Tethys tectonic evolution and its bearing on the distribution of important mineral deposits in the Sanjiang region, SW China

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Article info

Abstract

The Sanjiang region in SE Tibet Plateau and NW Yunnan is known to have formed by amalgamation of Gondwana-derived continental blocks and arc terranes as a result of oceanic subduction followed by continental collision from Paleozoic to Mesozoic. In this paper we provide a synthesis of tectonic evolution, magmatism and metallogeny in the region based on data from literatures. Early Paleozoic ophiolites (473–430 Ma) in the Changning–Menglian belt indicate the existence of a Proto-Tethys ocean in this region. Two episodes of subduction-related magmatism in the early-Paleozoic, one occurred in the Baoshan and Tengchong blocks at 502–455 Ma and the other occurred in the Simao block at 421–401 Ma, are regarded as evidence for two different events of subduction of the Proto-Tethys ocean at different locations. The Proto-Tethys was succeeded in early-Devonian by the Paleo-Tethys which comprised the main ocean and three branches: Ailaoshan, Jinshajiang and Garzê–Litang. The Changning–Menglian main ocean existed from middle-Devonian to middle-Triassic. The remnants of the oceanic crust are preserved in a few places in the Longmu Tso–Shuanghu suture as well as in the Changning–Menglian ophiolite belt. The eastward subduction of the main oceanic plate from early-Permian to early-Triassic formed a prominent arc terrane stretching >1500 km from Yunnan to eastern Tibet. From the waning stage of subduction to post-subduction, numerous S-type granite plutons with ages varying between 230 and 219 Ma, such as the Lincang batholith in Yunnan were emplaced at or close to the suture. This event produced several hydrothermal W–Sn deposits in the region. The tectonic evolution and associated magmatism of the Jinshajiang and Ailaoshan branch oceans are generally comparable to those of the main ocean. However, the branch oceans were subducted westward instead. The Garzê–Litang branch ocean also underwent westward subduction from middle-Devonian to late-Triassic. Arc-related high Sr/Y porphyry intrusions and associated porphyry-skarn Cu–Mo–Au deposits are common in the Jinshajiang–Ailaoshan region, especially in the Yidun arc which formed prior to Jurassic. The VMS deposits in the Sanjiang region formed in diverse tectonic settings including middle-Silurian back-arc basins, Carboniferous oceanic islands, Paleozoic subduction zones and Triassic post-subduction rift environments. The Mesozoic and early-Cenozoic evolution of the Baoshan and Tengchong blocks were largely influenced by eastward subduction of the Meso- and Neo-Tethys from late-Permian to middle-Cretaceous and from late-Cretaceous to ~50 Ma, respectively. Abundant early-Cretaceous granitoids and associated skarn-type Pb–Zn and Sn–Fe deposits in the Baoshan and Tengchong blocks were produced in the background of the Shan boundary oceanic slab subduction to the west and the break-off of the Nuijiang-Bitu oceanic slab to the north. The subduction of the Neo-Tethys oceanic plate beneath the Tengchong block from Late Cretaceous to Paleogene formed abundant S-type granitoids and many skarn-type and greisen-type Sn–W deposits. Granitoids formed at 105 to 81 Ma and contemporaneous hydrothermal W, Mo, Ag and Au deposits, which temporally coincided with the subduction of the Neo-Tethys, are common in the Yidun arc terrane.

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1. Introduction

The Sanjiang (three rivers) region covers the southeastern part of the Tibet Plateau and western Yunnan province. It is run over by three major rivers: Jinshajiang, Langcangjiang and Nujiang. This region is the collage of Paleozoic arc terranes and Gondwana-derived microcontinental blocks (Mo et al., 1994; Metcalfe, 2002, 2013; C.M. Wang et al., 2013). The major continental blocks of the Sanjiang region are the South China, Simao–Indochina, and Sibumasu. They are separated by the Ailaoshan and Changning–Menglian sutures formed by closure of the Tethys oceans (Fig. 1a, b). The tectonic evolution of these blocks and the suture zones has been studied by many researchers in the last two decades (e.g. Metcalfe, 2002, 2006; Hall et al.,
Fig. 1. (a) Distribution of principal continental blocks and sutures of southeast Asia (modified after Metcalfe, 2011, 2013); (b) Tectonic framework of the Sanjiang region showing the major continental blocks, suture zones, localities of dated ultrabasic-basic rocks (including oceanic ridge granites). The ages in the Garzê–Litang suture are from Yan et al. (2005); those in the Jinshajiang suture are from Wei et al. (1999), Zhan et al. (1999), Lu et al. (2000), Liu et al. (1999, 2008, 2009a, 2009b), Liu and Liu (2002), Zhu et al. (2010), B.D. Wang et al. (2011), Wang et al. (2012), Li et al. (2012); those in the Ailaoshan suture are from Jian et al. (1998, 2009a, 2009b), W.M. Fan et al. (2010), Lin et al. (2012); and those in the Changning–Menglian suture and related Yunxian-Jinggu arc are from X.D. Duan et al. (2006), Jian et al. (2009a, 2009b), Chen et al. (2010), Lai et al. (2010), B.D. Wang et al. (2013), Hennig et al. (2009) and G.C. Li et al. (2012).
The northern part of the Sanjiang region consists of the Songpan–Garzê fold belt and three micro-continental blocks, namely the East Qiangtang, West Qiangtang and Lhasa blocks. They are separated by the Jinshajiang, the Longmu Tso–Shuanghu, the Bangong–Nuijiang sutures formed by closure of the Tethys oceans (Fig. 1a, b). The tectonic evolution in this region has been studied recently by some researchers (e.g., K.J. Zhang et al., 2011; Zhai et al., 2011; Zhu et al., 2012, 2013).

In this paper, we present a modified tectonic framework for the Sanjiang region and the temporal and spatial relationships between the evolution of the Tethys oceans, magmatism and metallogeny, which are based on available dating data in recent years. The opening of the Tethys oceans is constrained from the ages of MORB-type ophiolite assemblages, and the subduction is based on the ages of the supra-subduction zone (abbreviated as SSZ-) type ophiolite (Dilek and Furnes, 2011) and high-pressure metamorphism in convergent margins, and subduction-related magmatism in arcs. The closure of the oceans is determined using the ages of stitching plutons across the sutures and sedimentary rocks. The ages of igneous rocks are based on zircon U–Pb dating. The ages of metamorphic rocks are based on phengite or sodic amphibole Ar–Ar dating as well as zircon U–Pb dating. The ages of hydrothermal ore deposits are based on U–Pb isotopes of zircons from associated igneous rocks, molybdenite Re–Os dating and Ar–Ar dating of K-bearing minerals from mineralized samples.

