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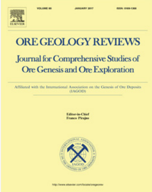

No genetic link between Late Cretaceous felsic dikes and Carlin-type Au deposits in the Youjiang basin, Southwest China

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ABSTRACT

The Youjiang basin in southwest China is distinguished by preserving a number of Carlin-type gold deposits. Tens of felsic dikes occur in this region, and some are present within the ore fields. A genetic link between these felsic dikes and ore-formation has previously been proposed, but detailed field investigation shows that the dikes crosscut the main ore body, and clearly postdate gold mineralization. Three felsic dikes in the Youjiang basin have been dated, and SIMS zircon U-Pb dating results show that the Liaotun and Xiabaha dikes were emplaced at 97.2 ± 1.1 Ma (MSWD = 2.9) and 95.4 ± 2.4 Ma (MSWD = 0.56), respectively, broadly consistent with a LA-ICP-MS zircon U-Pb age for the Bama dike (99.4 ± 0.37 Ma, MSWD = 1.4). Combined with published dates of the other felsic dikes in this region, it is suggested that the felsic magmatic event in the Youjiang basin occurred between ∼100 and 95 Ma. Although a wide range of ages for gold mineralization (275–46 Ma) has been reported by a variety of methods, the best available ages suggest a timing between 235 and 193 (Direct Re-Os dating on Fe-sulfides; Chen et al., 2015, Re–Os isochron ages for arsenopyrite from Carlin-like gold deposits in the Yunnan–Guizhou–Guangxi "golden triangle", southwestern China), significantly older than the emplacement age of the felsic dikes. Taken together, we conclude that there is no genetic link between these Late Cretaceous felsic dikes and Carlin-type Au mineralization in the Youjiang basin.

1. Introduction

Carlin-type Au deposits are characterized by fine-grained disseminated gold mineralization in sedimentary rocks. The type locality is in the Carlin Basin of northern Nevada, but similar deposits also occur in south China, including in the Youjiang basin (Dian-Qian-Gui area; Fig. 1) and the West Qinling belt (e.g. Hofstra and Cline (2000), Hu et al. (2002), Zhang et al. (2003), Cline et al. (2005), Hofstra et al. (2005), Kesler et al. (2005), Peters et al. (2007), Su et al. (2009a), Hu and Zhou (2012), Berger et al. (2014), Hu et al. (2016a,b)). The Carlin-type deposits in northern Nevada have been shown to have Eocene ages ranging from 42 to 33 Ma (e.g. Hofstra et al. (1999), Tretbar et al. (2000), Cline (2001), Arehart et al. (2003)), with a clear spatial and temporal relationship to Eocene magmatism (Henry and Boden, 1998; Ressel et al., 2000; Ressel and Henry, 2006; Johnson et al., 2015). Nevertheless it is debated whether the magmatism provided fluids and metals for gold mineralization, or was simply a heat source driving hydrothermal convection (e.g. Henry and Boden (1998), Cline et al. (2005), Large et al. (2011), Muntean et al. (2011)).

The Carlin-type Au deposits in the Youjiang basin of China share many features with those in northern Nevada (Cunningham et al., 1988; Hu et al., 2002; Zhang et al., 2003; Cline et al., 2005, 2013), but their age is not as well constrained. A wide range of ages from 275 to 46 Ma has been proposed from the dating of various hydrothermal minerals (Table 1; e.g. Hu et al. (1995, 2002), Su et al. (2009b), Chen et al. (2015)). Furthermore, exposures of igneous rocks are rare except for Late Permian diabase (∼259 Ma, zircon U-Pb; Zhang and Xiao, 2014) related to the Emeishan Large Igneous Province (Fig. 1A, ELIP; Xu et al., 2008), and tens of felsic and ultramafic dikes in the southeast and northern parts of the basin, respectively (Fig. 1B; Liu et al., 2010; Chen et al., 2012, 2014). The ultramafic dikes generally occur at least 30 km away from known gold deposits (Su et al., 2009b), and have ages ranging from 88 to 85 Ma (zircon U-Pb; Liu et al., 2010). In contrast, some felsic dikes are present within the ore fields, and limited dating

