and Tibetan plateau (Chung et al., 2005). Subsequently, ca. 27–22 Ma southeastward continental extrusion caused a sinistral offset of more than 600 km along the NW- to WNW-trending Ailaoshan–Red River shear zone (Fig. 1; Chung et al. (1997)).

Numerous igneous suites formed during the evolution of Jinshajiang–Ailaoshan Tethys Ocean (Fig. 1). Two dominant epochs of intermediate to felsic intrusive activity and associated mineralization have been identified along the Jinshajiang–Ailaoshan orogenic belt (Mo et al., 1993; Z.Q. Hou et al., 2007). The Triassic felsic bodies comprise the Baimaxueshan (253–248 Ma) (Zi et al., 2012a), Ludian (231–214 Ma) (Zi et al., 2013) and Jiaren intrusions (~233 Ma) (Wang et al., 2010; Yang et al., 2011; Zhu et al., 2011). The investigated Yangla felsic magmatic system is part of the Jiaren batholith and is spatially associated with the Cu mineralization. Only sparse mineralization occurs in association with the other two intrusions (Zhu et al., 2015). The latter episode of mineralization is spatially extensive and is related to the Eocene–Oligocene high-K magmatic belt along the NW-striking Jinshajiang fault system and Ailaoshan–Red River strike-slip fault (Mao et al., 2014b).

2.2. Yangla skarn Cu deposit

The Yangla porphyry–skarn copper deposit is genetically linked to Middle–Late Triassic magmatism (Fig. 2) and has a resource estimate of 130–150 Mt. @ 1% Cu. The deposit includes multiple ore zones with similar stratigraphic and structural controls, bounded by the Jinshajiang fault to the east and the Yangla fault to the west. Although seven linear mineralized segments were identified from north to south within the area during exploration, only two of these are economic. They are
Linong and Lunong ore zones, including the conjunction zone between them that is manifested by the NE-oriented F4 normal fault (Fig. 2). The Linong ore zone is the most significant one and accounts for 90% of the copper resource. Five types of hypogene Cu mineralization in the district have been described as skarn type, hornstone type, hydrothermal breccia type, granodiorite type and quartz monzonite porphyry type. Supergene events resulted in weathered ore zones, which are mainly centered at the surface of the Lunong ore zone. Previous study illustrated that the granodiorites are spatially associated with the skarn deposit (Zhu et al., 2015). Recent Re–Os isotopic dating of molybdenite from the skarn ore type by Yang et al. (2013b) yielded a mineralization age of 233 ± 2 Ma, which is identical to the zircon

![Diagram showing the distribution of principal continental blocks and sutures of southeast Asia and the tectonic framework of the Sanjiang domain in southwestern China, including the Yangla Cu deposit and primary intrusion-related Cu-Au deposits.](image)

**Fig. 1.** (a) Distribution of principal continental blocks and sutures of southeast Asia (Metcalfe, 2006, 2013). (b) Tectonic framework of the Sanjiang domain in southwestern China, showing the major terranes, suture zones, arc volcanic belts, and location the Yangla Cu deposit and other primary intrusion-related Cu-Au deposits (Zi et al., 2012a; Deng et al., 2014).
U–Pb age of ~233 Ma for the granodiorite stocks (Zhu et al., 2011; Yang et al., 2013a). Furthermore, local porphyry-type Cu mineralization has been observed within the quartz monzonite porphyry stocks, but it does not reach economic levels.

The mineralization is best developed surrounding the three major granodiorite stocks (Linong, Jiangbian, and Lunong) and two minor stocks (Beiwu and Nilv), which are emplaced into rocks of the Devonian Jiangbian and Linong suites and Early Carboniferous Beiwu suite (Fig. 2). The Jiangbian suite is mainly composed of marble interlayered with sericite–quartz schist and amphibole-bearing andesite, whereas the Linong suite contains sericitic slate, metasandstone, and marble. The Beiwu suite comprises massive basalt, and tuff that is interlayered with sericite-bearing slate, and marble. Granodiorite intrusions are exposed as stocks along the northern part of Jiaren granite belt, which trend N–S in the western part of the southern Jinshajiang orogenic belt.

Granodiorites range from medium- to coarse-grain and are the principal igneous phase in the Linong (Fig. 3a, b), Jiangbian, and Lunong stocks. The granodiorite (Fig. 3g) exhibits an equigranular texture and contains about 35–40% plagioclase, 15–20% K-feldspar, 20–25% quartz, ~10% amphibole, and ~5% biotite, as well as accessory minerals including zircon, apatite, magnetite, and ilmenite. Abundant MMEs (Fig. 3b) are present in the Linong stock, which preserve transitional or irregular sharp contacts with the host granodiorite. They are average 2–10 cm in diameter, although giant enclaves, approximately 0.6 m in diameter (Fig. 3c), are recognized within the Jiangbian stock. The MMEs are generally dioritic in composition (Fig. 3h), yielding a porphyritic texture with phenocrysts of plagioclase, accompanied by minor amounts of biotite, hornblende, and K-feldspar. Hornblende phenocrysts are commonly acicular and twinned, whereas only a few plagioclase phenocrysts show complex zoning. The Cr-spinel and Fe$_2$S$_3$ granules are hosted in the hornblende (Fig. 3i). The younger igneous activity within the ore district is represented by the fine-grained monzogranite dikes, about 10–40 cm in width, ~8 m in length (Fig. 3a), that cut the Linong granodiorite stock. The dikes (Fig. 3j) are mainly composed of plagioclase (30–35%), K-feldspar (30–35%), and quartz (25–30%), with minor biotite (5%), and are relatively fresh. The highly weathered granites (Fig. 3d) are proposed to be Yanshanian (late Mesozoic) intrusions (Zhu et al., 2009), but there are no definitive age data. The quartz monzonite porphyry (Fig. 3f) dike is intensely altered, with silicification and carbonatization zones that contain quartz veins with chalcopyrite and pyrite. In addition, late diabase dikes intruded the Linong granodiorite stock and yield a zircon U–Pb age of 222 Ma (Wang et al., 2010).

### 3. Sampling and analytical methods

The studied zircons were separated from representative samples that were collected from the surface exposures and underground mine workings within the Yangla district. We analyzed 10 samples of intrusive phases from the Jiangbian, Linong, and Lunong felsic stocks, which included granodiorite (LUN01, LUN02, JB03, JB04, LM01, JM01), granite (WG06), and quartz monzonite porphyry (P01, P02). All samples selected for zircon separation were crystal-rich and the detailed sampling locations are marked on the geological map (Fig. 2). The zircon crystals were obtained from crushed and sieved rocks using heavy liquid and magnetic separation techniques. Approximately 200 zircons were studied.
handpicked from each sample under a binocular microscope and mounted in epoxy blocks. The same grains were then embedded in epoxy and polished down to approximately one-half their thickness and carbon-coated for cathodoluminescence (CL) imaging to establish the positions of inclusions, cracks, and internal compositional zoning. The CL imaging of analytical pits was used to assess analytical quality, cracks, and the presence of inclusions, although avoiding all sub-surface heterogeneities is impossible.