2. Sutures and arc terranes

2.1. Garzê–Litang suture and Yidun arc

2.1.1. Garzê–Litang suture

The Garzê–Litang suture extends for a distance over 1000 km from west of Garzê in the north, through Litang in the center, to Muli in the south. This suture separates the Songpan–Garzê fold belt and the Yidun arc (Fig. 1b). Ophiolite assemblages composed of MORB-type basalts, mafic–ultramafic intrusive rocks and sheeted dikes (Mo et al., 1993; Zhong, 1998) are present in the suture. The radiolarian cherts overlying the ophiolite assemblages are parts of middle–Devonian to middle–Triassic strata (Fig. 3) (Zhang et al., 2000; Feng et al., 2002; W.Q. Yang et al., 2010). SHRIMP U–Pb isotope data of zircons from a gabbro sample with N–MORB geochemical signatures give an age of 292 ± 4 Ma (Yan et al., 2005). The gabbros in the northern part of the Garzê–Litang ophiolite belt show SSZ-type geochemical signatures (Duan et al., 2009). Zircon crystals separated from the gabbros yield a SHRIMP U–Pb isotope age of 239.8 ± 3.1 Ma (Duan et al., 2009).

2.1.2. Yidun arc

The Yidun Arc is bounded by the Jinshajiang suture to the west and by the Garzê–Litang suture to the east. The oldest rocks in the Yidun Arc are Paleozoic meta-sedimentary rocks exposed in the western part of the arc. This area is commonly referred to as the Zhongga block in literatures (Fig. 1b). Fossils found in the Zhongga block are similar to those found in the Paleoziac strata in the northern margin of the Yangtze block (Chang, 1997). The Zhongga block could have derived from the Yangtze block by opening of the Garzê–Litang ocean in late Paleoziac (Zhang et al., 1998). W.C. Li et al. (2012) reported a N–S trending ophiolite belt, namely the Shudu ophiolite belt, within the Yidun arc. Jurassic radiolarian cherts are present close to the ophiolite belt (Feng et al., 2002). Such association suggests that a back-arc basin possibly existed until Jurassic in the middle of the Yidun arc.

The Paleozoic meta-sedimentary rocks in the Yidun Arc are overlain by Triassic clastic and intercalated volcanic rocks of the Qugasi and Tumugou Formations. The volcanic rocks formed in response to the westward subduction of the Garzê–Litang oceanic plate beneath the Yidun arc. The Late Triassic sedimentary–volcanic sequence hosts numerous VMS, skarn and hydrothermal ore deposits (Hou et al., 2003a).

The outcrops of granite and granodiorite plutons with zircon U–Pb ages varying from ~230 Ma to ~204 Ma (Roger et al., 2003; Lin et al., 2006; Cao et al., 2007; Leng et al., 2008; S.X. Wang et al., 2008; Cao et al., 2009; Pang et al., 2009; B.Q. Wang et al., 2011; Q. Wang et al., 2011; Ren et al., 2011a,b; W.C. Li et al., 2011a, 2011b; Leng et al., 2012) cover 10–20% of the surface of the Yidun arc. These plutons intruded the Paleozoic-Triassic volcano-sedimentary sequences (Fig. 2).

The Late Triassic plutons are characterized by abundant hornblende, enrichments in LILE and LREE, depletions in HFSEs, negative εNd(t) (−3.8 to −2.1), high initial 87Sr/86Sr ratios (0.7051 to 0.7059), slightly positive zircon εHf(t) from −0.2 to 3.2 (averaging 1.5), and high Sr/Y ratios from 23 to 92 (Cao et al., 2007; Leng et al., 2007, 2012; Ren et al., 2011b; W.C. Li et al., 2011b). Some of these researchers suggested that the magmas of these plutons formed by melting of the subducted slab. However, the geochemical features of these plutons are also consistent with parental magmas formed by flux melting in an arc setting (e.g., Richards et al., 2012). Zircons from some of the plutons show positive Ce anomalies and slightly negative Eu anomalies, indicating highly-oxidized parental magmas (Ren et al., 2011b).

The LA–ICP–MS U–Pb dating of zircons from the granitoids in the Yidun arc yielded crystallization ages varying from 105 to 81 Ma (Reid et al., 2007; L.Q. Wang et al., 2008; S.X. Wang et al., 2011; W.C. Li et al., 2012). These Cretaceous granitoids are characterized by high SiO2, depletions of Ba, Sr and Eu, and slight enrichments of Zr, Hf, Nb and Ta. Such geochemical characteristics are similar to those of within-plate granites (Pearce et al., 1984). The granitoids in the Yidun arc are characterized by εNd(t) varying from −4.96 to −8.40 and (87Sr/86Sr)i, varying from 0.713456 to 0.853879, indicating that their parental magmas were mainly crust-derived with only minor mantle inputs (Qu et al., 2002).

2.2. Jinshajiang and Ailaoshan sutures and associated volcanic belts

2.2.1. Jinshajiang suture and Jomda–Weixi volcanic belt

The Jinshajiang suture is marked by ophiolite assemblages that occur over a distance of hundreds of kilometers within a N–S trending tectonic mélangé zone (Fig. 1b). The ophiolite assemblages are composed of serpentinitized peridotites, gabbros, and mafic volcanic rocks including pillow basalts that are intercalated with limestones and radiolarian cherts (Zhang et al., 1994). The degrees of regional metamorphism are greenschist facies. The ophiolites are spatially associated with the Permo-Carboniferous meta-sedimentary rocks of the Gajinxueshan Group (Wang et al., 2000) and middle-late Triassic volcano-sedimentary rocks (YNGMR, Yunnan Bureau of Geology and Mineral Resources, 1990).

Two amphibolite xenoliths from low-Ti basalts in the Jinshajiang ophiolite mélange have zircon ages of 439 Ma and 404 Ma (Jian et al., 2009a, 2009b). The Dongzhulin trondhjemites close to this suture have zircon U–Pb age of ~347 Ma (Zi et al., 2012a). These rocks are characterized by highly variable zircon Hf isotopic compositions, high LREE/ Hf(t) from 5 to 11 and low εNd(t) from 3.1 to 11 and low ε18O values from 6.1 to 6.8. These
values are similar to those of altered oceanic crust, and have been regarded as evidence for partial melting of subducted oceanic lithosphere (Zi et al., 2012a). Radiolarian fossils of middle-Devonian to middle-Permian ages have been found in the siliceous sedimentary rocks associated with the ophiolites (Fig. 3) (Sun et al., 1995, 1997; Feng and Ye, 1996; Wang et al., 2000; Q.F. Duan et al., 2006).