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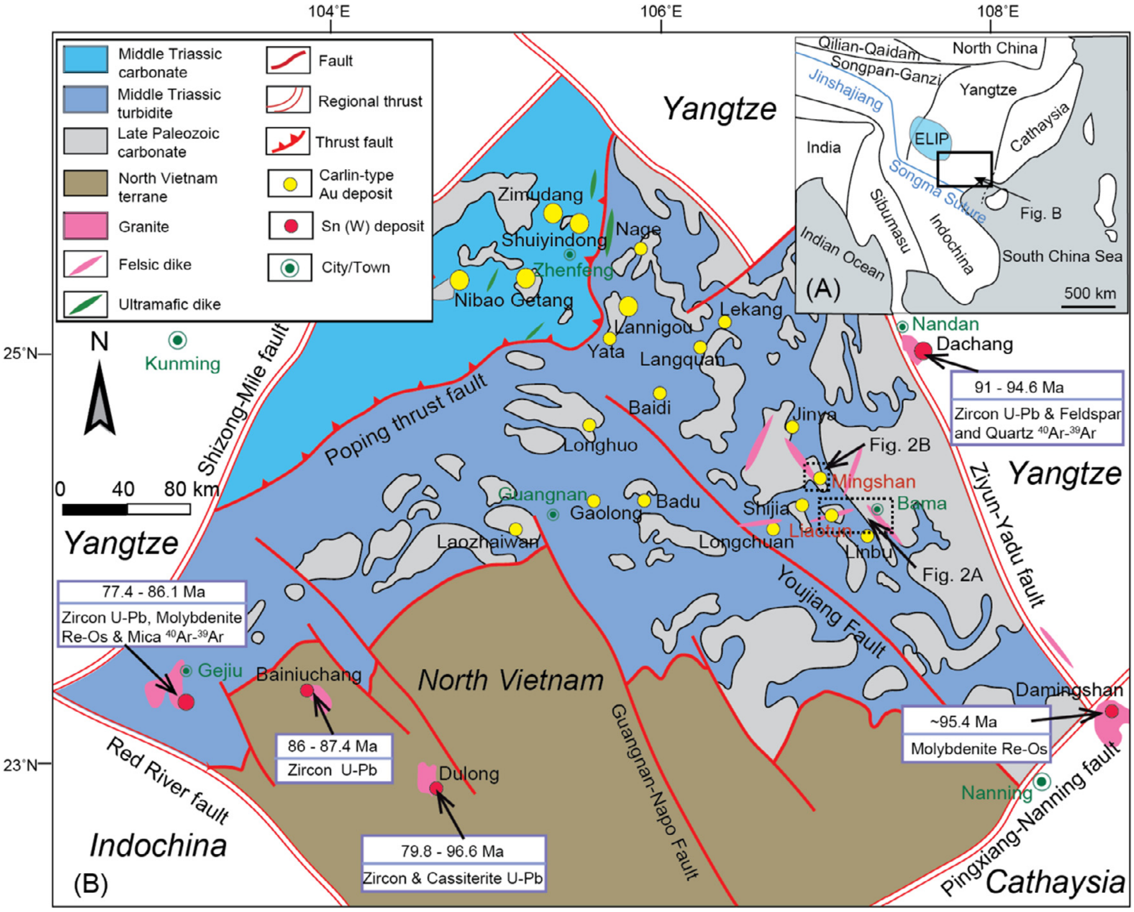

Fig. 1. (A) Regional tectonic setting of the Youjiang basin; (B) geology of the Youjiang basin showing the distribution of Carlin-type gold deposits and igneous intrusions and Sn-(W) deposits around the basin (modified after Cai and Zhang (2009), Hou et al. (2016)). Ages for the Sn-(W) deposits are summarized from Wang et al. (2004), Li et al. (2008), Cheng and Mao (2010), Cheng et al. (2013), Mao et al. (2013), and Xu et al. (2015). Note the dikes are shown schematically, and only the largest are illustrated. The sizes of circles for the Carlin-type Au deposits generally denote the scales of individual mines.

Table 1
Summary of Geochronological results for the Carlin-type Au deposits in the Youjiang basin, southwest China.

Dating Methods	Minerals	Ages (Ma)	Au deposits	References
Electron spin resonance (ESR) age	Quartz	60 & 80	Shuiyindong	Liu et al. (2006a)
		63.4	Yata	Zhu et al. (1998)
		46.0	Getang	
		55.4	Lannigou	
Fission-track age	Quartz	84.5 ± 6.8 & 90.8 ± 6.4	Baidi	Zhang and Yang (1993)
		82.3 ± 7.5 & 83.4 ± 8.3	Lannigou	
Single-stage model lead age	Pyrite & realgar	82–130	Jinya	Li et al. (1995)
	Pyrite	138–275	Gaolong	Li (1990)
		142–266	Jinya	
Rb-Sr isochron age	FIs of quartz & calcite	259 ± 27	Lannigou	Hu et al. (1995)
	FIs of quartz	105.6 ± 4.5		Su et al. (1998) & Hu et al. (2002)
		142 ± 2	Nibao	Liu et al. (2006b)
	FIs of pyrite & arsenopyrite	267 ± 28	Jinya	Wang (1992)
	Sericite	206 ± 12		Li et al. (1995)
^{40}Ar-^{39}Ar plateau age	Sericite	194.6 ± 2	Lannigou	Chen et al. (2009)
		215.3 ± 1.9	Zhesang	Pi et al. (2016)
U-Pb age	Hydrothermal rutile	213.6 ± 5.4	Zhesang	Pi et al. (in press)
Re-Os isochron age	Arsenian pyrite	193 ± 13	Lannigou	Chen et al. (2007)
	Arsenopyrite	204 ± 19		Chen et al. (2015)
		206 ± 22	Jinya	Liu et al. (2014)
		235 ± 33	Shuiyindong	Chen et al. (2015)
Sm-Nd isochron age	Calcite	134 ± 3 & 136 ± 3	Shuiyindong	Su et al. (2009b)
		148.4 ± 4.8	Zimudang	Wang (2013)

Note: FIs = fluid inclusions.

results suggest a Late Cretaceous age (~95 Ma, muscovite ^{40}Ar/^{39}Ar dating; Chen et al., 2012, 2014), which falls within the broad range of reported ages for gold mineralization. Because some of these dikes are reported to be mineralized where they occur in proximity to gold the deposits, a number of authors have proposed a genetic link between these felsic dikes and gold mineralization (e.g. Guo (1994, 2000), Huang and Cui (2001), Ma et al. (2013), Li et al. (2014, 2015)).

In this paper, we evaluate the above hypothesis by dating three felsic dikes in the Youjiang basin, critically assessing published ages for gold mineralization, and evaluating field geological relationships. We conclude that the Late Cretaceous felsic dikes have no genetic relationship to the Youjiang Carlin-type Au deposits.