Prior to U–Pb dating, the carbon coating necessary for CL imaging was removed to prevent surface lead contamination. Approximately 20–30 grains in each sample were selected for analysis. Trace element and U–Pb analyses of the zircons were carried out using an Agilent 7500a ICP-MS coupled with a New Wave Research UP193FX Excimer laser (New Wave Instruments, USA) at the Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing. The detailed analytical and calculating procedures were described by Cai et al. (2012). Uranium, Th, and Pb concentrations were calibrated by using 29Si as an internal standard and NIST610 as an external standard, and they were analyzed for every six analyses. Common lead correction was made by using the recommended program (Andersen, 2002). The software GLITTER 4.0 was applied to calculate the U–Pb ages, which were calibrated for both instrumental mass bias and isotopic fractionation against zircon standard Plesovice (337 ± 0.37 Ma, Sláma et al. (2008)). The ISOPLOT (version 3.0) program was used for plots and age calculation (Ludwig, 2003), with mean and weighted mean 206Pb/238U concordant ages used for standard Plesovice and magmatic zircons.

Zircon trace element concentrations were simultaneously obtained with U–Pb isotope measurements. Calibration was performed by normalizing count rates for each analyzed element to those for Si to obtain its concentration, assuming SiO2 to be stoichiometric in zircons with a concentration of approximately 32.8%, and multiplying by a correction factor.

Fig. 3. Field example and microscope photo for outcrops of the main intrusive phases in the Yangla ore district. (a) The crosscutting relationship between granodiorite and monzogranite dikes within the Linong stock; (b) The representative characteristics of the MMEs and their relationship with granodiorite in the Linong stock; (c) The coarse MME in the Jiangbian stock; (d) Granite (highly weathered) to the eastern part of the Linong stock; (e) Barren quartz monzonite porphyry; (f) Mineralized quartz monzonite porphyry; (g) Granodiorite; cross-polarized light; (h) MME; cross-polarized light; (i) MME; FeS sulfide globule, chromian spinel, and zircon enclosed in amphibole phenocryst, BSE; (j) monzogranite dike; cross-polarized light; (k) Barren quartz monzonite porphyry; cross-polarized light; (l) Mineralized monzonite porphyry, plane-polarized light, with plagioclase, K-feldspar and quartz phenocrysts; cross-polarized light. Abbreviations: Amp = amphibole, Bt = biotite, Kfs = K-feldspar, Pl = plagioclase, Qz = quartz, Zrn = zircon, Py = pyrite; Ccp = Chalcopyrite.
factor based on concurrent measurement of standard glass NIST610 with concentration values recommended by Pearce et al. (1997).

The analyses of Lu–Hf isotope compositions were acquired by a Newwave UP213 laser ablation microprobe attached to a Neptune multi-collector ICP-MS at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing for most samples, although sample GV-01 was instead analyzed at the State Key Laboratory of Continental Tectonics and Dynamics, Beijing. Similar sites to those used for U–Pb isotope analyses were chosen using a spot size of 45 μm. Ablation was carried out in helium, later mixed with argon and nitrogen, using a pulsed laser at 4 Hz with an energy density of ~6 J cm⁻² over 60 s. Correction for isobaric interferences and mass bias followed K.J. Hou et al. (2007). Correction for the isobaric interferences of ¹⁷⁶Lu and ¹⁷⁶Yb with ¹⁷⁶Hf utilizes ¹⁷⁶Lu/¹⁷⁵Lu = 0.02658 and ¹⁷⁶Yb/¹⁷³Yb = 0.796218. Mass bias effects on interference-free ¹⁷⁵Lu were conducted as-4. Results

within-run precision (2σ). Data are presented in chronological order, and error bars represent the result of a depleted mantle source with present ¹⁷⁶Hf/¹⁷⁷Hf at 0.28325, whereas the two-stage Hf model age (TDMC) was based on the assumption of a mean ¹⁷⁶Hf/¹⁷⁷Hf value of 0.015 for the average continental crust. The initial ²⁰⁶Pb/²³⁸U age for each zone. Epsilon values were normalized by Sun and McDonough (1989). The hafnium isotope database are shown in Supplementary Data 1. Zircon REE patterns and average ²⁰⁶Pb/²³⁸U ages are presented in Supplementary Data 2. They include the determinations of rare earth elements (REE), Ti, Hf, U, Nb, Ta, and Y. Zircons in the felsic rocks have limited variations of the high-field strength elements, such as Nb, Ta, and Ti, which substitute for Zr. All analyses display large chemical variations ranging up to rather high concentrations: HF (5687–13,860 ppm), Y (327–2398 ppm), U (357–2108 ppm), Th (124–774 ppm), Nb (0.74–6.55 ppm) and Ta (0.60–4.59 ppm). Overall, both U and Th concentrations are fairly uniform at low HF contents, but they progressively increase with increasing HF concentrations (Fig. 6a, b). Uranium is relatively enriched compared to Th in all zircons (Fig. 6c). Zircon Th/U ratios are relatively scattered between 0.14 and 0.89, whereas the Th/Hf ratios range from 40 to 67. The Th/U ratios remain constant with changing Hf contents (Fig. 6d). Titanium is notably abundant in zircons, with average contents of 13.0 ppm, 2.41 ppm, 2.47 ppm, and 1.65 ppm in granodiorite samples LUN01, LUN02, JB03, and JB04, respectively. Other samples exhibit similar average Ti concentrations, with 4.95 ppm for the monzogranite dikes, 2.82 ppm for the granite, 1.56 ppm and 2.73 ppm for the MMEs, and 2.70 ppm for the barren and mineralized quartz monzodiorite porphyry, respectively.

4.1. Crystalline features and trace element abundance of zircons

Zircons are typically enclosed within the major silicate phases, such as K-feldspar, biotite, quartz, and particularly hornblende (e.g., monzogranite dike, Fig. 4). Zircon crystals within the host rocks related to the mineralization and in the barren stocks are present in all samples examined in Fig. (5). They are mainly moderately elongated, euhedral, and concentric, although some of them occur as equant, subhedral grains with slight to moderate rounding of crystal phases. They are transparent, colorless, and moderate in size, mostly ~70–230 μm in length and 45–100 μm in width, and with aspect ratios ranging from 1:1–3:1, excluding some quartz monzonite porphyry samples being outliers. Most of the zircon populations in the quartz monzodiorite porphyry exhibit anhedral to euhedral crystals, and yield low-wavelength–moderate-amplitude oscillatory zoning in smaller grains with aspect ratios of 1:5:1 on CL images, illustrating the characteristics of primary magmatic zircons. The detailed information about the length, width, and aspect ratios for single zircon crystals is displayed in Supplementary Data 2. Their magmatic origin indicates their measured date represents the emplacement age of the host rocks.

