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The endogenetic metallogeny of northern Laos and its relation to the intermediate-felsic magmatism at different stages of the Paleotethyan tectonics: A review and synthesis

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ABSTRACT

Northern Laos is at the junction of the Paleo-Tethys convergence and assemblages of several crustal blocks such as the Sibumasu, South China and the Indochina blocks, and also comprises the Houayxay-Sukhothai, the Simao-Phongsaly, the Louang Phrabang-Loei, the Truong Son and the Song Da terranes. During the amalgamation of the terranes derived from Gondwana, calc-alkaline magmatic rocks, peraluminous magmatic rocks, sub-alkaline volcanic-intrusive complexes, and alkaline rocks and related endogenetic metallogenic systems were emplaced in multiple stages during subduction-collision and post-collision events. According to chronological order, the tectonic-magmatic development processes and the metallogenic assemblages can be divided as follows: (1) Subduction arc related magmatic hydrothermal metallogenic systems, formed in calc-alkaline magmatic rocks due to the initial subduction during the late Carboniferous including porphyry Cu-Au deposits, skarn and epithermal Cu-Au deposits; (2) Arc-continent collisions and back-arc extensional settings and associated magmatic hydrothermal mineralization with calc-alkaline porphyry Cu-Au deposits, as well as alkaline porphyry and epithermal Cu-Au deposits during the early Permian; (3) Collisional orogenic magmatic hydrothermal metallogenic systems formed in the late Permian to the early to middle Triassic comprising high alumina magmatic rocks with Au-Pb-Zn(Ag)-Fe-Cu deposits associated with both orogenic type and hydrothermal vein type, and; (4) Post-orogenic extensional tectonic-hydrothermal metallogenic assemblages, which were formed in calc-alkaline to alkaline rocks within a extensional tectonic setting during the late Triassic-early Jurassic, including: porphyry Cu-Mo-Sn deposits, porphyry-skarn and epithermal Cu-Au deposits, and also subalkaline volcanic-intrusive complex-related hydrothermal stratabound Cu-Pb-Zn and Au-Sb-Hg deposits. Further detailed studies and classification of metallogenic assemblages in Laos is of significance to understand the nature and timing of different mineralization styles in relation the evolution of the Paleo-Tethys.

1. Introduction

The tectonic evolution of convergent margins occurs in several stages and episodes (e.g., Groves and Bierlein, 2007), and the corresponding metallogenic systems are controlled by the tectonic processes and structural settings formed during the entire geodynamic framework (Hou, 2010). Therefore, the study of regional metallogenic types, their characteristics and ages are profoundly affected by the tectonic evolution of the convergent margins. Northern Laos provides such an opportunity to study since it is a region consisting of the various segments of the Paleo-Tethys Ocean and the converging multi-terranes (Fig. 1). Tectonically, it belongs to the amalgamation zone of the Kontum, Sibumasu, and South China blocks (Fig. 1a). The Houayxay-Sukhothai terrane, the Luang Prabang-Loei, the Truong Son, Song Da and the Phonsaly-Simao terranes are between these three blocks (Fig. 1; Khin Zaw et al., 2014; Metcalfe, 2011; Sone and Metcalfe, 2008; Wang et al., 2016). These blocks and terranes were originally separated from northern Gondwana since the late Paleozoic and drifted within the Paleo-Tethyan Ocean, then later joined together by the terrane accretion in the present Southeast Asia region. These tectonic processes are first manifested by low-angle subduction of oceanic crust and arc-continent collision, followed by transformation into collisional orogenic