2. Geological background

The Youjiang basin is located near the southwestern margin of the Yangtze craton (northern part of the South China block), and separated from the Indochina block by the Red River fault to the southwest (Fig. 1; Peters et al., 2007; Hu and Zhou, 2012). It is separated from the Cathaysia block to the southeast by the Pingxiang-Nanning fault, and by the Shizong-Mile and Ziyun-Yadu faults from the Yangtze craton to the northwest and northeast, respectively. The North Vietnam terrane with Precambrian basement lies to the south, in fault contact with the Youjiang basin (Fig. 1).

The Youjiang rift basin formed during the opening of the Paleo-Tethys Ocean in the Devonian, followed by deposition of a carbonate platform and shallow-water facies sediments in the Late Paleozoic (Fig. 1B; e.g. Liu et al. (2002), Du et al. (2013)). In the Middle Triassic, the Youjiang basin became a foreland basin as a result of the closure of the Paleo-Tethys Ocean, and deep-water sediments (siltstone and sandstone turbidites) were deposited on the earlier carbonate platforms (e.g. Liu et al. (2002), Enos et al. (2006)). Bounded by the Poping thrust fault, shallow-marine platform carbonates are locally distributed in the northwest (Fig. 1B), which was considered to be part of the Yangtze passive continental margin in the Middle Triassic (Chen et al., 2011).

The gold-bearing sedimentary strata vary from the Late Paleozoic to Middle Triassic in age, including both shallow- and deep water facies rocks (Hu et al., 2002; Peters et al., 2007; Su et al., 2009a; Goldfarb et al., 2014), and both fault-hosted and stratabound mineralization has been identified (Zhang et al., 2003; Xia et al., 2012). The former is hosted mainly by faults occurring in Triassic clastic rocks including sandstone, siltstone and silty mudstone. In comparison, the stratabound mineralization is mainly hosted by the Late Paleozoic shallow-water facies carbonate rocks. Both NW- and NE-trending folds and faults have been defined in this area (Fig. 1B). Although the exact ages of these structures is uncertain, it is known that both have had a long evolution since the Late Paleozoic, and the NW-trending structures are thought to have formed earlier than the NE structures (Zeng et al., 1995; Liu et al., 2015). The gold deposits are spatially related to anticlines or second-order faults controlled by the regional fault zones, such as the Youjiang fault system (e.g. Hu et al. (2002), Zhang et al. (2003), Peters et al. (2007), Su et al. (2009a), Xia et al. (2012)). In some deposits, gold mineralization was controlled by second-order NW-striking structures and cut by NE-trending faults (e.g., the Lannigou and Zimudang gold deposits; Tai and Li, 2006; Chen et al., 2011).

3. Genetic models

Despite over thirty years of research, there is still no a widely accepted genetic model for the Carlin-type Au deposits in the Youjiang basin of China. Conflicting data regarding the ages and interpretation of isotopic compositions (S, H, O, C, Pb) of these deposits have hindered the development of a common model of ore genesis (Liu and Geng, 1985; Cunningham et al., 1988; Li, 1990; Tu, 1990; Wang, 1992; Zhang and Yang, 1993; Guo, 1994, 2000; Hu et al., 1995, 2002; Su et al., 1998, 2009a,b; Zhang et al., 2003; Liu et al., 2006a; Peters et al., 2007; Chen et al., 2011, 2015; Hu and Zhou, 2012; Hou et al., 2016; Hu et al., 2016a). Three models of deposit formation include: (1) deep metamorphic, meteoric, or basin fluid convection, with extraction of gold from basement or deep basinal rocks (Liu et al., 2001; Hu et al., 2002; Peters et al., 2007; Su et al., 2009a; Gu et al., 2012; Xia et al., 2012); (2) magmatic models, in which hidden felsic intrusions or epizonal dikes contributed heat to drive hydrothermal convection (Liu et al., 1997; Zhang et al., 2003; Hu and Zhou, 2012), and fluids and metals (Guo, 1994, 2000; Zhu et al., 1997; Huang and Cui, 2001; Liu and Liu, 2005; Liu et al., 2006a; Ma et al., 2013; Li et al., 2014, 2015); and (3) mixed models, wherein metals and fluids were derived from both magmas and sedimentary or volcaniclastic rocks (Zhu et al., 1997; Li et al., 2005; Wang et al., 2010; Han et al., 2011; Zhang et al., 2010; Wang, 2013). Here, we test the evidence in models 2 and 3 for a metallogenic relationship between the felsic dikes and gold mineralization.

4. Field relationships

The felsic dikes occur mainly in the southeast of the Youjiang basin, and were mostly intruded along NW- and NE-trending faults. Many dikes occur far from any known gold deposits, but a few occur within the orefields (Fig. 1). The dikes have widths ranging from 1 to 20 meters, and can extend to 20 km in length, with steep dips (Chen et al., 2012; Zhu et al., 2016).

In this study, we focused on three dikes in the Youjiang basin, two of which (the Liaotuan and Xiabaha dikes) are spatially related to gold mineralization, and the other one (Bama) is for comparison.

The Liaotun felsic dike intruded Carboniferous limestone and Triassic sandstone along an ENE- to NE-trending fault across the Longtian dome (Fig. 2A; Zhu et al., 2016). The main orebody is mostly hosted by the NW-trending fault, but locally extends into the Baifeng Formation wall rocks where they are cut by the fault (Chen et al., 2014). The Liaotun dike can be seen cutting the NW-trending stratiform part of the main ore body in Fig. 4. The Liaotun gold mine was closed and back-filled at 2013, so further investigation of these crosscutting relationships is not possible. The dike is locally mineralized where it contacts the ore body where gold has probably been remobilized from the existing orebody by the heat of intrusion, but it is generally barren. The dikes are leucocratic and porphyritic, with phenocrysts of quartz (10%; 0.2–2 mm) and muscovite (5%; 0.1–1 mm), set in a groundmass of quartz, alkali feldspar, and muscovite. Accordingly, they can be termed quartz porphyries.