Concentrations of trace elements of zircons that yielded concordant ages are presented in Supplementary Data 2. They include the determinations of rare earth elements (REE), Ti, Hf, U, Nb, Ta, and Y. Zircons in the felsic rocks have limited variations of the high-field strength elements, such as Nb, Ta, and Ti, which substitute for Zr. All analyses display large chemical variations ranging up to rather high concentrations: HF (5687–13,860 ppm), Y (327–2398 ppm), U (357–2108 ppm), Th (124–774 ppm), Nb (0.74–6.55 ppm) and Ta (0.60–4.59 ppm). Overall, both U and Th concentrations are fairly uniform at low HF contents, but they progressively increase with increasing HF concentrations (Fig. 6a, b). Uranium is relatively enriched compared to Th in all zircons (Fig. 6c). Zircon Th/U ratios are relatively scattered between 0.14 and 0.89, whereas the Th/Hf ratios range from 40 to 67. The Th/U ratios remain constant with changing Hf contents (Fig. 6d). Titanium is notably abundant in zircons, with average contents of 13.0 ppm, 2.41 ppm, 2.47 ppm, and 1.65 ppm in granodiorite samples LUN01, LUN02, JB03, and JB04, respectively. Other samples exhibit similar average Ti concentrations, with 4.95 ppm for the monzogranite dikes, 2.82 ppm for the granite, 1.56 ppm and 2.73 ppm for the MMEs, and 2.70 ppm for the barren and mineralized quartz monzonite porphyry, respectively.
The REE abundances (292–1613 ppm) are moderately low within the range of values reported for crustal zircons (~250–5000 ppm: Hoskin and Schaltegger (2003)). The steep chondrite-normalized REE patterns of zircons are enriched in heavy rare earth elements (HREE) relative to light rare earth elements (LREE), with positive Ce and negative Eu anomalies (Fig. 7). Although these features rule out accidental
analysis of REE-rich mineral inclusions, a few spots reveal enrichment in LREE. The elevated LREE probably reflect sub-surface inclusions, such as apatite. The anomalous data, particularly the zircons with highly variable La contents, were not considered in the below discussion.

4.2. U–Pb geochronology

Selected zircon crystals from the felsic rocks in the Yangla ore district were dated by U–Pb using the LA-ICP-MS method and are presented in Supplementary Data 3, and the CL images of some studied grains are shown in Fig. 5. In Fig. 8, Concordia diagrams and weighted average plots are shown.

Granodiorite samples were selected from the Lunong and Jiangbian stocks for U–Pb dating. Seventeen spot analyses of zircons from LUN01 (coarse-grained granodiorite from the Lunong stock, Fig. 8a) plot on or near the Concordia, yielding a weighted average 206Pb/238U age of 230 ± 1.9 Ma (MSWD = 3.1, n = 17). Zircons from LUN02 (22 spot analyses; a fine-grained granodiorite from the Lunong stock, Fig. 8b) fall in a group with a Concordia U–Pb age of 233 ± 0.4 Ma (MSWD = 0.6, n = 22). Sample JB03 (Fig. 8c), the granodiorite sampled from Jiangbian stock, yields a Concordia U–Pb age of 232 ± 0.5 Ma (MSWD = 0.05) with 24 analyzed spots falling into a group. The other granodiorite sample (JB04, Fig. 8d), which contained more amphibole crystals, has 20 analyses of the zircons yielding a coherent group with a Concordia U–Pb age of 232 ± 0.9 Ma (MSWD = 0.18).

The MME samples (LM01, JM01) were selected from the Linong and Jiangbian stocks. Zircons from the sample LM01 yield a Concordia U–Pb age of 232 ± 0.4 Ma (Fig. 8e) with 19 spots falling into a group.
The fine-grained monzogranite dike (CV04) was sampled at the outcrop where the dike cuts the Linong granodiorite stock. Zircons (20 analyzed spots) from the dike have a Concordia U–Pb age of 223 ± 0.5 Ma (MSWD = 2.6, Fig. 8g).

The granite (WG06) sampled to the east margin of the Linong stock is significantly weathered and altered. Twenty-three concordant analyses of zircons give a Concordia U–Pb age of 223 ± 0.4 Ma (MSWD = 0.94, Fig. 8h), implying that the crystallization age of the rock is identical to that of the monzogranite dike and is younger than the granodiorite.

The quartz monzonite porphyry samples (P01, barren; P02, mineralized) were both collected in the Linong deposit segment. Analyses of zircons from the barren quartz monzonite porphyry give a weighted mean 206Pb/238U age of 232 ± 0.5 Ma (MSWD = 0.13, n = 17, Fig. 8i), whereas analyses of the zircons from the mineralized quartz monzonite porphyry yield a Concordia U–Pb age of 234 ± 0.6 Ma (MSWD = 6.9, n = 13, Fig. 8j). Xenocrystic cores in the barren one have two spots that are much older (e.g., 2418 ± 10 Ma and 2537 ± 19 Ma).

In brief, U–Pb data for the felsic rocks collectively document discontinuous emplacement of felsic stocks between 238 Ma and 223 Ma. Discrete magmatic pulses are recognized to be granodiorite and quartz monzonite porphyry at 234–230 Ma, and then granite and monzogranite dike at ~223 Ma.

4. Zircon Lu–Hf isotopic characteristics

In situ Lu–Hf isotope analyses were carried out on approximately 160 zircons with concordant ages from various felsic rocks in Yangla ore district and the results are presented in Supplementary Data 3, as well as in Fig. 9. The Lu–Hf analytical points were located at the same spots or in the same growth domains used for U–Pb dating, therefore making it possible to correlate the Lu–Hf isotopic data with the absolute ages (Fig. 9a, b).

The magmatic zircons from the Lunong and Jiangbian granitoids have relatively similar εHf values (−3.2 to +1.7 with avg. −0.7 for Lunong granitoid, −2.8 to +0.7 with avg. −0.9 for Jiangbian granitoid) at the time of crystallization, with single- and two-stage Hf model ages ranging from 0.81–1.01 Ga and 1.15–1.47 Ga for the Lunong granitoid, and 0.85–0.98 Ga and 1.22–1.43 Ga for the Jiangbian granitoid. Zircons from the dioritic enclaves yield a range of εHf from −5.3 to +1.9 with an average εHf of −1.5, and Hf model ages 0.81–1.09 Ga and TDMC = 1.15–1.61 Ga. The zircons from the granite yield εHf values of −5.9 to +0.3, with an average of −2.4, and scattered Hf model ages of 0.87–1.12 Ga and 1.24–1.63 Ga.