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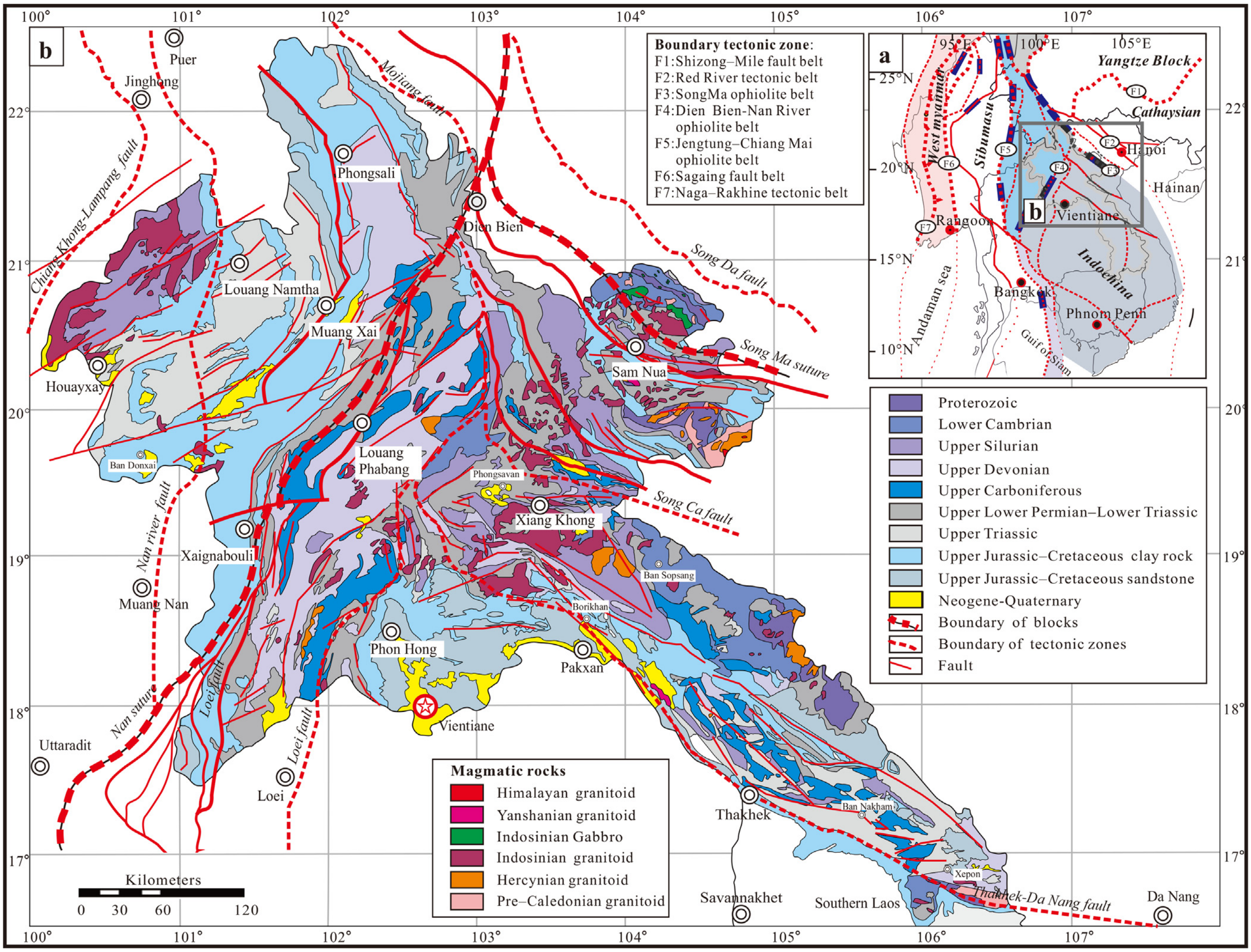

Fig. 1. A brief map of the geology in northern Laos PDR (modified after Tien et al., 1991).

belts and a post-orogenic extensional environment during the late Palaeozoic to Mesozoic (Khin Zaw et al., 2014; Richards, 2015). Recent research data show that the intermediate-felsic magmatic activity in the Truong Son tectonic belt corresponds with those within the Song Ma suture (Shi et al., 2015; Wang et al., 2016; Qian et al., 2019). In comparison, the intermediate-felsic magmatic activities in the Luang Prabang-Loei and Sukhothai belts correspond to the subduction resulting from the closure of the Paleo-Tethys Ocean (Wang et al., 2018). These belts were formed within the four different tectonic stages, i.e., the beginning of subduction stage, an arc-continent collision stage, a continental orogeny stage, and a post-collision extensional stage. By studying the characteristics of major endogenous metal deposits in northern Laos, we recorded that most of the deposits were closely related to the magmatic activities at each different tectonic stage. A detailed study of the relationships between the tectonic stages and metallogenesis is of important significance to the understanding of the metallogenic mechanisms during the Paleo-Tethys convergence. Early studies already showed a relationship between the regional tectonics and metallogenesis along the Indochina Peninsula of Southeast Asia (Tien et al., 1991; Dickins and Tien, 1997), and they defined the metallogenesis according to the regional tectonic units (Lu et al., 2009; Shi et al., 2011). Although previous researchers have done considerable work in petrology and ore deposits, the geological mapping and research on the endogenetic deposits in Laos require further investigation. Many deposits and related magmatic events have not been constrained. Studies on the ore deposits are mostly based on the geological features and descriptions of an individual deposit. The detailed division and timing of the tectonic-magmatic activities and metallogenic systems are lacking constraint. This paper will, therefore, focus on the relationships between the different tectonic stages and the magmatic-hydrothermal metallogenic systems during the process of Paleo-Tethys convergence and tectonic transformation in northern Laos. The corresponding tectonic-magmatic mineralization is divided into four stages, namely a subduction arc magmatic-metallogenic stage, an arc-continent collision metallogenic stage, an intracontinental orogeny metallogenic stage and a post-collision extensional metallogenic stage. The relationship between the regional tectonic evolution and mineralization is also further reviewed and synthesized through the available information on ore deposit types, ore characteristics and metallogenic assemblages.