The Xiabaha felsic dike extends about 10 km along NW- to NNW-trending faults that cut Carboniferous limestone and Triassic sandstone. The dike cuts across the Mingshan Au field to the southeast (Fig. 2B), which is hosted by a WNW- to NW-trending fault within the Triassic Baifeng Formation (Fig. 3B). The crosscutting relationship between the dike and mineralization is uncertain because contacts are not exposed. The Xiabaha dike is barren and shares petrological features with the Liaotun dike, but muscovite phenocrysts are less abundant (<5%).

The Bama felsic dike was intruded along a NW-striking fault that cuts across the Bama dome and extends for ~10 km (Fig. 2A). It cuts a Late Permian diabase intrusion (~259 Ma, zircon U-Pb; Zhang and Xiao, 2014), as well as Early Permian and Carboniferous limestone strata. There is no gold mineralization in the vicinity of this dike, which has compositions and textures similar to the Liaotun and Xiabaha dikes.

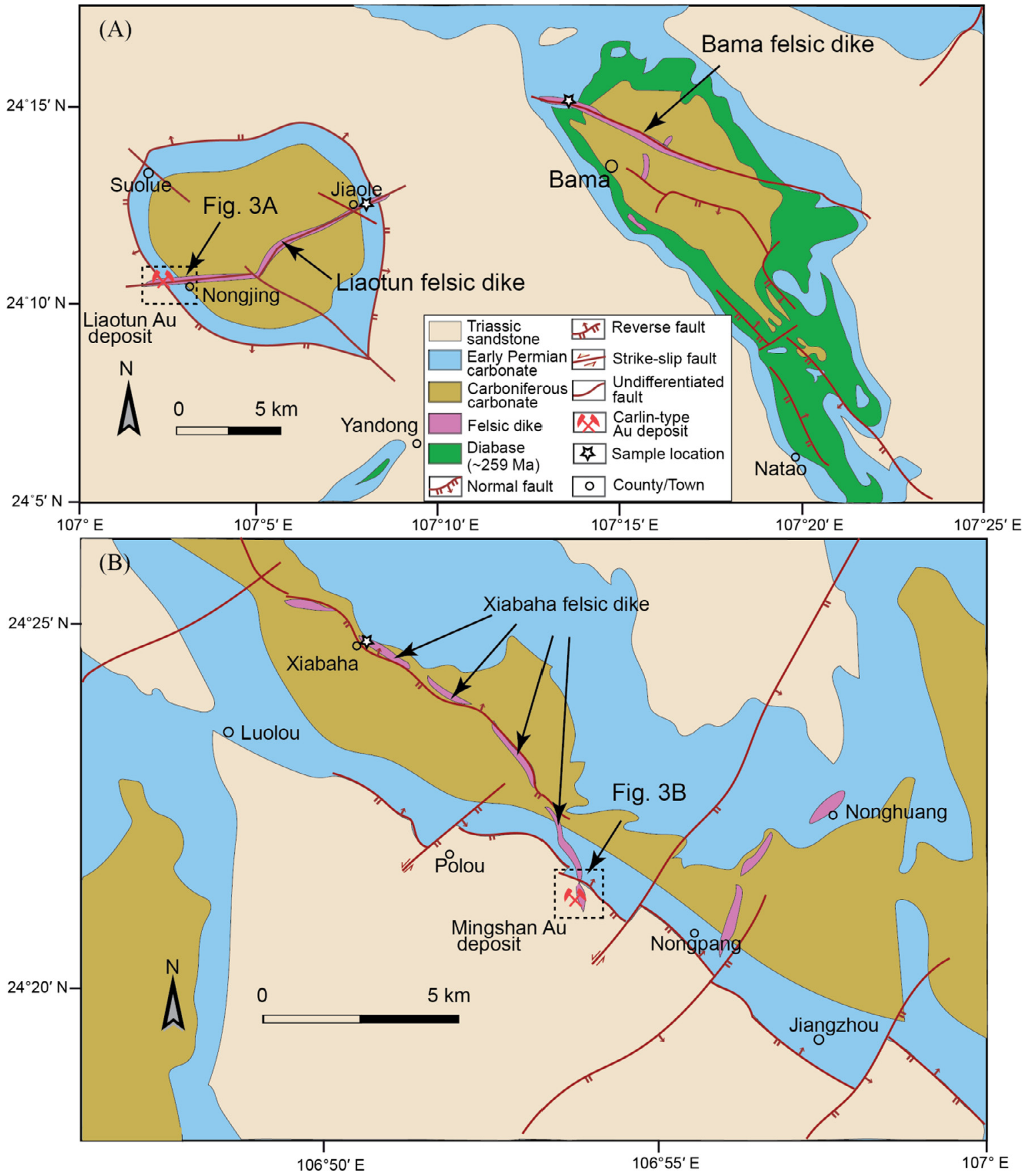

Fig. 2. Geological maps showing the locations of the (A) Bama and Liaotun, and (B) Xiabaha felsic dikes, and their relationship to the Liaotun and Mingshan Au deposits. Simplified after the 1: 200,000 geological maps of Donglan (A) and Tianlin (B) sheets (Regional Geological Survey of BGG, 1971).

5. Samples and zircon U-Pb dating

Zircons were separated from 20 kg samples of the Liaotun (NJ13-01), Xiabaha (XBH13-01), and Bama (BM13-01) dikes by the Chengxin Geological Service Corporation, Langfang, China, using magnetic and heavy-liquid separation methods, followed by hand-picking under a binocular microscope. Selected zircon crystals were mounted in an epoxy resin disc, and then polished to expose the grain mid-sections.