Zircons from the monzogranite dike also show identical spectrum of εHf values of −3.3 to +1.4 (avg. −1.5) and have Hf model ages of 0.82–1.00 Ga and 1.17–1.47 Ga. Those from the quartz monzonite porphyry exhibit slightly lower εHf values of −9.2 to −2.6 (avg. −4.5) and Hf model ages of 0.92–1.21 Ga and 1.33–1.79 Ga. The barren quartz monzogranite porphyry exhibits slightly lower zircon εHf values of −8.0 to −2.6 (avg. −4.8) than those of the mineralized one of −9.2 to −0.9 (avg. −4.1). The inherited zircons with a 2418 Ma age have an εHf of 6.8, and single- and two-stage Hf model ages of 2480 and 2518 Ma, respectively.

5. Discussion

Structural, chemical, and isotopic measurements have suggested that a single pluton is built up by a long succession of discontinuous inputs of magma (Vignerasse, 2007). Numerous magma chambers are open systems that receive more primitive magma in multiple pulses. The multiple pulses of magma may reflect different or similar source regions and (or) physical–chemical conditions under which the magmatic system formed, and these significantly impact the evolution of the magmatic chambers and the magmatic-hydrothermal system.

5.1. Timescales of magmatic activity

Integration of all geochronological information, including our new zircon U–Pb ages for ten representative samples from the studied magmatic system, the 222 Ma emplacement age of the diabase dike (Wang et al., 2010), and other zircon U–Pb ages for granodiorites published previously (Wang et al., 2010; Zhu et al., 2011; X.A. Yang et al., 2012), illustrates that the magmatic activity lasted for about 24 Myr, from approximately 238 to 214 Ma (Fig. 10).

TheMLME, quartz monzonite porphyry, and post-mineralized granite and monzogranite dike crystallization ages are first published in this present study. The data indicate that crystallization of both MLMEs and host granodiorites are coeval and range from 238 to 230 Ma. The Beiwu granodiorite stock, outside our study area, with a SIMS zircon U–Pb date of 234 Ma (Zhu et al., 2011) is inconsistent with the LA-ICP-MS zircon U–Pb date of 214 Ma (Wang et al., 2010). This may be caused by different sampling locations that reflect multiphase emplacement (Fig. 2). The ages for the quartz monzonite porphyry are 232 Ma and 234 Ma, indicating that its emplacement was synchronous with that of the granodiorite stock. In addition, two older xenocrystic zircons from the quartz monzonite porphyry show U–Pb ages of 2418 and 2537 Ma, thus suggesting the responsible magma assimilated crust component comprising of Paleoproterozoic and Neoproterozoic material. Previous workers argued that the granite crystallized during the Yanshanian epoch (Zhu et al., 2009), which is inconsistent with the crystallization age of 224 Ma obtained herein. The studied granodiorite displays three age populations for the zircon grains (Fig. 9b), with 90% in the oldest group crystallizing at 238–230 Ma. The two groups of younger Concordia ages are ~220 Ma (5%, identical crystallization age to GV and WG) and ~214 Ma (5%, comparable crystallization age of Beiwu stock in Yangla district, Wang et al., 2010)). These characteristics may indicate a diversity of magma plumes into the magma chamber, as the Hf isotopic compositions for both young and old zircons are similar and homogenous, which therefore precludes isotopic disequilibrium or zircon inheritance from host rocks.

In summary, an earlier major magmatic event (238–230 Ma) in the ore district is related to granodiorite, MME, and quartz monzonite porphyry formation. The later monzogranite dike was emplaced at 223 Ma after the nearly complete solidification of the current exposed granodiorite magma, contemporaneously with granite crystallization at 224 Ma. The age of 214 Ma (LA-ICP-MS zircon U–Pb) for Beiwu granodiorite (Wang et al., 2010) may be caused by multiphase emplacement.

5.2. Magma source and assemblage sequence

5.2.1. Magmatic source

According to Rubatto and Herrmann (2003), zircon is expected as a residual phase even after melting of subducted sediments under mantle conditions. The Hf isotopic ratios of zircons from the parental melts are difficult to change after the system is closed, even if it experiences partial melting or fractional crystallization (Bolhar et al., 2008). The wide range of εHf values defined for the individual felsic rocks is reconciled by the operation of open system processes that are capable of shifting 176Hf/177Hf ratios of the melt from which the zircon precipitated (Kemp et al., 2007).

Generally, the granodiorite, granite, and monzogranite dike share similar TDMC model ages of 1.1–1.6 Ga and εHf values ranging from −5.9 of +1.7, suggesting that Yangla felsic magmas are mainly derived from a heterogeneous source possibly consisting of an ancient component with negative εHf and a juvenile component with positive εHf. Because of the rare exposure of the Qamdo–Simao basement, studies of the basement need to rely on the geochemical and isotopic data from crustally-derived granitoids and the associated western Yangtze Block. As described above, both the basement and lower Paleozone sequences in the Qamdo–Simao terrane show similar lithologies to those of the Yangtze Block (Zi et al., 2012a), Precambrian basement, including minor
Mean $^{207}\text{Pb}/^{235}\text{U}$ weight age of 17 spots = 230±1.9 Ma, MSWD=3.1

Concordia Age of 24 spots = 232±0.5 Ma, MSWD=0

Concordia Age of 20 spots = 233±0.4 Ma, MSWD=0.18

Concordia Age of 19 spots = 239±0.4 Ma, MSWD=1.8

Concordia Age of 17 spots = 232±0.51 Ma, MSWD=0.13

Concordia Age of 13 spots = 234±0.6 Ma, MSWD=6.9
Paleoproterozoic strata, Mesoproterozoic and Neoproterozoic strata, and Neoproterozoic igneous rocks, are widespread in the Kangdian region of the western Yangtze Block (Greenstreet et al., 2006). The western Yangtze Block basement has experienced numerous Precambrian tectonomagmatic and metamorphic events at 2.7–2.6 Ga, 2.5–2.4 Ga, 2.0–1.9 Ga, 1.1–1.0 Ga, and 910–720 Ma (Greenstreet et al., 2006; Li et al., 2009; Zhao et al., 2012; Wang and Zhou, 2014). However, the Hf crustal model ages (1.1–1.6 Ga) of the felsic rocks do not correspond to any significant igneous events in Yangtze Block (X.M. Liu et al., 2008). Neoproterozoic mafic rocks from the western Yangtze Block generally exhibit positive zircon εHf(t) values (0–12, Fig. 9a), indicating addition of juvenile material to crust at that time (Zhai et al., 2008). The Hf isotopic compositions of the granodiorite, granite, and monogranite dike fall within the range of Neoproterozoic mafic rocks calculated at 230 Ma (Fig. 9a), suggesting that a significant proportion of Neoproterozoic crustal materials had been involved in their formation.