The westward subduction of the Jinshajiang oceanic slab produced the Jomda–Weixi continental arc which stretches over 400 km from Dali to Jomda (Fig. 1b). Volcanic rocks in this arc are Permian calc-alkaline basalts, andesites and dacites. Coeval intermediate-felsic plutons such as the Baimaxueshan pluton are common. Zircons from the Baimaxueshan pluton and mafic enclaves within this pluton yield U–
Pb ages of 235–248 Ma (Zi et al., 2012b). The granitoids of this pluton belong to I-type granite and are characterized by medium- to high-K and metaluminous compositions, εNd(t) from −9.2 to −6.3 and (87Sr/86Sr)$_{iso}$ from 0.7099 to 0.7113 (Zi et al., 2012b). Zircons from this pluton have average εHf(t) close to −10 and average δ18O close to 8‰ (Zi et al., 2012b). Based on these geochemical characteristics, Zi et al. (2012b) suggested that these rocks derived from hydrous magmas produced by partial melting of subduction-modified subcontinental lithospheric mantle. The volcanic rocks in the arc are overlain by Triassic turbidites and flyschs of the Malasongduo (in the north part), Pantangi and Cuibiyi Formations (in the south part) (Fig. 2) (Mou and Wang, 2000; Tan, 2002; B.D. Wang et al., 2011). The volcanic rocks within the Pantangi Formation are dominated by high silica rhyolites with whole-rock K/Ar ages from 222 to 185 Ma. The mineralized Cu multistage intrusion (Zi et al., 2012c) suggested that these rocks derived from hydrous magmas produced by partial melting of subduction-modified subcontinental lithospheric mantle in an extension setting after the ocean was consumed by subduction. The Cuibiyi Formation is unconformably overlain by late-Triassic clastic rocks of the Shizhongsan Formation. In summary, the compositional variations of volcanic rocks with time within the Jomda–Weixi volcanic belt are consistent with subduction-related magmatism before ~250 Ma and post-subduction magmatism afterward (Fig. 2).

2.2. Ailaoshan suture and Yaxianqiao volcanic belt

The Ailaoshan shear zone (Fig. 1b) is not a continental suture for the Indochina and South China blocks. The actual location of the suture between these two continental blocks is west of the shear zone based on the crop of Emeishan basalt (Chung et al., 1997). The center of the suture is marked by plagioclase amphiboles, glaucophane and phengite from the blueschist in the Lüchun area (Zhao et al., 2013). In summary, the transition from subduction-related magmatism to post-subduction magmatism of the Ailaoshan suture appears to be at ~260 Ma.

2.3. Changning–Menglian suture and Yunxian–Jinggu volcanic belt

2.3.1. Changning–Menglian suture

The Changning–Menglian suture, marked by dismembered ophiolites and associated deepwater sedimentary rocks, can be traced from Menglian in the south to Changning in the north (Fig. 1b). The suture is truncated in the north by the Chongsan metamorphic belt which runs through the north margin of the Baoshan block. In the south the suture passes through Burma and extends into northern Thailand. The southmost part of the suture is called the Chiang Mai–Inthanon suture in literature (e.g., Metcalfe, 2011). The 40Ar–39Ar plateau ages of sodic amphiboles, glauconephite and plagioclase from the blueschist in the Changning–Menglian suture vary from 294 to 279 Ma (Fig. 2) (Zhang et al., 1993; Heppe et al., 2007).

The Proto-Tethys and Paleo-Tethys oceans are both preserved in some places within this suture. The Proto-Tethys reliefs include the Nantinghe ophiolite complex which is composed of metamorphosed peridotites, gabbros, amphibolites and basalts. The gabbros have zircon LA–ICP–MS U–Pb ages ranging from 473 ± 1.8 Ma to 439.6 ± 2.4 Ma (B.D. Wang et al., 2013).

The Paleo-Tethys ophiolites are composed of harzburgites, pyroxenites, gabbros, diabase and basalts. They are surrounded by strongly sheared sandstones, siltstones and shales. Deepwater marine cherts embedded in basalts contain radiolaria of middle–Devonian to middle–
Triassic ages (Fig. 3) (Wang et al., 1994; Feng and Ye, 1996; Feng et al., 2001; Sone and Metcalfe, 2008). Zircons from the gabbros of the Ganlongtang ophiolite complex in the Gengma area give U–Pb ages from 349 to 331 Ma (Q.F. Duan et al., 2006; X.D. Duan et al., 2006). Basalts with N-MORB and trace element characteristics are present in the ophiolite complex (Lai et al., 2010). In the Loachang area, basalts
imbedded in late-Carboniferous strata have $\varepsilon_{Nd}(t)$ from 0.28 to 0.94 and OIB trace element signature (Chen et al., 2011). The meta-gabbros in the Damoguanfang suture have zircon U–Pb age of 267.1 ± 3.1 Ma and arc trace element signature (Jian et al., 2009a, 2009b). The geochemical variations of the ophiolite complexes in the Changning–Menglian suture zone indicate an early MORB-type source mantle and a late SSZ-type source mantle.