Only a small number of zircon grains were found in the Liaotun and Xiabaha dikes (~90 and ~30 grains, respectively), with diameters of less than 50 μm. Because of their small size and rarity, we used secondary ion mass spectrometry (SIMS; Cameca IMS 1280, at the University of Alberta, Canada) to determine their U-Pb isotopic compositions. In contrast, zircons were much more abundant and larger in the Bama dike (~300 grains, 100–200 μm long, with length-to-width ratios of ~2). U-Pb dating of this sample was conducted by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS: 193 nm GeoLasPro 2005 System and ELANDRC-e ICP-MS) at the State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, China. The detailed analytical methods are presented in Appendix A.

SIMS zircon U-Pb data for the Liaotun and Xiabaha felsic dikes are presented in Supplementary Table A.1. Many of the zircons analyzed are inherited zircon fractions with five groups of model $^{206}Pb/^{238}U$ ages (i.e., 130–140 Ma, ca. 242 Ma, 400–450 Ma, 700–1000 Ma, and 1700–1800 Ma; Fig. 5; Zhu et al., 2016). Only three

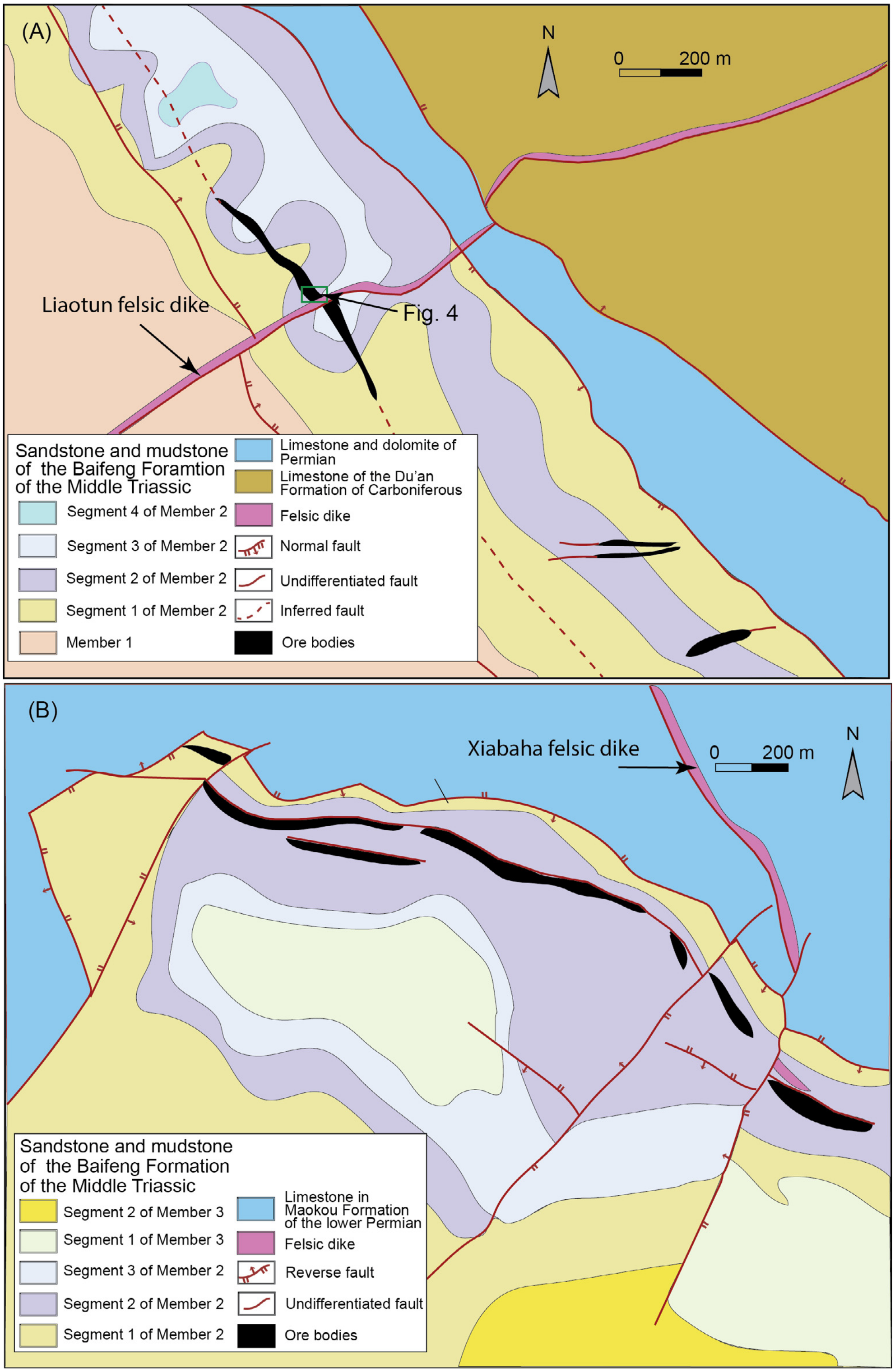

Fig. 3. Geological maps of the (A) Liaotun and (B) Mingshan Au deposits and felsic dikes. Simplified after Chen et al. (2014) and Pang et al. (2014), respectively.

crystals from the Liaotun dike have typical magmatic oscillatory zoning, and yielded the youngest ages, interpreted to be the dike crystallization age. These crystals have high concentrations of U (2079–3446 ppm) and Th (131–1888 ppm), with Th/U ratios of 0.05–0.91, and yielded a Concordia age (Ludwig, 1998) of 97.2 ± 1.1 Ma (2σ, MSWD = 2.9; Fig. 5A), consistent with the weighted mean 206Pb/^{238}U age of 97.3 ± 1.1 Ma (2σ, MSWD = 1.2). This Concordia age is interpreted to best represent the emplacement age of the Liaotun felsic dike.