As shown in Fig. 9c, εHf values of the zircon grains have a positive correlation with Th/U ratios, with the Th/U ratios being proxies for the degree of differentiation (Kemp et al., 2007). The positive correlation between εHf and Th/U ratios is evidence for a progressive reduction in the 176Hf/177Hf ratio during evolution of the magmatic suite. Similar to the classic I-type granites of eastern Australia (Kemp et al., 2007), such reduction may be induced by addition of continental-crust components. Thus, trace element microanalyses and Hf isotope signatures reveal that the magmatic system increasingly assimilated a crustal component throughout its evolution. The most likely assimilated crust materials are supported by the two rare xenocrystic zircons observed in the quartz monzonite porphyry. They are analyzed to be Paleoproterozoic and Neoarchean in age and characterized by high εHf values, suggesting that the melt of the quartz monzonite porphyry assimilated with crustal component comprising early Paleoproterozoic or Neoarchean igneous rock. Xenocrystic cores have only been found in some crystals from the quartz monzonite porphyry that were sampled from the Linong deposit, with the cores from two spot analyses showing oscillatory magmatic zoning with thin rims. The internal structures of the zircons studied here could indicate an igneous rock source, whereas local resorption zones disrupting the oscillatory zoning (Fig. 5e) may be the product of corrosion of zircon grains when they interacted with the hotter magma. Meanwhile, the εHf values of the zircons in the quartz porphyries are more crustal, whereas εHf values for other types of felsic rocks tend to be more primitive. The above information indicates that the magmatic system dissolved an increasing and eventually significant amount of crustal material.

In conclusion, the Hf isotopic data of the felsic magmatic system indicate the Neoproterozoic crustal source mixed with subordinate mantle components (Fig. 9), which is also supported by the occurrence of MMEs in the granodiorite. The magma from which the quartz monzonite porphyry crystallized was derived from a mixed source which needed an additional Paleoproterozoic crustal component (>1.6 Ga). This suggests a major episode of crustal growth in Neoproterozoic time and remelting of the crust in Middle–Late Triassic time. This also supports the view that voluminous high-K calc-alkaline magmas are generated by remelting of the lower crust in post-collisional regimes (Zhu et al., 2011).

5.2.2. Assemblage sequence

5.2.2.1. MME and host granodiorite. It is widely accepted that the MMEs are the product of mixing of mafic and felsic magmas, although at least four hypotheses for the process have been proposed as follows: (1) altered xenoliths from wall rocks; (2) residual source material (Chappell et al., 1987); (3) early cumulate from a common parent magma (Dahlquist, 2002); and (4) mixing of coeval mafic and felsic magmas (Frost and Mahood, 1987; Barbarin, 2005). The MMEs and host rocks were coeval. The extremely rare observation of inherited zircons during this study suggests little reaction between magma and wall rocks, thus precluding the origin of altered xenoliths from wall rocks. Zircons from the granodiorite and MMEs yield similar chondrite-normalized REE patterns, indicating the magmatic origin. The MMEs hosted by the granodiorite are generally of a magmatic origin and do not show cumulate textures, implying they existed in a liquid state in the magma chamber. This observation rules out hypothesis 2. Absence of cumulate textures in MMEs makes the accumulation mechanism less likely. The MMEs commonly occur in the granodiorite, show weak quenching boundaries, and share similar accessory mineral (e.g., zircon) sizes with the host phase. Furthermore, only slight differences in the calculated crystallization temperature and oxidation state of the MMEs and host rocks are observed. Zircons from the two studied MMEs share similar εHf values with those of the host granodiorite (Fig. 9). Similar features are also reported in Gushan granite in the eastern North China Craton (Li et al., 2012), the Meiwu batholith in the western Qinling orogen (Luo et al., 2015), and the Los Pedroches granodiorite in Spain (Donaire et al., 2005). The aforementioned phenomenon underpins a cognetic relationship or near complete isotopic equilibrium between the MMEs and granodiorite. Because zircon in the initial mafic magma is not a stable phase, it will begin crystallization when considerable chemical equilibrium results in an increase of silica and zirconium. Furthermore, isotopic equilibrium is acquired more rapidly than chemical equilibrium (Lesher, 1990, 1994) and thus results in a similar Hf isotopic composition of zircons in dioritic enclaves and granite. Similar to the model proposed (Li et al., 2012; Luo et al., 2015), the dioritic enclaves in the granodiorite are therefore more likely representative of the remnants of the mafic component injected into the felsic magma, via a process in which droplets of hot magma (the mafic component) shrink to form a round or elliptical enclave due to the temperature difference (Sparks and Marshall, 1986).

5.2.2.2. Granodiorite and quartz monzonite porphyry. Two pairs of differentiation indices, Th/U and Zr/Hf, were employed to track compositional changes and assess the degree of differentiation of various types of magmas in the Yangla magmatic system. The Zr/Hf ratio of the residual melt may be reduced by fractional crystallization of metastable and peraluminous granitic melts from which the zircons crystallized, and thus can also be utilized to indicate the degree of differentiation during magmatic evolution (Linnen and Keppler, 2002; Clai borne et al., 2006). A plot of Th/U versus Zr/Hf for the studied zircons (Fig. 6e) reveals a good correlation as both ratios decline with progressive magmatic evolution, implying the magma which resulted in the formation of quartz monzonite porphyry is a later and more evolved melt stage compared to the granodiorite. The evolving pattern envisaged above can be further supported by the elevated LREE and HREE contents of the studied zircons from granodiorite and quartz monzonite porphyry. The HREE/LREE enrichment was evaluated by the (Yb/Sm)N values. The extreme HREE enrichments of early magmatic zircons in granodiorite illustrate that they crystallized as the first major REE acceptor from a silicic melt. As seen in the diagrams for Ce/Nd versus (Yb/Sm)N (Fig. 6f), the HREE relative to LREE enrichment decreases systematically from granodiorite to quartz monzonite porphyry (although overlaps in Fig. 6f), showing an evolutionary process from early to later magmatic stage.