2. Geology and tectonic settings

Geotectonically, Laos belongs to the Eastern Tethyan tectonic domain (Richards, 2015). It is divided into three major tectonic blocks (i.e. Sibumasu, Indochina block and South China; Fig. 1). The Sibumasu block lies at the west and Indochina block in the east, which are bounded by the Nan-Uttaradit suture (Barr and Macdonald, 1987; Ueno and Hisada, 2001). The South China Block is located in the north and the Indochina block in the South (Tong and Vu, 2006; Cai and Zhang, 2009; Faure et al., 2014), both bounded by the Ailaoshan suture (Metcalfe, 1988; Bunopas et al., 1992; Trung et al., 2006; Vượng et al., 2013). Among these three blocks, the Tamky-Phuc Son suture (Lepvrier

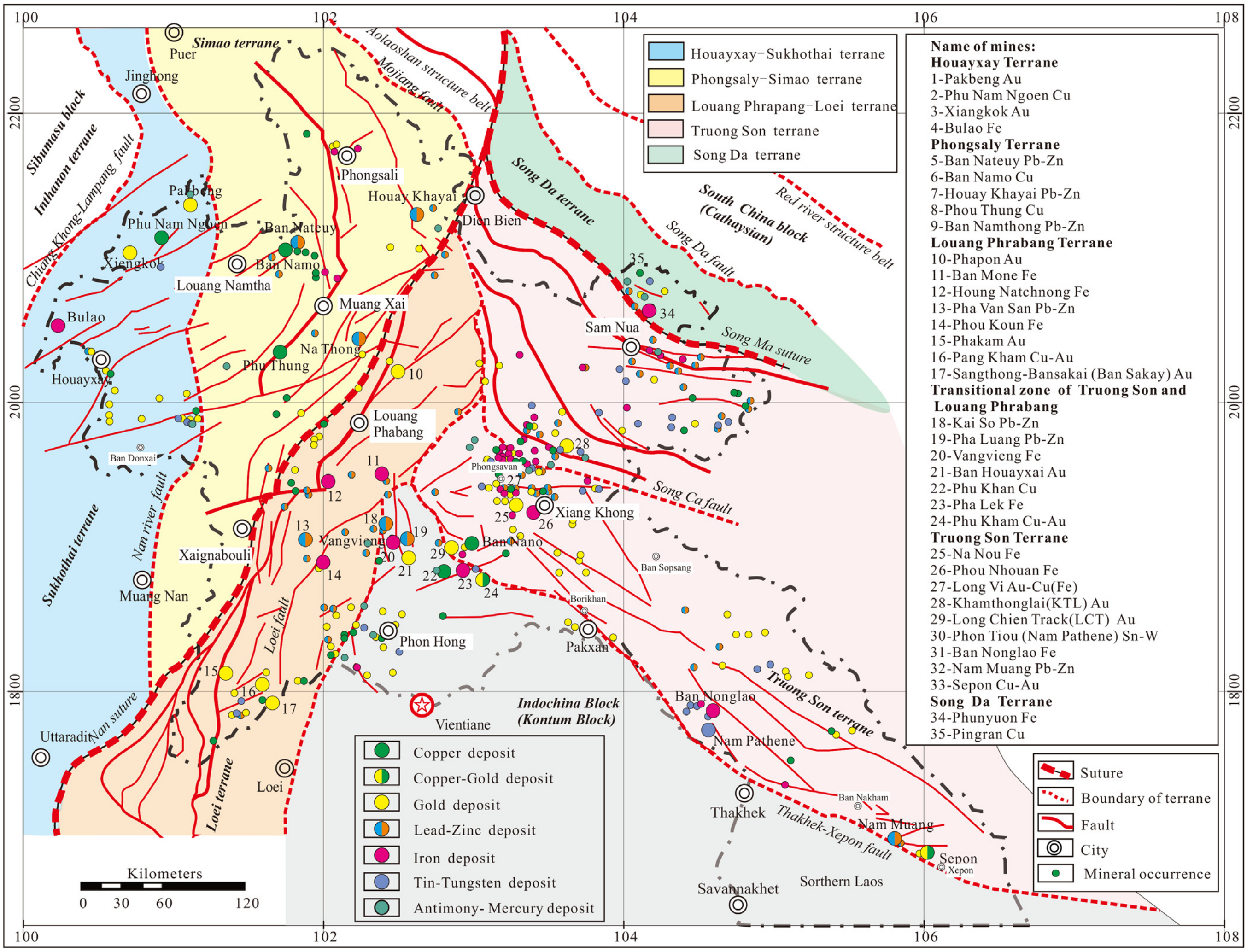

Fig. 2. Distribution of endogenetic metal deposits in northern Laos PDR (modified after Cromie et al., 2018; Kamvong et al., 2014; Khin Zaw et al., 2007, 2014; Leaman et al., 2019; Manaka et al., 2014; Tien et al., 1991; Zhao et al., 2011; Zhu and Wu, 2009; Khin Zaw et al., 2007).

et al., 2004), the Loei suture (Takositkanon et al., 1997) and the Jinghong suture (Sone and Metcalfe, 2008) were identified together with the Houayxay-Sukhothai, Phongsaly-Simao, the Luang Prabang-Loei, the Truong Son and the Song Da terranes (Fig. 2). According to the 1:1,000,000 geologic map of Laos (Tien et al., 1991), the geological, stratigraphic and structural features are described as follows:

2.1. Stratigraphy

The oldest known stratigraphic sequences are Proterozoic high-grade metamorphic gneisses and schists with amphibolite (Tien et al., 1991). The Proterozoic rocks are known to occur in the northwest and northeast of Laos. At Sepon District, noted some Proterozoic ages in older zircon cores rimmed by Permo-Carboniferous ages and interpreted the cores of zircons derived from older crustal blocks of the Indochina terrane (Cromie, 2010). The lower Paleozoic strata are mainly exposed at the eastern part of northern Laos. The Cambrian strata are mostly carbonate and clastic rocks