Only two zircons from the Xiabaha felsic dike sample are interpreted to have crystallized during dike emplacement. They have younger ages than the much more abundant inherited zircons (Fig. 5B), and show oscillatory zoning, indicative of a magmatic origin. They have high U (2187–4503 ppm) concentrations, but

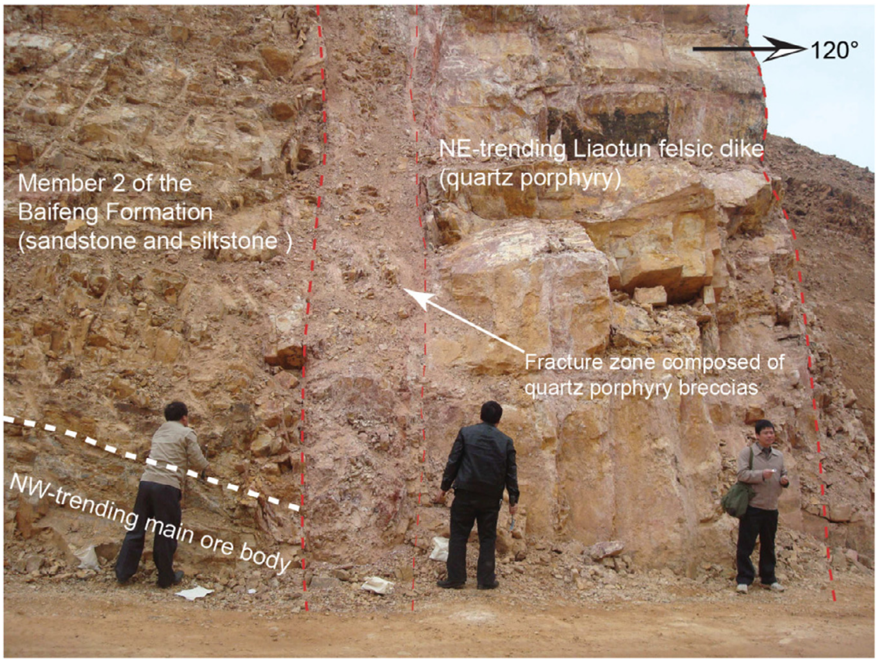

Fig. 4. Field photo showing the felsic dike crosscutting stratabound gold mineralization at the Liaotun deposit. Note that the mineralization here occurs in the wall rock, whereas elsewhere in this deposit the mineralization is mainly fault-controlled. The original photo is from Chen et al. (2014), republished with revision and permission of journal of Mineral Deposits (in Chinese).

relatively low Th (90–109 ppm) abundances and Th/U ratios (0.02–0.05). Three spot analyses were conducted on the two grains, and yielded a Concordia age of 95.4 ± 2.4 Ma (95% confidence, MSWD = 0.56; Fig. 5B), consistent with the weighted mean $^{206}Pb/^{238}U$ age of 95.4 ± 6.1 (95% confidence, MSWD = 5.4). One analysis (XBH-01-A7@2) had a larger error, but is broadly consistent with the other two analyses and is included in the Concordia age calculation. The Concordia age is interpreted to best represent the emplacement age of the Xiabaha felsic dike.

LA-ICP-MS zircon dating results for the Bama dike are reported in Supplementary Table A.2. Thirty-four spot analyses were selected from ~300 zircon grains. Five zircons with older model $^{206}Pb/^{238}U$ ages of 1136 to 406 Ma are interpreted to be assimilated from the country rocks (Fig. 5C; Zhu et al., 2016). The remaining twenty-nine zircon grains have ages between ~108 and ~78.7 Ma. The main population with twenty-five grains intersects Concordia at 99.4 ± 0.37 Ma (MSWD = 1.4; Fig. 5C), which is interpreted to represent the emplacement age of the Bama dike. Two zircon grains with slightly older model $^{206}Pb/^{238}U$ ages of 106 and 108 Ma likely represent antecrysts, whereas two other zircon grains with younger discordant ages (BM13-01-3@1 and BM13-01-17@1) are interpreted to reflect lead loss (Fig. 5C). The main group of zircons has relatively homogenous concentrations of Th (345–766 ppm) and U (467–866 ppm), with higher Th/U ratios (0.62–1.45) compared with zircons from the Liaotun and Xiabaha dikes.

6. Discussion

6.1. Ages of felsic dikes in the Youjiang basin

The Liaotun felsic dike is here dated at 97.2 ± 1.1 Ma (MSWD = 2.9; SIMS), the Xiabaha dike at 95.4 ± 2.4 Ma (MSWD = 0.56; SIMS) and the Bama dike at 99.4 ± 0.37 Ma (MSWD = 1.4, LA-ICP-MS). Chen et al. (2014) previously reported a muscovite $^{40}Ar/^{39}Ar$ plateau age of 95.5 ± 0.7 Ma (2σ) for the Liaotun dike, which overlaps the U-Pb age within error. Given the tendency for $^{40}Ar/^{39}Ar$ dates to record cooling ages or to be affected by later overprinting, the U-Pb zircon age is thought to be a better estimate for the emplacement age of the dike. Two other felsic dikes in the Youjiang basin have been dated by $^{40}Ar/^{39}Ar$ on muscovite, also yielding ages of ~95 Ma (Chen et al., 2012). Taken together, all the dating results confirm that the felsic magmatic event in the Youjiang basin broadly occurred at ~100–95 Ma. This timing is generally contemporaneous with the age of Cretaceous Sn-W-related granitic intrusions that occur around the margin of the Youjiang basin (Fig. 1B), implying they might have formed in a similar extensional tectonic setting (Cheng et al., 2013; Mao et al., 2013; Xu et al., 2015).