### 2.3.2. Yunxian–Jinggu volcanic belt

The Yunxian–Jinggu arc experienced two major episodes of subduction-related magmatism that took place in Silurian and Permo-Triassic, respectively. Silurian calc-alkaline volcanic rocks and granodiorite with arc geochemical signatures have zircon U–Pb age of 421 Ma at Dazhonghe (Mao et al., 2012) and 401 Ma (Ru et al., 2012) at Dapingzhang respectively. Mafic–ultramafic intrusions such as the Nanlinshan and Banpo intrusions in the Yunxian–Jinggu magmatic belt have zircon U–Pb ages of 298–292 Ma and 295–286 Ma respectively, positive $\varepsilon_{Nd}(t)$ values and negative Nb–Hf anomalies (Hennig et al., 2009; Jian et al., 2009a, 2009b; C.C. Li et al., 2012). These intrusions were previously interpreted as ophiolites (e.g., Zhang et al., 2001) or Alaskan-type zoned complexes (Jian et al., 2009a, 2009b). Recently, C.C. Li et al. (2012) concluded that they are the products of subduction-related basaltic magmatism based on petrological characteristics and geochemical signatures including Sr–Nd isotopes and trace elements. Granodiorite plutons in the Jinghong area (see Fig. 2) are slightly younger, giving zircon U–Pb ages of 284–282 Ma (Hennig et al., 2009). They are characterized by negative $\varepsilon_{Nd}(t)$ varying from −3.6 to −3.1, elevated initial Sr isotope ratios from 0.709 to 0.710, and trace element patterns similar to those of calc–alkaline rocks formed in an arc setting (Hennig et al., 2009). The subduction-related calc-alkaline magmatism in the Jinghong area roughly coincided with the 294–279 Ma high-P metamorphism in the Changning–Menglian suture to the west (Zhang et al., 1993; Heppe et al., 2007). Triassic volcanic rocks in the Jinghong area are dominated by basaltic andesites, andesites and rhyolites, which have zircon U–Pb ages ranging from −249 to −230 Ma and arc geochemical signatures such as enrichments in U–REE and depletions in HFSE (Peng et al., 2008; Y.J. Wang et al., 2010).

As shown in Fig. 2, the Yunxian–Jinggu arc was intruded by the Lincang granitic pluton which covers an area of nearly 370 km in length and ~50 km in width. This pluton belongs to peraluminous S-type granites. It is characterized by enrichments in LILEs plus Pb, significant depletions in HFSE, negative $\varepsilon_{Hf}(t)$ of zircons from −11 to −14 and U–Pb ages of zircons from 230 to 219 Ma (Peng et al., 2006; Hennig et al., 2009; Dong et al., 2013; Kong et al., 2012). As pointed out by these authors, the geochemical characteristics are consistent with granites formed by magmas derived from old crustal materials. Coeval mafic–felsic volcanic rocks with zircon U–Pb ages of 235–210 Ma are present east of the Lincang pluton in the Manghuai and Xiaodingyi areas (Fig. 2) (Peng et al., 2006; Y.J. Wang et al., 2010; W.G. Zhu et al., 2011; Chen et al., 2013).

### 3. Major continental blocks

#### 3.1. Yangtze block

The Yangtze block is separated from the Simao block to the west by the Mojiang suture (Fig. 1b). The western part of the Yangtze block consists of an Archean-Proterozoic metamorphosed-folded basement and a Paleozoic sedimentary cover. Several Proterozoic metamorphic core complexes such as the Ailaoshan, Shigu and Diancangshan complexes occur in the western margin of the Yangtze block. The Ailaoshan Complex predominantly comprises gneisses (1571–1737 Ma, zircon U–Pb ages; Wang et al., 2000), amphibolite (1367 ± 46 Ma, Sm–Nd whole-rock isochron age; Zhong, 1998), marble, and minor granulites. The western margin of the Yangtze block was modified by subduction-related magmatism from 865 Ma to 750 Ma (Zhou et al., 2002, 2006). The Paleozoic cover of the Yangtze block is dominated by marine sedimentary rocks and the ~260 Ma Emeishan continental flood basalts (Jian et al., 2009b; Deng et al., 2010). Triassic limestones and fine-grained clastic rocks, and Cretaceous terrestrial red beds are present in the Mesozoic Chuxiong basin.

#### 3.2. Simao block

The metamorphosed basement of the Simao block is composed of Mesozoic and Neo-Proterozoic meta-volcanic and meta-sedimentary rocks of the Daininglong and Chongshang Groups (e.g., YNGMR, Yunnan Bureau of Geology and Mineral Resources, 1990; Zhong, 2000). Zircons from migmatic parts of the basement have U–Pb ages of 833–843 Ma (Li et al., 2008). Early-Ordovician sedimentary rocks, which are the oldest sedimentary rocks exposed in the area, are unconformably overlain by middle-Devonian to Triassic shallow-marine, paralic and continental successions, which in turn are overlain by Mesozoic red beds (YNGMR, Yunnan Bureau of Geology and Mineral Resources, 1990; Metcalfe, 2006; Zhong, 2000) suggested that the Simao block belongs to the Yangtze craton, whereas Metcalfe (2013) suggested that the Simao and Indochina blocks belong to a single Gondwana-derived micro-continental. Other researchers proposed that the Simao and Indochina are separate Gondwana-derived micro-continent (Ferrari et al., 2008). Detrital zircons from the Indochina block show an age peak at ~1.0 Ga, which is similar to age distribution of detrital zircons from the Indian block (Usuki et al., 2012). Such similarity in detrital zircon ages suggests that these two blocks were together prior to Gondwana breakup.
3.3. Baoshan and Tengchong blocks

The Baoshan and Tengchong blocks are believed to be northern extension of the Sibumasu block by some researchers (e.g., Sone and Metcalfe, 2008). We concur with a general consensus that the Baoshan and Tengchong blocks were derived from the margins of Gondwana supercontinent based on the occurrence of Permo-Carboniferous glacio-marine deposits and overlying post-glacial black mudstones, as well as the Gondwana-like fossil assemblages in these blocks (Jin, 1996). Detrital zircons from the Sibumasu area show a large age peak at 1.0 Ga and a small age peak at 1.2 Ga, which are also present in the Indian and Australian blocks, respectively (Sevastjanova et al., 2011; Hall and Sevastjanova, 2012). Based on the detrital zircon data and Paleozoic glacialmarine sedimentary sequences and faunas in different blocks Metcalfe (2013) suggested that before Gondwana breakup the Sibumasu block was attached to the Australian block but far from the Indian block and that the Indian block provided significant amounts of detrital materials to the basins in the Sibumasu block.

3.3.1. Baoshan block

The metamorphosed basement of the Baoshan block is the Neoproterozoic–Cambrian Gongyanghe Group. The Paleozoic and Mesozoic sedimentary cover is composed of clastic rocks, carbonates and Permian volcanic rocks (Huang et al., 2012). Zircons from mafic intrusions to the meta-sedimentary strata of the Baoshan block yield U-Pb ages of ~450 Ma (Yang et al., 2012). Zircons from the Pinghe monzogranites in the Longling area give U-Pb ages of 500–455 Ma (S. Liu et al., 2009; Dong et al., 2012; Xiong et al., 2012). The Pinghe monzogranites are characterized by enrichments in LILE, LREE and Pb, depletions in HFSE, high initial 87Sr/86Sr from 0.7132 to 0.7144, negative εNd(t) from −9.7 to −9.4, and negative εHf(t) from −13.1 to −3 (S. Liu et al., 2009; Dong et al., 2012). The Pingdajie granite pluton has zircon U-Pb ages of 472–466 Ma and negative εHf(t) from −4 to −12 (Chen et al., 2007).