together with intermediate to mafic volcanic rocks and some low-grade metamorphic rocks, such as marbles, greenschists, and quartzites. The Ordovician to Silurian strata are a sequence of fossil-bearing limestones, sandstones, and shales interbedded with thin volcanic rock layers. The upper Paleozoic to middle Triassic strata are mainly exposed in the northeastern part of Laos. The Devonian and lower Carboniferous rocks are marine sedimentary strata, consisting of clastic rocks, calcareous slates with limestone lenses and thin-bedded intermediate to mafic volcanic layers. The middle Carboniferous to middle Triassic strata consists of limestone, marl with sandstone, shale, siliceous rock and intermediate to felsic volcanic rocks (mainly lower Permian-middle Triassic rhyolitic, dacitic and andesitic lavas, tuffs and breccias, and small amounts of basalt). Carboniferous to Permian continental sedimentary sandstones, shales with thin marls and coal seams also occur in the vicinity of the Vientiane and Phonsaly regions. The upper Triassic to Cretaceous strata are mainly continental or marine-continental interfacial deposits, including late Cretaceous evaporite intercalations. Marine sedimentary rocks and intermediate to felsic volcanic rocks are mainly found in the Sam Nua area. Cenozoic strata largely occur as intermountain basin and pan-plain depositional sequences (Fig. 1; Tien et al., 1991).

2.2. Tectonics

Faults and fold structural alignment can be observed as two groups. Firstly, a NW-SE trending system in the northeast of Laos consisting mainly of the Thakhek-Xepon, Song Ca, Song Ma and Song Da faults. The Hercynian Truong Son fold belt is developed between the Thakhek-Xepon fault and the Song Ma fault. Superimposed are Triassic intracontinental tectonic-volcanic basins and tensional tectonic belts (i.e. such as the Nam Pathene, Song Ca and Sam Nua areas) with rhyolites, dacites, and basalts. A NE-SW trending system in the northwest mainly consists of the Nan River, Dien Bien, and Loei faults (Tien et al., 1991).