5.2.2.3. Granite and monzogranite dike. The latest magma pulse was associated with crystallization of the monzogranite dike and granite, sharing comparable chondrite-normalized REE pattern (not shown) and zircon Hf isotopic characteristic with granodiorite which suggest identical magma source with granodiorite.
5.3. Magma recharge: evaluation from T-fO2 crystallization conditions

5.3.1. Crystallization temperature

The amount of titanium incorporation in the zircon crystal structure is primarily influenced by temperature and activity of TiO2 and SiO2 (Watson and Harrison, 2005; Watson, 2006; Ferry and Watson, 2007). The concentration of titanium in zircon can thus be employed to estimate the temperature of zircon crystallization if the TiO2 and SiO2 activities in the melt are well constrained, although the Ti-in-zircon thermometer exhibits moderate pressure dependence (Ferry and Watson, 2007; Ferriss et al., 2008). Furthermore, the experimental calibration is for a pressure of 1 GPa (10 kb) for well characterized natural samples (Claiborne et al., 2010a, 2010b), whereas the zircons studied herein crystallized over a limited range of pressure (1.3–1.7 kb, granodiorite magma).
emplacement pressure, estimated from amphibole-pressure calibration, Supplemental Data 4), therefore enabling us to neglect pressure effects. The relatively accurate assessment of the activities is critical in calculating the temperatures of melt from which zircon crystallized. The magmas in this study are SiO$_2$ saturated and coexisting Ti-bearing phases (ilmenite presented in granodiorite) indicate αTiO$_2$ is not low (Hayden and Watson, 2007). They are thus assigned an activity of TiO$_2$ of 0.7. The calculation reveals that the zircons in all igneous rock types have a model temperature range of 615–775 °C, with average crystallization temperatures of approximately 650 °C (Table 1), which is consistent with near-eutectic temperatures close to the solidus of hydrous granite (Fig. 11a). It is notable that the crystallization temperatures of monzogranite dike and granite are slightly higher than those of most granodiorite samples (Table 1).

As seen from our study, the Th/U and Zr/Hf ratios and Th content of zircon increase gradually but not obviously with increasing Ti-in-zircon model crystallization temperature (Fig. 11a–c), and the negative correlation between Hf content and the temperature, as documented by other workers (Li et al., 2014; Dilles et al., 2015), is lacking (Fig. 11d). The systematic correlations between differentiation parameters with model temperature are not totally consistent with magma fractionation during cooling in a stable silicic magma chamber (Ballard et al., 2002; Claiborne et al., 2010b; Wang et al., 2013; Dilles et al., 2015) where the Ti-in-zircon temperature cannot increase positively with Hf contents and Th/U will decrease with Hf contents, which may indicate thermal perturbation (e.g., magma recharge) rather than an undisturbed parental magma reservoir. Normally, a single magma body cannot stay molten for more than a few Myr and kept it cooling slowly, which can explain the intrusive units bracketing a larger time span of ca. 24 Myr.

5.3.2. Relative oxidized state

The Ce$^{4+}$ ion displays a radius (0.97 Å) closer to Zr$^{4+}$ (0.84 Å) and Hf$^{4+}$ (0.83 Å) compared to Ce$^{3+}$ (1.143 Å) and neighboring La$^{3+}$ (1.16 Å) and Pr$^{4+}$ (1.126 Å) (Shannon, 1976). Zircon, therefore, commonly exhibits a positive Ce anomaly because Ce$^{4+}$ is more compatible than Ce$^{3+}$ in zircon. The magnitude of Ce anomalies in zircon can be utilized to evaluate oxygen fugacity. However, spectroscopic measurements of Ce$^{4+}$/Ce$^{3+}$ have not been successful because the ratio of $10^{-3}$ is so low, and the La and Pr abundances in magmatic zircons are commonly close to the limit of detection, hindering the accurate determination of the Ce anomaly. Meanwhile, tiny melt or apatite inclusions in zircon may affect determination of La contents and lead to the inaccurate results, in which the highly variable La contents are the cause of the apatite inclusions that lead to the problem. The log$_{10}$ Ross FMQ calculation using La–Ce–Pr contents in zircons, as suggested (Trail et al., 2011, 2012) to be possibly unrealistic (Wang et al., 2013) and therefore is not solely used here. Instead, Ce/Nd ratios could replace the Ce anomaly to assess the oxidation state of melt from which the zircons crystallized because Nd concentrations can be determined more accurately and precisely than La and Pr (Chelle-Michou et al., 2014). Both methods were applied for comparison in this study and show a positive scattered trend, then favor the application of Ce/Nd ratios (Fig. 12a). Another potential parameter evaluating the oxidation state of a melt, the zircon Eu/Eu* ratio, can be accurately calculated because Sm, Eu, and Gd are relatively abundant in zircon and these elements can be examined using LA-ICP-MS. However, variability in this ratio is affected by both the redox state of the magma and the crystallization of plagioclase. The Ce/Nd versus Eu/Eu* diagram (Fig. 12b) for all analyzed zircons does not show an ideal positive correlation that would be expected if both are simply controlled by the oxidation state during zircon crystallization in an undisturbed and progressively oxidized parental magma reservoir (Ballard et al., 2002; Claiborne et al., 2010b; Wang et al., 2013; Dilles et al., 2015). This leads us to conclude that Ce/Nd (Ce/Ce*) is more sensitive to the relative oxidation state and is the better approach for evaluation of the oxidation state of the magma. The Ce/Nd values of zircons show a slightly decrease from granite and quartz monzonite porphyry (Fig. 6f), which indicates

Fig. 11. Summary of results from Ti-in-zircon geothermometry (abbreviated as T as following, °C) from zircons in diverse intrusive phases. (a) Th/U vs. T; (b) Zr/Hf vs. T; (c) Th vs. T; (d) Hf vs. T.
that they are relatively reduced compared to the dioritic enclave and granodiorite.

Generally, the wide variation for Ce/Nd values at any given HF concentration (Fig. 12c) indicates a variable oxidation state of the magmatic system throughout its evolution. The wide constant scattered Ce/Nd and slight decrease of Eu/Eu* with Hf contents (Fig. 12c, d) are contrasted with the zircons from the progressive oxidation of the magma during magmatic processes (Ballard et al., 2002; Claiborne et al., 2010b; Wang et al., 2013; Dilles et al., 2015). In addition, the fact that Eu/Eu* values decrease with increasing magmatic fractionation may not only be controlled by the plagioclase fractionation but also influenced by the injection of reduced melts into the magma batch (Simmons, 2013). In conclusion, the exposed Yangla magma system was once being influenced by its hidden intrusive portion. The injected pulses of reduced melt into the hidden intrusive portion cause thermal perturbation and lead to crystallization of the granite and associated monzogranite dike (with higher Ti-in-zircon crystallization temperature) which derived from the identical source region with the granodiorite.