Available geochronological data show a hiatus of felsic magmatism between ~450 Ma and ~270 Ma in the Baoshan block. Permian magmatism in the Baoshan block is indicated by the Muchang A-type granitic pluton which has a zircon U-Pb age of ~266 Ma and is characterized by depletions in Ba, Sr and Eu and enrichments in Zr, Hf, Nb and Ta (Ye et al., 2010). Cretaceous magmatism in the Baoshan block is indicated by the Zhibenshan granite pluton (Fig. 2). Zircons from this pluton yield an U-Pb age of 126.7 ± 1.6 Ma and is characterized by negative εHf(t) from −0.7 to −8 (Tao et al., 2010).

U-Pb dating of two zircon crystals from a small ultramafic body in the Longling area also provided rough ages in Permian (Zou et al., 2011a). The ultramafic rocks are characterized by negative εNd(t) from −6.2 to −10.6 and γOs(t) from −4.8 to 8.5, and thought to be related to continental rifting along the margin of the Baoshan block (Chu et al., 2009). Some researchers suggested that the Longling–Ruili shear zone between the Baoshan and Tengchong blocks was originally a collision suture between these two blocks (Mo et al., 1993). This needs to be verified by future study.

3.3.2. Tengchong block

The Tengchong block has a Mesoproterozoic metamorphic basement (i.e., the Gaoligong Mountain Group), overlain by late-Paleozoic clastic sedimentary rocks and carbonates, Mesozoic-Tertiary granitoids and Tertiary-Quaternary volcano-sedimentary sequences (YNMR, Yunnan Bureau of Geology and Mineral Resources, 1990). The Gaoligong Mountain Group is composed of quartzites, two-mica quartz schists, feldspathic gneisses, migmatites, amphibolites and marbles. Zircons from a paragneiss sample and an orthogneiss sample give 1035–635 Ma and 490–470 Ma, respectively (Song et al., 2010). The Paleozoic sedimentary strata are dominated by Carboniferous clastic rocks, late-Triassic to Jurassic turbidites, Cretaceous red beds and Cenozoic sandstones (YNMR, Yunnan Bureau of Geology and Mineral Resources, 1990; Zhong, 2000).

Granitoids with zircon U-Pb ages of 232–206 Ma are present in the Tengchong block (H.Q. Li et al., 2011; Zou et al., 2011a). The granitoids are characterized by peraluminous compositions, depletions in Ba, Nb, Sr, and Eu and negative εHf(t) varying from −1 to −8.5, and are hence interpreted to be the products of crustal melts mixing with only small amounts of mantle-derived magma (H.Q. Li et al., 2011; Zou et al., 2011a). We suggest that the crustal anatexis in this region was triggered by flat subduction of the Meso-Tethyan oceanic plate at the time. This remains to be tested in the future.

Younger granitoids with zircon U-Pb ages of 127–115 Ma are common in the east part of the Tengchong block (Fig. 2) (Tao et al., 2010; Xie et al., 2010; Cong et al., 2011a, 2011b; Qi et al., 2011; Zou et al., 2011b; Luo et al., 2012; Xu et al., 2012). These felsic intrusive rocks are mostly S-type granites and characterized by negative zircon εHf(t) values from −2 to −12, enrichments in LILE and depletions in HFSE (Cong et al., 2011a, 2011b). Comagmatic diorite enclaves in the granitoids have higher εHf(t) values from 3.6 to 6.2, which are consistent with mixing between mantle-derived mafic magma and crust-derived granitic melt for the diorites (Cong et al., 2011a, 2011b). Contemporary magmatic rocks occurred in eastern Lhasa block was explained to be induced by slab break-off after the Nuijiang-Bitu ocean was consumed up (Fig. 4e) (Zhu et al., 2009). While during this time, the slab of the Shan boundary ocean was subducted along the western margin of Tengchong (Fig. 4e) (Boonchaisuk et al., 2013).

Late-Cretaceous S-type and A-type granitoids with zircon U-Pb ages of 76–68 Ma and variable εHf(t) values from −12 to 0.5 are also present in the Tengchong block (Fig. 2) (Jiang et al., 2012; Xu et al., 2012; Ma et al., 2013). In addition, granites with zircon ages as young as 66–52 Ma have been found near the border between China and Burma in the Tengchong (Booth et al., 2004; Liang et al., 2008; Chiu et al., 2009; Xie et al., 2010; Xu et al., 2012). These youngest granites include I-type granites with εHf(t) varying from −4 to +6 and S-type granites with εHf(t) varying from −12 to −2 (Xu et al., 2012).

4. Evolutions of the Tethys oceans

The existence of a Proto-Tethys ocean is evidenced from the 473–439 Ma ophiolite complexes (B.D. Wang et al., 2013; C.M. Wang et al., 2013) in the Changning–Menglian belt, the 502–455 Ma subduction-related magmatism (Chen et al., 2007; S. Liu et al., 2009; Dong et al., 2012; Xiong et al., 2012) in margins of the Lhasa, Baoshan and Tengchong blocks, and the 421–401 Ma subduction-related igneous rocks in the Simao block (Mao et al., 2012; Ru et al., 2012). Based on paleoecologic reconstruction, during the initial stage of Gondwana breakup in early Paleozoic, the Simao block and the Indochina block were together; they were separated from the Lhasa and Sibumasu blocks (Usuki et al., 2012). According to this model, the 502–455 Ma arc magmatism in the Lhasa and Sibumasu blocks can be explained by the subduction of the branch ocean beneath these blocks whereas the 421–401 Ma arc magmatism in the Simao block can be explained by the subduction of the main Proto-Tethys ocean beneath the Simao–Indochina block.