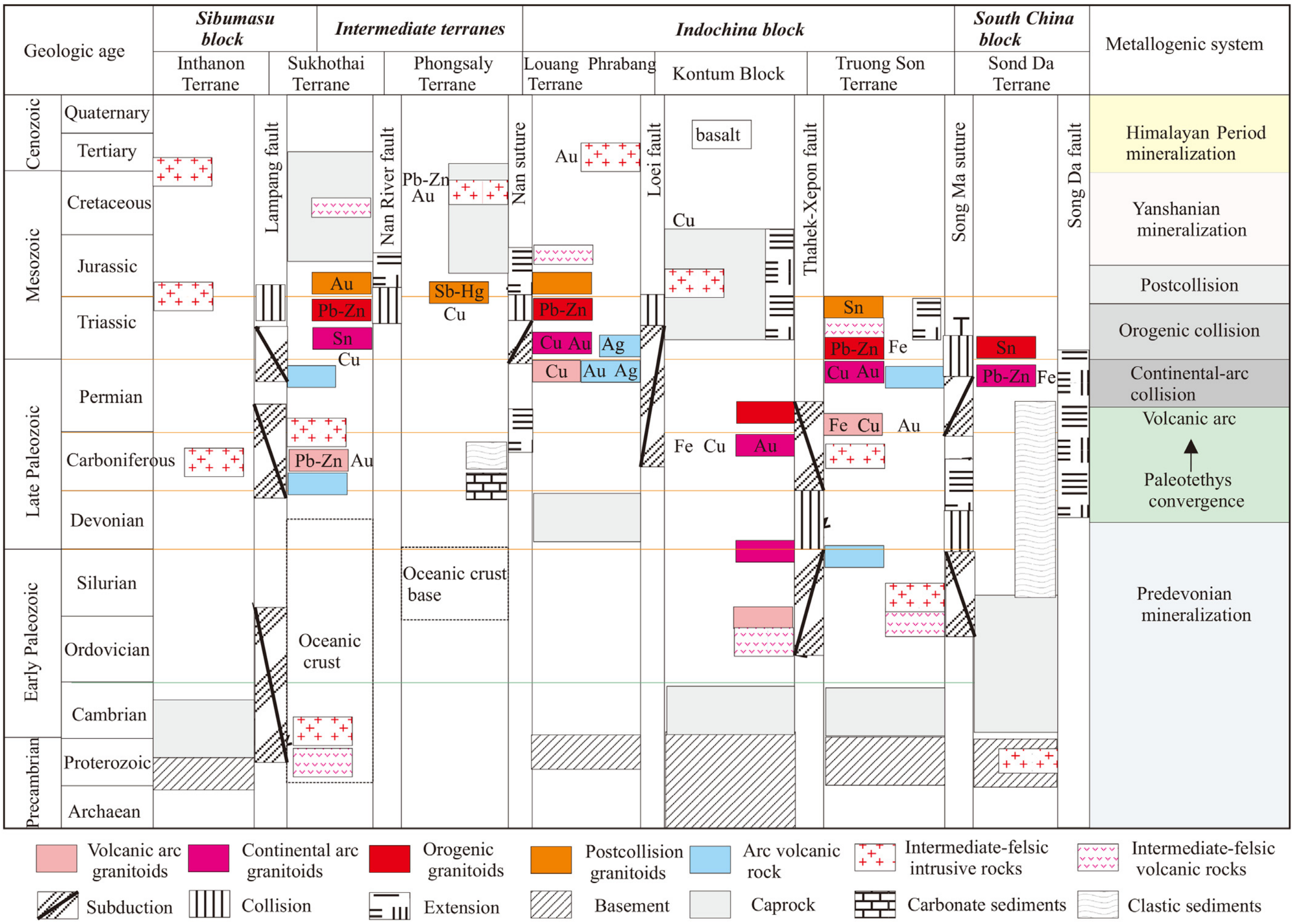

Fig. 3. Framework of endogenous metal assemblages and their relationships with the magma source in northern Laos PDR (Generation data of magmatic rocks are derived from Shi et al., 2015; Wang et al., 2016; Qian et al., 2015, 2016a, b, 2019; Wang et al., 2018).

The Loei fold belt with moderate-strong folding developed between the Dien Bien and Loei faults emplaced by some early Triassic intermediate-felsic rocks and also superimposed onto the late Triassic-Cenozoic intracontinental fault basins. The main ophiolite belts are distributed in the Song Ma and Luang Prabang areas (Fig. 1; Tien et al., 1991).