6.2. Crosscutting relationship between Carlin-type gold deposits and felsic dikes

The Liaotun and Xiabaha felsic dikes occur in close proximity to the Liaotun and Mingshan Carlin-type Au deposits, respectively (Figs. 2 and 3). Field investigations show that the NE-trending Liaotun dike cuts the NW-trending ore body, and clearly postdates gold mineralization (Fig. 4).

Some authors have noted that the felsic dikes are locally enriched in gold where they cut the orebodies (e.g., at Liaotun), and have proposed that they are contemporaneous with, or even generated, the Au deposits (Ma et al., 2013; Li et al., 2014). However, the textural relationships of these gold-bearing samples are not well described, including their alteration characteristics and occurrence of gold, such that it is difficult to interpret the origin of gold in these samples. Our observations suggest that the dikes are generally barren except locally where they contact the orebody, where gold has probably been remobilized from the existing mineralization by the heat of intrusion or late stage hydrothermal fluid. This interpretation is also supported by gold contents of the Liaotun dike, which are abnormally high near the ore body and faults, and decrease to a background level as extending away (Chen et al., 2014). In the Mingshan Au field, where the Xiabaha dike does not directly contact the orebodies, the igneous rock is

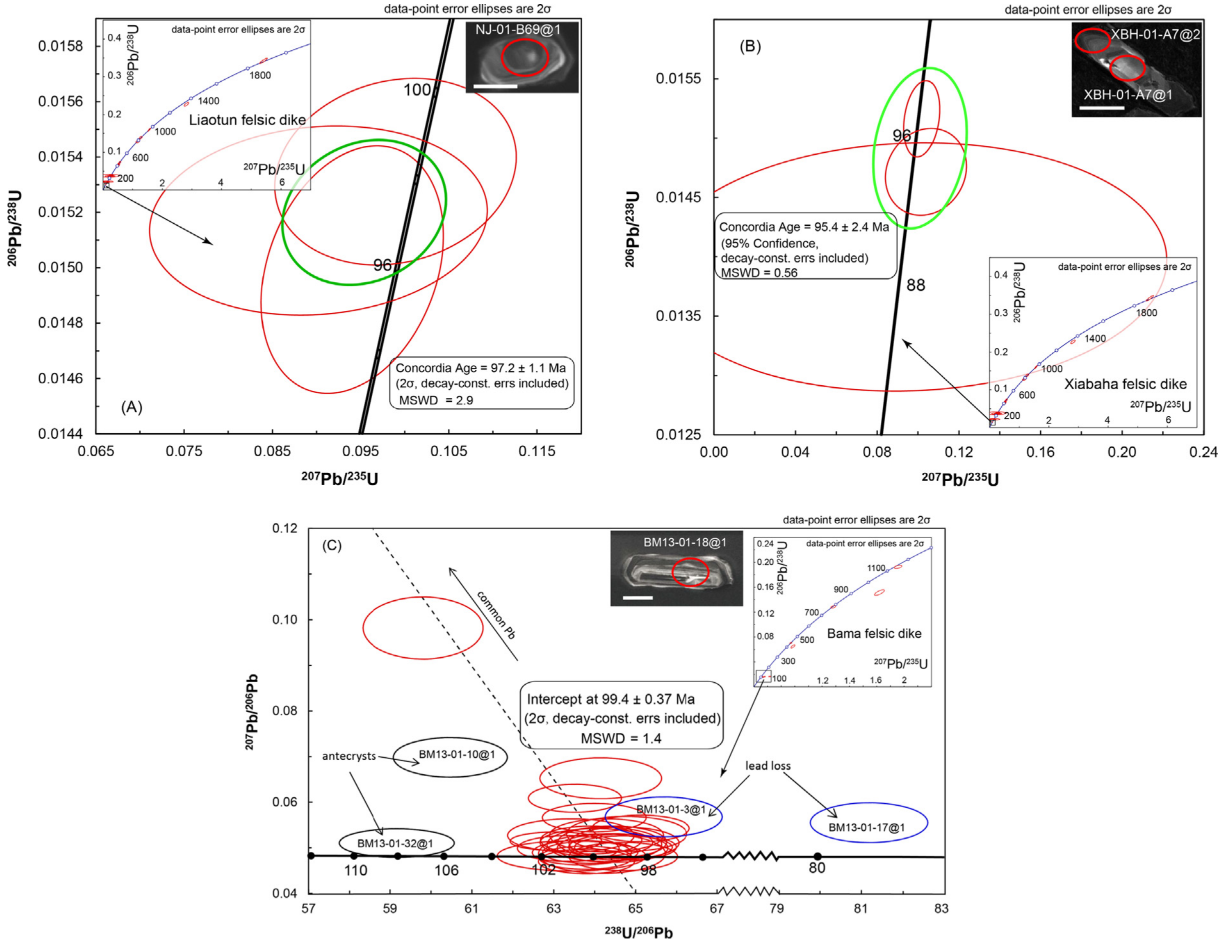

Fig. 5. SIMS U-Pb Concordia diagrams for crystallization zircons from (A) the Liaotun and (B) Xiabaha dikes, and (C) LA-ICP-MS reverse Concordia diagram for zircons of the Bama dike. Concordia diagrams for all zircons including inherited grains are shown as insets. The green ellipses in A and B denote the calculated Concordia ages. The blue and black ellipses in C reflect lead-loss or antecrystic grains, and are excluded from the regression. Cathodoluminescence images of representative zircons with spot numbers and positions (red ellipse) are shown in insets, and white scale bars are 20 μm long. Data for crystallization zircons are from Tables A.1 and A.2, and inherited zircon data are from Zhu et al. (2016). See text for details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

relatively fresh and unmineralized. Furthermore, the main Carlin-type deposits with larger gold reserves (e.g., the large to giant scale Lannigou and Shuiyindong Au deposits; Su et al., 2009b; Chen et al., 2015; Fig. 1b) are mainly located in the north of the Youjiang basin, where there are no felsic dikes to be found yet. Therefore, it is hard to claim that felsic dikes have significantly contributed to gold formation.