Available data given above show that the Changning–Menglian main ocean and the Ailaoshan and Jinshajiang branch oceans lasted until middle-Triassic whereas the Garzé-Litang branch ocean lasted until late-Triassic (Fig. 4a, b, c, d). The westward subduction of the branch oceans and the eastward subduction of the main ocean resulted in the formation of multiple, sub-parallel Paleoecologic continental arc terranes on both sides of the Simao and East Qiangtang blocks. Calc-alkaline volcanic-intrusive rocks in the arc terranes are the expression of subduction-related magmatism as a result of flux melting in the mantle wedge whereas the associated, younger S-type granitoids are the expression of post-subduction magmatism as a result of crustal anatexis possibly related to post-collisional extension.
Fig. 4. Schematic models for the Tethys oceans evolution in the Sanjiang region.
The main units of the Paleo-Tethys in the Sanjiang region include the Changning–Menglian main ocean, and the Ailaoshan, Jinhajiang and Garze–Litang branch oceans. Radiolarian fossils and radiometric dating reveal that the Longmu Tso–Shuanghu ocean and the Changning–Menglian ocean were possibly connected to each other from Devonian to Triassic (Fig. 3) [K.J. Zhang et al., 2011; T.N. Yang et al., 2011]. The volcanic arc along the Longmu Tso–Shuanghu suture zone [Zhu et al., 2012, 2013] is comparable with the Yunxian–Jinggu arc in the age of arc magmatism and magma types. Most of the volcanic rocks in these arc terranes are interpreted to have formed during the subduction of the oceanic plates beneath the Simao and East Qiangtang micro-continents (Fig. 4c).

The subduction of the Proto-Tethys oceanic plate underneath the Simao–Indochina block was coupled with the opening of the Paleo-Tethys ocean. It is suggested that the East Qiangtang and Simao blocks,
two important Gondwana-derived micro-continents, were amalgamated to the South China block through the westward (with current orientation as reference) subduction of Paleo-Tethys oceanic plates (Fig. 4d). Subsequently, the West Qiangtang and Sibumasu blocks, which are interpreted by us to have been derived from the Indian and Australian margins of the Gondwana supercontinent, respectively, were accreted to the East Qiangtang and Simao blocks by eastward subduction of the Paleo-Tethys oceanic plate beneath both East Qiangtang and Simao blocks. Then, the Lhasa and West Burma blocks, which are believed to have been derived from the Australian margin of the Gondwana supercontinent (Zhu et al., 2013), were accreted to the West Qiangtang and Sibumasu blocks by northward-eastward subduction of the Mesozoic oceanic plate beneath the West Qiangtang and Sibumasu blocks by northward-eastward subduction of the Mesozoic oceanic plate beneath the Yidun terrane. The deposit is characterized by enrichments in LILE and LREE, elevated Pb isotopic ratios (206Pb/204Pb = 18.595–18.685, 207Pb/204Pb = 15.597–16.752) and low εNd(t) from 0.3 to 0.9 (Chen et al., 2011). The U–Pb age of zircons from the volcanic rocks is 323 Ma (Chen et al., 2010). The mineralization occurs as stratiform lenses and veins in trachyandesite tuffs, and stratiform lenses in the overlying limestones. Pyrite, sphalerite and galena are the major sulfide minerals and molybdenite, chalcopyrite, arsenopyrite, opal and realgar are the minor phases in the ores. The Luhun deposit is associated with postcollisional rhyolitic volcanic–sedimentary sequence in the Weixi arc. Magmatic zircons from the volcanic rocks give U–Pb ages of 249–247 Ma (B.D. Wang et al., 2011). The sulfide mineralization occurs as multiple sheets or lenses plus minor stringers. Laminated, banded, massive and brecciated textures are common in the ore bodies. Pyrite, sphalerite, galena and chalcopyrite are the major sulfide minerals in the ores. The Gacun deposit occurs within the accretionary Yidun arc terrane. It formed during the westward subduction of Ganzê–Litang oceanic plate beneath the Yidun terrane. The mineralization is hosted in a volcanic–sedimentary sequence dominated by felsic rocks. The deposit is composed of a lower stringer–stockwork zone (pyrite–sphalerite–galena) within the dacitic–rhyolitic and rhyolitic–volcanic units and an upper massive zone (alternating sulfide and sulfate thin layers) associated with exhalative sedimentary rocks. The sulfide ores yield a Re–Os isochron age of 217 ± 28 Ma (Fig. 5) (Hou et al., 2003b).

Most VMS deposits are believed to have formed in the supra-subduction zone, post-subduction rift, and oceanic island setting. Only a few of them, such as the Tongchangjie Cu deposit (Yang and Mo, 1993), may have formed in oceanic rifting environment. The deposit metal species are under the control of the tectonic settings, e.g., the OIB setting tends to develop Pb–Zn–Ag mineralization.

5.2. Porphyry-skarn Cu–Mo deposits

5.2.1. Porphyry-skarn deposits in the Yidun arc

In the southern Yidun arc, numerous Late Triassic intermediate-felsic high Sr/Y porphyry bodies, which intruded volcanic–sedimentary rocks, host porphyry-type or skarn-type deposits containing valuable Cu plus other base metals. The porphyry bodies occur in two separate belts, an eastern belt and a western belt separated by the Geza River (YNMR, Yunnan Bureau of Geology and Mineral Resources, 1990; W.C. Li et al., 2011a). The eastern belt hosts the Pulang, Langdu and Qiansui deposits; the western belt hosts the Xuejiping, Lannitang, and Chundu deposits (Fig. 5). The ages and characteristics of mineralization in both belts are similar (Leng et al., 2012).