2.3. Magmatic rocks

Magmatic rocks in Laos were intruded mainly during the Proterozoic, Variscan, Indosinian, Yanshanian and Himalayan epochs, the majority of which were formed during the Indosinian epoch (Figs. 2 and 3; Tien et al., 1991). The Proterozoic intrusive rocks are sparse and mainly represented by gneissic biotite granites and gneissic tourmaline-bearing muscovite granites. Magmatism during the early Variscan period occurs in the north and is dominated by norites and gabbros. During the late Variscan, dunites, harzburgites, gabbros and gabbronorites are the main lithologies and are found mostly in the Sam Nua and Luang Namtha areas. The most important and widespread magmatic events in this region occurred during the Indosinian period and mostly comprised quartz diorite, granodiorite, quartz monzonite and biotite granite lithologies. Yanshanian magmatic intrusions (90–100 Ma) in the central and southern regions are dominated by intermediate to felsic rocks, mainly porphyritic granites and light-colored granite. The Himalayan magmatic activity was dominated by Pleistocene aged plateau basalt eruptions, mainly at the Xieng Khoang and Houayxai regions in southern Laos (Marutani, 2006; Manaka et al., 2014).

2.4. Tectonic evolution

During the Proterozoic, the Houayxay-Jinghong area in northwest Laos belonged to the Sibumasu paleocontinental block (Metcalfe, 1988; Bunopas et al., 1992), while southeast Laos belonged to the Kontum paleocontinental block (Cai and Zhang, 2009; Faure et al., 2014). The Xieng Khoang-Sam Nua region in central northern Laos formed as an oceanic basin in the late Neoproterozoic, accompanied by a low volume of intermediate to felsic magmatism. From the Cambrian to the middle Silurian, the Tethys was in an embryonic stage until the late Silurian, and it started to expand forming an island arc zone developed in the east of the Sam Nua area. During the late Paleozoic to Triassic (Tien et al., 1991), Paleo-Tethys oceanic plate subduction and an arc-continent collision occurred as four stages: (1) From the early-middle Devonian to early Carboniferous, the basin began to expand and was mainly filled by marine sediments and regionally associated with intermediate to mafic volcanics. Folding and greenschist facies metamorphism occurred in the middle Devonian-lower Carboniferous, (2) From the middle Carboniferous to the late Permian, the basin expanded and developed. In the east of Sam Nua, thick carbonate sequences were deposited accompanied by intermediate to felsic volcanics and intruded by mafic to ultramafic rocks. This was followed by NNW-trending folding and uplift in the late Permian. In western Laos and within the Luang Prabang area, sequences were predominantly of clastic rocks together with andesites, dacites and some basalt and then subsequently folded and uplifted along a NNE-trend. (3) From the early Triassic to middle Triassic, the basin gradually narrowed and comprised continental sedimentary rocks. The basin closed at the beginning of the middle Triassic, accompanied by large-scale magmatic activities. (4) From the late Triassic to the late Cretaceous, most areas were uplifted above sea level and a few intracontinental basins were formed mainly by faulting. Only a few areas remained marine or transitional between a marine and continental environment. In the late Cretaceous, the history of transgression ended, and a large intracontinental basin was formed in the Vientiane area (Fig. 1).

3. Terranes and mineralization associated with the intermediate-felsic rocks

The geological setting in Laos and its adjacent areas can be divided into two groups (Fig. 2a): One group is a NE-trending tectonic zone associated with the Nan-Uttaradit suture. Early studies separated this region into the Sibumasu block, and the Inthanon zone and Sukhothai terrane encompassing the Indochina block (Ueno and Hisada, 2001; Sone and Metcalfe, 2008; Barr and Charusiri, 2011). In addition, more recent studies identified carboniferous back-arc basins and multi-stage arc magmatic activities along the Luang Prabang structural belt (Qian et al., 2016a; Rossignol et al., 2016; Yang et al., 2016; Thassanapak et al., 2017), which regionally connects with the Loei structural belt and can be classified as a terrane accreted to the western margin of the Indochina block. The second group is an NW-trending tectonic zone related to the Song Ma suture. It includes the Truong Son and the Song Da terrane and the South China Block (Roger et al., 2012; Shi et al., 2015; Wang et al., 2016; Rossignol et al., 2018). In this study, we follow this division and model and also draw particular attention to the traditional names of tectonic groups. Accordingly, the northern Laos region is divided into the Houayxay-Sukhothai, the Phongsaly-Simao, the Luang Prabang-Loei, the Truong Son, and the Song Da terranes (Fig. 2). We delineate and describe their geological features and mineralization characteristics in detail, as represented in Fig. 2 and Table 1.