5.4. Implications for metallogenesis

5.4.1. Tectonic setting

Even though the western Jinsha Ocean slab is thought to continue to subduct during Late Triassic based on studies of the Haxiu quartz diorite and the Yushu volcanic rocks (T.N. Yang et al., 2012), extensive studies have suggested the initial collision of south Jinshajiang suture took place during or before the Early Triassic (Jian et al., 2009a; Zi et al., 2013; Wang et al., 2014). Recently, many studies support either the collisional or post-collisional setting (Zhu et al., 2011; Zi et al., 2013) for granodiorite emplacement in the Yangla ore district along the south-Jinshajiang belt, rather than a pre-collisional convergent subduction-related environment (Yang et al., 2011; X.A. Yang et al., 2012; Yang et al., 2013b). Felsic magmatic rocks (granodiorite, monzogranite, and granite) formed from 238 to 223 Ma in our studied area have been shown to share identical tectonic provenance and magma source regions (Fig. 9). On the Rb vs. Y + Nb tectonic discrimination diagram (not shown) (Pearce, 1996), data for these Yangla felsic rocks plot in a post-collision granite, suggesting a post-collisional tectonic affinity.

The Jinshajiang–Ailao Shan Paleo-Tethys Ocean basin reached its peak extent in Late Carboniferous to Early Permian (Sun and Jian, 2004), and then began to close through westward consumption of the ocean floor beneath the Qamdo–Simao terrane throughout the remainder of the Permian (Wang et al., 2000; Jian et al., 2008; Zi et al., 2012b). The subduction process ceased at the start of the Triassic, just prior to final collision between the Yangtze block and Qamdo–Simao terrane, and this is reconciled with the change in tectono-sedimentary facies, regional metamorphism, and the bimodal volcanism (Zi et al., 2013). The widespread mafic–felsic bimodal volcanic rocks were thought to have formed through crustal anatexis in collision-related settings (Mo et al., 1993; Hou et al., 2003; Wang et al., 2014). The timing of collision between the Qamdo–Simao terrane and Yangtze Block has been established as ca. 247–237 Ma by SHRIMP U–Pb dates for the associated bimodal volcanic rock suite (Zi et al., 2012c; Wang et al., 2014). Subsequently, the ophiolite zone was unconformably overlain by Late Triassic Molasse. Furthermore, synorogenic granitoids, such as the Xumai and Zhongmu granites, were emplaced along the orogenic belt in Late–Middle Triassic (Wang et al., 2000). The evolved, high-K calc-alkaline plutons, such as the Ludian and Jiaren granitoid batholiths, were emplaced later during the transition from compressional to extensional regime associated with the late- or post-collisional tectonism (Zhu et al., 2011; Zi et al., 2013). Types of plutons are typical of those that form in post-collisional settings driven by sustained oblique convergence (Bonin, 1990, 2004), indicating an early tectonic collapse and thermal relaxation in a post-collisional setting (Mo et al., 1993; Zhu et al., 2011; Zi et al., 2013). The abrupt change from Carboniferous–Permian volcanic sedimentary basin facies to Upper Triassic shallow marine sedimentary facies, and the absence of Early to Middle

![Fig. 12. Compositional variations within zircon crystals illustrating the oxygen fugacity are plotted.](image-url)
Triassic rocks within this area indicate uplift and extensive erosion in the earlier Triassic.

5.4.2. Generation of the post-collisional fertile melt

Remelting of ancient subduction-modified arc lithosphere commonly suggests the process for generating intrusion-related Cu mineralized systems in continental collision regimes (Richards, 2009). Causative felsic magmatism plays a role in transferring metal and sulfur from the thickened lower crust to the overriding upper crust. The or-forming magma exhibits Hf isotopic characteristics which are remarkably different from the Triassic subduction-associated Baimaexueshan granodiorite along Jinshajiang belt and similar to the Neoproterozoic mafic rocks in Yangtze Block (Fig. 9a). The hydrous lower crustal cumulates residual from prior arc magmatism (Richards, 2009) are thus more likely derived from Neoproterozoic oceanic subduction rather than the Jinshajiang Triassic subduction (Fig. 14a), where a slab-derived fluid metasomatized the subcontinental lithospheric mantle beneath the Yangtze Block (Wang et al., 2009). The Neoproterozoic VMS-type Cu deposits (e.g., the Xiqiu and Pingshui deposits) occur in the Shuangxiwu Group which is thought as the product of the Neoproterozoic arc magmatism along the margin of Yangtze Block (Li et al., 2010; Mao et al., 2011). Their occurrences suggest the potential of Neoproterozoic lower arc crustal rocks supplying the copper sources without major contribution from the mantle in Triassic. In addition, the source of the Yangla felsic system is similar to that proposed for the Beiya Cu–Au skarn deposit (Lu et al., 2013), indicating that residual sulfides had been left at the base of the crust by arc magma in the Neoproterozoic (Fig. 9a). The arc magma generated during the subduction process was enriched in metals (e.g., Cu) and S, and had a relatively high oxygen fugacity and high water content (Kelley and Cottrell, 2009). Remobilization of the chalcophile elements left as residues in deep Neoproterozoic crustal hydrous arc cumulates in Late Triassic or Cenozoic, potentially provide the copper sources for the intrusion-related Cu ± Au deposits along the Jinshajiang–Ailaoshan suture zone.

Intrusion-related Cu mineralization, typically expressed as porphyry Cu deposits or related skarns, is generally associated with evolved intermediate to felsic calc-alkaline intrusions that are highly oxidized, hydrous, and rich in sulfur (Richards, 2003; Sillitoe, 2010). A high oxidation state of the felsic magma ensures that sulfur is dominantly present as sulfate, which suppresses the separation of Cu-sulfide melts (Spooner, 1993; Zajacz et al., 2013) and ultimately results in Cu enrichment in the upper crustal intrusion-related mineralization. The $f_{O2}$ of the Linong granodiorite stock, determined using the amphibole oxygen barometer (Ridolfi et al., 2010), is $\Delta$NNO (Supplementary Data 4) and indicates a relatively oxidized granodiorite magma. High oxidation state and high H$_2$O content of the magma are deemed to be responsible for such Cu mineralization (Ishihara, 1977; Richards, 2003; Sun et al., 2013; Zajacz et al., 2013), but the former is secondary to the requirement of sufficient water in the melt (Richards, 2011). The evolved and hydrous melts have densities that allow them to rise into the upper crust and exsolve an aqueous volatile phase. The melts from which the granodiorite crystallized appear to be hydrous on the basis of mineralogy (≥2.5 wt.% H$_2$O for rocks with biotite, and ≥4 wt.% H$_2$O for rocks with amphibole; Naney, 1983)). The H$_2$O-in-melt calculated using the chemometric empirical equation of Ridolfi and Renzulli (2012) is >6.0 wt.% (Supplementary Data 4). Numerical batch-melting modeling (Fig. 13) of a basaltic source with variable mineralologies was conducted using the geochemical data of granodiorite phases from Zhu et al. (2011), to reflect the mineralogy of a fertile reservoir in lithospheric roots and estimate arc crustal thickness (pressure and depths). Low degree partial melting (5–10%) of a garnet-bearing (up to 5%) basaltic amphibole source, and the lack of plagioclase as a residual mineral, followed by low-level amphibole crystallization and fractionation, can explain the higher La/Yb ratios of the Linong granodiorite. The high water content (>6%) of the melt may be caused by increasing availability of water in the lower crust by dehydration melting during crustal thickening. During the process, the water in the melt increases by successive breakdown of amphibole (Tepper et al., 1993). The La/Yb–Yb plot also indicates that the arc crustal base had already reached a pressure of >12 kbar, corresponding to maximum crustal thickness of 40–45 km (Rapp and Watson, 1995), which resulted from the collision between Yangtze Block and Qamdo–Simao terrane.