Fig. 5. Spatial distribution of mineral deposits related to the evolution of Tethys ocean in the Sanjiang region. Abbreviation: Mo, Molybdenite; Sd, Siderite; Sul, Sulfide; Zr, Zircon. 1. Jiling Sn deposit; 2. Dongzhongda Sn–Cu polymetallic deposit; 3. Dingqinnong Ag-polymetallic deposit (Dong, 2004); 4. Jiaoduoling Fe deposit (Dong, 2004); 5. Gayiqiong Ag-polymetallic deposit; 6. Shengmolong Pb-polymetallic deposit; 7. Gala Au deposit; 8. Zhaifeng Sn deposit; 9. Baoemba Sn deposit; 10. Guanxian Pb–Mo deposit (Hou et al., 2003b); 11. Dinggoukou Au–Ag deposit (Huan et al., 2011); 12. Xionglongxi Au deposit (Huan et al., 2011); 13. Erkunshan Pb–Ag deposit (Huan et al., 2011); 14. Jiaduoling Sn deposit; 15. Hailong Sn–polymetallic deposit (F.L. Zhu et al., 2011); 16. Xiaogangou Au deposit; 17. Jinchang Au deposit (Xie et al., 2004); 18. Hongshan Cu-Pb deposit; 19. Najiaoxi Pb–Zn deposit; 20. Dapingzhang Cu–Zn deposit (Dong et al., 2005); 21. Chundu Cu deposit; 22. Tuoding Pb–Zn deposit; 23. Laochang Pb–Zn deposit; 24. Kuaci Cu–Zn deposit; 25. Sunan Pb–Zn deposit; 26. Baohuashan Sn deposit; 27. Baohuashan Sn deposit; 28. Sanjiacun Pb–Zn deposit; 29. Jiaogenma Sn deposit; 30. Wumulan Sn deposit (Ye et al., 2010); 31. Jintaishan Sn deposit; 32. Diantan Sn–Zn deposit; 33. Sanjiacun Pb–Zn deposit; 34. Tongchanggou Mo–Zn deposit; 35. Chundu Cu deposit; 36. Tuoding Pb–Zn deposit; 37. Tongchanggou Mo–Cu deposit (W.C. Li et al., 2011b); 38. Baji Sn deposit (Xu et al., 2012); 39. Sanjiaoxi Sn–Pb deposit; 40. Shiganghe Sn–Zn deposit; 41. Shaozhuang Sn–Pb deposit; 42. Yunlong Sn–W deposit; 43. Xinqi Sn deposit; 44. Xueshan Sn–Pb deposit; 45. Jinchangjie Au–Ag deposit; 46. Diantang Sn–Fe deposit (Chen et al., 2010); 47. Shangqin Pb–Zn deposit; 48. Qiansui deposits; the eastern belt hosts the Xuejiping, Lannitang, and Chundu deposits (Fig. 5). The ages and characteristics of mineralization in both belts are similar (Leng et al., 2012).
The Pulang deposit is the largest one in the eastern belt. Its orebodies are hosted in a quartz monzonite porphyry dike that cut a quartz–diorite porphyry dike. From core to margin, silicic, potassic, phyllic (quartz–sericite), propylitic, and hornfels zones are present in the mineralized porphyry bodies. The mineralization occurs as disseminated chalcopyrite in the potassic and phyllic zones or chalcopyrite veins within the alteration zones. Outside the host porphyry body, chalcopyrite mineralization occurs in hydrothermal breccia zones, and small sphalerite–galena veins occur in the nearby fractures (W.C. Li et al., 2011b). Re–Os dating of molybdenite associated with chalcopyrite in the main ore bodies of the Pulang deposit gives 235.4 ± 2.4 to 221.5 ± 2.0 Ma. These ages are within the range of zircon U–Pb ages (228–206 Ma) of the associated porphyry bodies (S.X. Wang et al., 2008; Pang et al., 2009; Q. Wang et al., 2011).

The Xuejiping deposit is the largest one in the western belt. It is mainly hosted in quartz–diorite and quartz–monzonite porphyry bodies that intruded the clastic–volcanic rocks of the late-Triassic Tumugou Formation. From core to margin, potassic, strong silicic and phyllic, argillic, and propylitic alteration zones occur in the mineralized porphyry bodies. Copper mineralization is most closely associated with silicic and phyllic alterations, and occurs as stockwork and veins of variable sizes. Chalcopyrite and pyrite are the major phases, and chalcocite, cuprite, galena, sphalerite, and molybdenite are the minor phases in the ore bodies. Re–Os dating of molybdenite from the deposit yields an age of 221.4 ± 2.3 Ma (Leng et al., 2012).

The Yidun arc also hosts some important Cretaceous hydrothermal deposits such as the Liantong Sn–Ag deposit, the Xiaai Ag deposit, the Xiuxucu W–Mo deposit, the Tongchanggou porphyry Mo deposit and the Hongshan porphyry Mo–Cu deposit. The molybdenite Re–Os age of the Tongchanggou deposit is 88–82 Ma (W.C. Li et al., 2012) and that of the Hongshan deposit is 77 ± 2 Ma (Xu et al., 2006), which are similar to the zircon U–Pb age of 81.1 ± 0.5 Ma for the associated porphyry bodies (X.S. Wang et al., 2011).

In the Yidun arc, the deposits associated with late-Triassic porphyry bodies are dominated by Cu with minor Mo–Au. The younger deposits associated with late-Cretaceous porphyry bodies are dominated by Mo with minor Ag, W, and Sn. The temporal variation could be due to decreasing contribution of metals from the mantle with time. This is an interesting topic to investigate in the future.

5.2.2. Yangla skarn deposit in the Jinhshajiang suture

Copper mineralization in Yangla skarn-type deposit in the Jinhshajiang suture occurs as disseminated sulfides in the contact zones between granodiorite intrusion and country rocks. Sulfide minerals in the ore bodies are chalcopyrite, pyrite, bornite, chalocite, pyrrhotite, galena, sphalerite and magnetite. Skarn-type mineral assemblages include garnet and diopside, quartz and calcite. Re–Os dating of molybdenite from the deposit yield 230 Ma (X.A. Yang et al., 2011). These ages are similar to the zircon U–Pb age of 239–214 Ma for the associated granodiorite intrusion that is believed to have formed by crustal anatexis in a post-subduction setting (Gao et al., 2010; Y.B. Wang et al., 2010; X.A. Yang et al., 2011; J.J. Zhu et al., 2011).

5.3. Skarn and hydrothermal Sn–W deposits

The Yunlong Sn–W deposit in the northern Baoshan block is interpreted to be a metamorphic deposit (Jiang and Yu, 2004; Jiang et al., 2004). It is hosted in high-grade metamorphic rocks including migmatites of the Chongshan group. Orebodies occur as cassiterite–quartz–tourmaline veins. Tourmaline and cassiterite are characterized by LREE enrichments relative to HREE and variable Eu (0.16–2.51) and Ce (0.95–3.75) anomalies, indicating a parental metamorphic fluid (Jiang et al., 2004).

A cluster of polymetallic deposits with ages varying from 125 to 118 Ma (Chen, 1987; Dong et al., 2005; Xu et al., 2012) occurs in the NE corner of the Tenchong block. These include the Dadongchang skarn-type Pb–Sn–Zn deposit and the Tieyaoashan and Diantan skarn-type Sn deposits. In the central part of the Tengchong block, several hydrothermal Sn–W deposits such as the Xiaolishan–Dasongpo and Xinqi greisen-type Sn–W deposits are found to be associated with the Guyong pluton with zircon U–Pb ages from 76 to 68 Ma (Xu et al., 2012; Ma et al., 2013). In the SW part of the Tengchong block, Paleogene deposits such as the Laiilashan greisen-type W–Sn deposit with U–Pb age of 53 Ma for zircons from the associated felsic intrusive rocks (Xu et al., 2012) are present. In the western Simao block, several hydrothermal deposits such as the Songshan skarn-type Sn–W deposit and the Bulangshan skarn–greisen Sn deposit associated with the Lincang pluton (zircon U–Pb ages of 230–219 Ma) are found (C.M. Wang et al., 2013). These Sn and W deposits are interpreted to have formed by hydrothermal activities associated with the evolution of the peraluminous granitoids in the region. The granitoids are interpreted to have formed by crustal melting from the waning stage of subduction to post continental collision.