3.1. The Houayxay-Sukhothai terrane

The Houayxay-Jinghong terrane is located between the Chiang Khong-Lampang and Nan River faults (Fig. 2). To the south, it is connected to the Sukhothai arc terrane in Thailand (Barr, 1991; Sone and Metcalfe, 2008). The sedimentary rocks were formed mainly in the middle to the upper Paleozoic and granitic rocks during the late Paleozoic. The strata include upper Carboniferous-Triassic terrigenous clastic rocks, limestones, and volcanic rocks comprising Permian-Triassic dacites, andesites, and basalts (Ueno et al., 2018). Late-stage folding formed the NE-trending fold belts that were unconformably overlain by late Triassic to Cretaceous continental sandstones. The intrusive rocks are mainly early-middle Triassic island arc granites and late Triassic S-type granites (Wang et al., 2018). The related metallogenic types are represented by the Bulao skarn-type iron ore deposit, the Pha Yinshui hydrothermal copper deposit and the Xiangkok tectonic-orogenic gold deposit (Fig. 2).

3.2. The Phongsaly-Simao terrane

The Phongsaly-Simao terrane is located in the Phongsaly-Muong Say region and positioned between the Nan River fault and Nan Suture. This terrane extends northwards to China and is connected with the Simao terrane (Chonglakmani and Helmcke, 2001). The geological formations are mainly Mesozoic-Cenozoic sedimentary basin deposits onto a late Paleozoic crust that were folded during an orogeny in the late Hercynian-early Indosinian period and then later formed as intracontinental basins due to basin-mountain conversion. The strata are composed of middle-upper Triassic argillaceous clastic rocks and Jurassic-Paleogene red sandstones (Wang et al., 2017b). The Indochina granite intruded the middle-upper Triassic strata in the eastern part of Muang Ngeun, indicating that magmatic activity also existed during the process of basin rifting (Tien et al., 1991). The related metallogenic types are hydrothermal and strata-bound deposits, represented by the Ban Namo hydrothermal copper deposit and the Houay Khayap strata-bound lead-zinc deposit (Fig. 2).

3.3. The Luang Prabang-Loei terrane

The Luang Prabang-Loei terrane is located along the Luang Prabang-Loei range between the Nan suture and the Loei fault, which is connected in the south to Thailand with the Loei tectonic belt (Khin Zaw et al., 2014; Qian et al., 2016; Rossignol et al., 2016; Thassanapak et al., 2017; Yang et al., 2016). This terrane consists mainly of middle to upper Paleozoic, lower Mesozoic sedimentary sequences, and late Paleozoic granitic rocks. The oldest strata are represented by Devonian-Carboniferous sedimentary rocks which mainly include claystones, shales, and sandstones. The Carboniferous sedimentary rocks also include carbonates and coal-bearing shales. The Carboniferous-Permian sediments are mainly limestones and sandstones. Triassic sedimentary rocks are mainly volcanic clastic rocks, claystones and limestones. The Jurassic-Cretaceous sedimentary rocks are composed of red sandstones and claystones. These sedimentary sequences were intruded during the late Carboniferous-middle Triassic period by numerous mafic and intermediate to felsic intrusive rocks. A large number of middle Triassic calc-alkaline granodiorites are known (Fig. 1). The related metallogenic types are represented by the Vangvieng skarn type iron deposit, the Pan Van San hydrothermal type lead-zinc deposit, the Palton tectonic-orogenic type gold deposit and the Pang Kuam copper-gold deposit (Fig. 2). The Loei tectonic belt contains the Phu Lon oxidized skarn type copper-gold (Kamvong and Khin Zaw, 2009), the Phu Thap Fah reduced gold skarn deposit (Khin Zaw et al., 2009a,b, 2011, 2014), the Puthep skarn-porphyry copper deposit (Kamvong et al., 2014) and also the Chatree epithermal gold and silver deposit (Salam et al., 2014).