Melting of the thickened lower arc crust requires an additional heat from the mantle caused by asthenospheric upwelling following thinning of mantle lithosphere (Thompson and Connolly, 1995; Pettford et al., 2000), because the production of felsic melt in lower arc crust needs higher temperatures than the breakdown temperature of amphibole (>1050 °C; Peacock et al., 1994; Rapp and Watson, 1995)) to allow separation of the melt from the amphibole and garnet residues (Bissig et al., 2003). Slab breakoff or lithospheric delamination was invoked as possible triggers for the heat for post-collisional magmatism (Wortel and Spakman, 2000; Keskin, 2003; Bonin, 2004). The two mechanisms result in distinct surficial landscapes. Lithospheric delamination produces a broad region of magmatism and uplift above the

![Fig. 13](image-url)
5.4.3. $f_{O_2}$ relationship between the deep-seated pluton and shallow porphyry dikes

The precursor plutons are considered as the middle to upper crustal crystallization sites of mafic to felsic magmas that ascended from deeper reservoirs before porphyry Cu systems were developed (Richards, 2003; Sillitoe, 2010). The composite precursor plutons within porphyry Cu systems tend to lie at inaccessible depths. Only in a few porphyry districts, such as the Globe-Miami, Chuquicamata, and Cadia districts, can the precursor plutons be observed. However, the relationship between different igneous bodies in these districts, particularly the change in $f_{O_2}$, is poorly recorded. The coexistence of the granodiorite and quartz monzonite porphyry dikes in the Yangla ore district (e.g., Linong, Jiangbian, and Lunong stocks and porphyry dike swarms) is another example that can give us insight into the change of $f_{O_2}$ from composite precursor pluton to related porphyry–skarn system.

The quartz monzonite porphyry resulted from residual melts for granodiorite (Li et al., 2013), as revealed by lowering of the Zr/Hf and Th/U ratios of the zircons than those of the granodiorite. The εHf values decrease from the granodiorite (−0.9 to −0.6), to the mineralized quartz monzonite porphyry (−4.1), and then to the barren quartz monzonite porphyry (−4.8). The decreasing trend is similar to that for the $f_{O_2}$ of the corresponding rocks. The average Ce/Nd values of granodiorite, and mineralized and barren quartz monzonite porphyry are 8.8, 4.7, and 3.7, respectively, indicating a consistently more reduced phase of the magma. The process may be ascribed to the incorporation of a crustal component (Ripley and Li, 2013) which involved sediments with variable water content and oxygen fugacity. For example, the terrigenous sedimentary rocks may exert a great influence on the oxygen fugacity, because of the low Fe$^{3+}$ and/or organic carbon content of the sediments that were assimilated during ascent of the melt that formed the quartz monzonite porphyry. The anhedral xenocrystic zircons and the lower εHf values of magmatic zircons identified in the porphyry support this scenario, although the source of the xenocrystic zircons cannot be distinguished. The incorporation of the crustal component may be the primary factor, at least in part, causing the diverse magma $f_{O_2}$ and ore-affiliation of porphyry Cu–Au stocks or dikes during the timescale of an evolving magmatic system.

Fig. 14. Schematic cartoon cross-sections illustrating the proposed petrogenetic model of the Yangla felsic magmatic system. (a) Subduction-induced mantle metasomatism at 1100–900 Ma and subduction-related magmatism during underplating of the lower crust of the Yangtze Block. Slab-derived fluids metasomatized the Yangtze subcontinental lithospheric mantle. Modified from Wang et al. (2009). Sketch not to scale. (b) Cartoon cross-section showing the tectono-magmatic activity during the post-collisional phase of the jinshajiang orogenic belt, modified from Zi et al. (2013). Sketch not to scale. (c) Cartoon crustal section illustrating the formation of the Yangla magmatic system. Magma pools of variable sources in the lower crust comprising the Neoproterozoic hydrous cumulate arc creating the “Lower Crust Hot Zone” (Annen et al., 2006). The crystallized mafic magma is hybridized with crustal melt yielding the granodiorite, MME, quartz monzonite porphyry, monzogranite dike and granite.
6. Concluding remarks

(i) Our zircon U–Pb ages confirm that the felsic intrusive phases in the Yangla ore district were emplaced from 238 to 223 Ma, corresponding to a post-collisional tectonic regime. Two epochs of felsic magmatic activity are recognized: (1) an early stage (238–230 Ma) forming micro-granular dioritic enclaves, granodiorite, and quartz monzonite porphyry and (2) a late stage (224–223 Ma) of granite and monzogranite dike.

(ii) The MMEs are remnants of the mafic melt injected into the granodiorite-forming felsic magma. The granodiorite, monzogranite dike, granite, and quartz monzonite porphyry share an identical magma source fingerprint defined by a uniform Hf isotopic composition, in which εHf values of the quartz monzonite porphyry are more crustal. The rocks are derived from a Neoproterozoic lower arc crust. The data show a remarkably homogenous Hf isotopic composition over a period of more than 15 Myr, indicating a stable and long-lived hot reservoir in the deep lithosphere.

(iii) The zircons qualitatively describe an evolutionary trend towards a more differentiated composition from granodiorite to quartz monzonite porphyry, and this trend is accomplished by decreasing $f_{O_2}$ as measured by zircon Ce/Nd ratio. Beginning after the crystallization of granodiorite and MMEs, the injection of more reduced magma batches was associated with formation of granite and monzogranite dike.

(iv) The Cu and water of the fertile magmas are mainly sourced from the remelting of the Neoproterozoic lower arc crustal rocks triggered by asthenospheric upwelling. The decrease in $f_{O_2}$ from granodiorite through ore-fertile porphyry to ore-barren porphyry is caused by the incorporation of crustal components into the melt.

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