5.4. Skarn and hydrothermal Pb–Zn deposits

In the Baoshan block, both skarn-type and vein-type Cu–Pb–Zn (~Au) deposits are common. The former group includes the Jinchanghe, Hetapong and Luziyuan deposits and the latter group includes the Xiyi, Mengxing and Yangmeitian deposits. The skarn-type deposits are associated with granodiorite–granite plutons that intruded the Upper Cambrian strata whereas the vein-type deposits are controlled by faults and fractures in meta-sedimentary rocks.

The styles of mineralization of the skarn-type deposits in the Baoshan block are similar. The skarn-type mineral assemblages are garnet and calcic pyroxene which has been partially altered to actinolite, tremolite, epidote and chlorite in place. The associated mineralization contains sphalerite, galena, chalcopyrite, pyrite and magnetite, and gangue minerals such as quartz, calcite, and dolomite. Most important ore bodies occur in the contact zones between the intrusions and carbonate country rocks. However, some orebodies are present in the nearby faults in the wallrocks, such as in the Hetaoping deposit (Xue et al., 2008). Outward mineral zonation from the contact with the intrusion due to decreasing temperature is clear in the Jinchanghe deposit (Zhou et al., 2008). Rb–Sr isotopes of sulfides and co-existing quartz and K-feldspar from the Luziyuan deposit yield an isochron age of 141.9 Ma (F.L. Zhu et al., 2012) and an isochron age of 116.1 ± 3.9 Ma for the Hetapong deposit (Tao et al., 2010). H–O–S–Si–Pb isotopes of mineralized samples from the Hetapong and Luziyuan indicate that magmatic fluids and mantle-derived components played major role in ore formation (Xia et al., 2005; Xue et al., 2008).

The styles of mineralization of vein-type deposits in the Baoshan block are variable. The Yangmeitian deposit is controlled by faults between carbonates and clastic rocks of late-Ordovician strata. The mineralization is composed of azurite, bornite, chalcocite and tetrahedrite plus minor pyrite, galena and sphalerite. Gangue minerals are quartz and calcite. The orebodies of the Mengxing deposit are controlled by faults in the carbonates, clastic rocks and phyllite of middle-Silurian strata. The orebodies of the Xiyi occur within the fault zones in early-Carboniferous strata as veins composed of sphalerite, galena and pyrite plus minor calcite, quartz and barite.

5.5. Hydrothermal Au deposits

Several Carlin-like Au deposits, such as Gala, Ajialongwa, Xionglonxi, and Suoluguogou, occur within the Garzê–Litang suture zone (Fig. 5) (Zhang et al., 2012). The zircon fission-track ages of the deposits vary from 120 Ma to 80 Ma (Huan et al., 2011). Hydrothermal Au-bearing deposits, e.g., Erze with a siderite Rb–Sr age of 118 ± 26 Ma (Zheng et al., 1995), which is similar to those of the Carlin-type Au deposits
Fig. 6. Temporal distribution of the evolution of Tethys oceans and the related ore deposits in the Sanjiang region. The sources of data are the same as in Figs. 2 and 3.
have also been found within the Yidun arc terrane. As described above, the Yidun arc terrane was likely an accretionary arc terrane formed before Jurassic. Cretaceous granitoids are present in the Yidun arc terrane. The post-accretion granitic magmatism and hydrothermal activity in the Yidun arc terrane clearly postdated the closure of the Meso-Tethys but coincided with the subduction of the Neo-Tethys which was a couple of micro-continent blocks away from the Yidun arc. Based on these relations, we suggest that the subduction of the Neo-Tethys to the west was the driving force for crustal extension and associated granitic magmatism and hydrothermal mineralization in the Yidun arc terrane. This is another interesting topic to study in the future.

The Jinchang Ni–Au deposit occurs in the Ailaoshan ophiolite mélange. This fracture-controlled deposit was hosted in the Devonian strata and highly-altered ultramafic rocks. Reliable mineralization ages are currently not available due to lack of suitable minerals for dating (Ying et al., 2005; LQ. Yang et al., 2010, 2011). Hence, the origin of this deposit in the context of tectonic evolution in the region is still unknown.

6. Summary

In the Sanjiang region, the Proto-Tethys ocean was present from 502 to 401 Ma based on recently discovered ophiolites and igneous rocks. The closure of the Proto-Tethys branch ocean in early-Devonian was succeeded by the Paleo-Tethys ocean. The Paleo-Tethys comprised a main ocean and three branches, Ailaoshan, Jinhajiang and Garzê-Litang. They were bounded by Gondwana-derived continental blocks and were consumed by oceanic subduction which lasted until late-Triassic. Hereafter, the evolution of the Baoshan and Teqongchong blocks was largely influenced by eastward oceanic subduction of the Meso- and Neo-Tethys from late-Permian to middle-Cretaceous and from late-Cretaceous to ~50 Ma, respectively.

Many important mineral deposits in the Sanjiang region are linked to the evolution of the Proto-Tethys and Paleo-Tethys oceans. The most important VMS deposits in this region occur in the middle-Silurian back-arc basins, Carboniferous oceanic islands, and Triassic rifted zones in continental margins (Fig. 6). The most important porphyry deposits in the region occur in the Yidun arc, associated with granodiorite–plutonite plutons formed during the subduction of the Garzê-Litang oceanic plate beneath the Zhongga block. The production of the Cretaceous granitoids in the Yidun arc was contemporary to the subduction of Neo-tethys oceanic plate subduction, and thereby it was considered to be triggered by the later. Another possible factor contributing to the magmatism is the closure of the Shudu arc-back basin developed in the Paleo-Tethys oceanic main basin and three branches, Ailaoshan, Jinshajiang and Garzê–Litang. This fracture-controlled deposit was hosted in the Devonian strata and highly-altered ultramafic mélange. This deposit is currently not available due to lack of suitable minerals for dating.

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