6.3. Assessment of published ages for gold mineralization

Due to the lack of suitable minerals for direct dating (Hu et al., 2002; Peters et al., 2007; Su et al., 2009b), the age of Carlin-type Au mineralization in the Youjiang basin remains controversial. A number of methods have been employed in attempt to constrain the timing of gold mineralization, and have yielded a wide range of ages (275–46 Ma; Table 1). Among these dates, those below 100 Ma were mainly obtained from quartz electron spin resonance and fission-track dating. Electron spin resonance dating has numerous applications in Quaternary settings, and the method has mainly been applied to samples younger than 2–5 Ma (e.g., Grün, 1991; Blackwell et al., 2016). Similarly, the fission-track method is best suited to uranium-bearing minerals such as zircon, apatite, and titanite (e.g. Westgate et al. (1997), Fleischer (2004), Tagami and O'Sullivan (2005)), and quartz is not generally suitable. Therefore, we suspect that these younger (<100 Ma) electron spin resonance and fission-track dates do not record the age of mineralization.

The model lead isotope (single-stage) method of dating was utilized by Li (1990) and Li et al. (1995) in an attempt to date ore-stage pyrite and realgar in the Jinya and Gaolong Au deposits, and returned a wide range of ages from 275 to 82 Ma (Table 1). This method is problematic because its interpretation is largely dependent on the inferred isotope evolution of the source, which is difficult to constrain with any precision (e.g. Nakai et al. (1990)). In addition, many ore deposits contain lead that has evolved by more complex processes than a single stage. This method is generally only useful in resolving disputes concerning large age differences, such as defining an ore deposit to be Precambrian versus Cenozoic (e.g. Doe and Stacey (1974)). The relatively wide range of dates and large errors obtained from individual deposits (e.g., Jinya, 266–82 Ma) also suggests that these results are not useful for constraining the age of mineralization.

Four fluid inclusion Rb-Sr isochron ages were published by Wang (1992), Hu et al. (1995, 2002), Su et al. (1998), and Liu et al. (2006b), and range from 267 ± 28 Ma to 105.6 ± 4.5 Ma. However, many of the quartz and calcite veins from the Carlin-type gold deposits in the Youjiang basin contain abundant secondary fluid inclusions (Zhang et al., 2003; Su et al., 2009a), which likely explains the large age range in these data; the younger dates likely reflect overprinting by late fluids.

$^{40}Ar/^{39}Ar$ and Rb-Sr isotopic dating of hydrothermal sericite from Carlin-type gold deposits in the Youjiang basin yielded ages of 194.6 ± 2 Ma, 215.3 ± 1.9 Ma, and 206 ± 12 Ma (Li et al., 1995; Chen et al., 2009; Pi et al., 2016), respectively. However, the use of sericite to date Carlin-type gold deposits has been called into question by Hofstra et al. (1999) and Arehart et al. (2003), who suggested that it is difficult to determine a clear relationship between multiple generations of sericite and gold mineralization, and the susceptibility of sericite to thermal resetting. Therefore, we suspect that these $^{40}Ar/^{39}Ar$ and Rb-Sr sericite ages are inaccurate estimates for gold mineralization, although it is noted that they are all substantially older than the felsic dikes.

The remaining published ages for gold mineralization can be divided into two groups: 235 ± 33 to 193 ± 13 Ma (Re-Os on sulfide minerals and U-Pb age of hydrothermal rutile), and 148.4 ± 4.8 to 134 ± 3 Ma (Sm-Nd on calcite; Table 1). Although the Re-Os dates have relatively large errors, they are broadly in agreement with each other and also U-Pb age of hydrothermal rutile intergrowth with gold-bearing pyrite (213.6 ± 5.4 Ma; Pi et al., in press), and are probably the best estimates for the age of mineralization (Chen et al., 2007, 2015; Liu et al., 2014). The Sm-Nd isochron ages for calcite are interpreted to reflect the timing of decarbonation and ore formation (Su et al., 2009b; Wang, 2013), but a clear determination of the relationship between these calcite veins and gold mineralization is not well constrained.

Consequently, based on the evaluation of published geochronological results, the best available ages for the Carlin-type Au deposits in Youjiang basin are probably between 235 and 193 Ma. These ages are significantly older than the emplacement ages of the quartz porphyry dikes, further confirming that there is no temporal and therefore genetic link between the felsic dikes and gold mineralization.

7. Summary and conclusions

Zircon U-Pb dating suggests that the Liaotun, Xiabaha, and Bama felsic dikes in the Youjiang basin were emplaced between ~100 and 95 Ma, and crosscut the gold mineralization. A variety of methods have been used to constrain the timing of Carlin-type deposits in the Youjiang basin, yielding a wide range of ages from 275 to 46 Ma. However, the most reliable dates constrain the age of mineralization to between 235 and 193 Ma, significantly predating the Late Cretaceous felsic dikes. Taken together, we conclude that there is no genetic link between the felsic dikes and gold mineralization.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.oregeorev.2017.01.014.

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