3.4. The Truong Son terrane

The Truong Son terrane is located along the Truong Son tectonic zone in Laos and Vietnam, positioned between the Song Ma Suture and the Thakhek-Xepon fault and extends southeast to Vietnam (Liu et al., 2012; Shi et al., 2015; Qian et al., 2019). Volcano-sedimentary rocks along the Truong Son were formed mainly in the middle to upper Paleozoic along with late Paleozoic granitic rocks. The basement in this zone is mainly Silurian granites and Carboniferous and Silurian limestones (Cromie et al., 2018; Smith et al., 2005; Tien et al., 1991; Thassanapak et al., 2018). From the late Carboniferous to early Triassic, magmatic activity occurred in a continental margin arc environment. The Song Ca fault which is a tensional tectonic belt developed in the middle-late Triassic. It is considered to be a boundary between the Southern Truong Son and the Northern Truong Son that are geologically different. The strata of the South Truong Son structural belt mainly consist of Ordovician-Silurian flysch sedimentary rocks, Devonian-Carboniferous calc-alkaline volcanic and intrusive rocks, early-middle Permian collisional orogenic granites and Jurassic intraplate granites (Lepvrier et al., 2004, 2008). The North Truong Son structural belt is characterized by Proterozoic migmatitzed amphibolites with biotite plagioclase gneisses, crystalline schists, and further Neoproterozoic-Early Cambrian metamorphic rocks. The Phanerozoic strata are mainly composed of late Carboniferous-Permian carbonate rocks, terrigenous clastic sediments, basalts, and andesites. The intrusive rocks are mainly a late Permian-early Triassic diorite-granodiorite-granite suite and Jurassic intraplate granites (Lepvrier et al., 2004, 2008). The Sam Nua rift zone of the middle-late Triassic period was also formed on the southern side of the Song Ma suture zone, and a volcanic-sedimentary rock series was developed in the upper Triassic (Fig. 1).

Table 1
Major endogenous metallic deposits and geological features in northern Laos PDR.

No.	Deposit No. location	Type of deposit	Wall rocks	Magmatic rocks	Mineralogenetic epoch	Structures	Cited references
1	Pakbeng Oudomxay Province	Lateritic, altered rock and quartz vein type gold deposit	Triassic-Jurassic andesite and andesitic tuff	Triassic altered andesite and silicification, cataclastic granite	Yanshanian period	NE-trending fault	Liu (2017)
2	Phu Nam Ngoen Luang Namtha Province	Volcanic hosted massive sulfide Cu deposit	Slate, tuffaceous sandstone and lapilli	Permo-Triassic (?) altered andesitic to rhyolite, basalt and basaltic andesite	Yanshanian period	NE-and NS-trending fault	Marutani (2006) Zhao et al. (2015)
3	Xiangkok Oudomxay Province	Shear zone type Au deposit	Siltstone and shale interbedded	Granodiorite and tonalite	Yanshanian period	NEE and NNW-trending fault	Chen et al. (2009)
4	Bulao Bokeo Province	Skarn-type Fe	Andesite; clastic rock, middle-acid volcanic to subvolcanic and volcanic clastic sedimentary rock	Granite, diorite and andesite	Indosinian epoch	NE and NW-trending fault	Zhu and Wu (2009)
5	Ban Nateuy Muang Nam Tha Province	Hydrothermal Cu deposit	Mesozoic red beds	Intermediate-felsic intrusion	Mesozoic	NE-trending fault	Wang et al. (2014a,b) Zhao et al. (2015)
6	Ban Namo Namo County, Oudomxay Province	Hydrothermal Cu deposit	Late Triassic clastic sedimentary sandstone	Diorite porphyry	Late Paleogene	Fault	Zhao et al. (2015)
7	Houay Khayai	Hydrothermal Pb-Zn deposit	Mesozoic red beds	Intermediate-felsic intrusion	Mesozoic	NE-trending fault	Wang et al. (2014a,b)
8	Phou Thung Oudomxay Province	Sedimentary-transformation Cu deposit	Late Triassic red beds	Diorite and granite-porphyry	Late Paleogene	Structural fracture belt	Zhao et al. (2015)
9	Ban Namthong Namo County, Oudomxay Province	Hydrothermal Cu-Pb-Zn deposit	Mesozoic red beds	Intermediate-acidic intrusion	Mesozoic	NE-trending fault	Wang et al. (2014a,b) Zhao et al. (2015)
10	Phapon Luang Prabang Province	Magmatic tectonic-hydrothermal Au deposit	Early Permian limestone	Andesite and andesitic tuff, locally diabase and dioritic porphyry	Late Triassic-Jurassic post-collisional	NNW-trending brittle fault system	Tong et al. (2015)
11	Ban Mone Xieng Khoang Province	Skarn type Fe deposit	Massive carbonates	Intermediate-felsic intrusion	Late Hercynian	Contact zone structure	Marutani (2006)
12	Houng Natchnong Luang prabang Province	Hydrothermal Fe deposit	Devonian-Triassic limestone	Late Hercynian granodiorite-monzonitic granite	Late Hercynian	NE-trending fault	Zhu et al. (2012)
13	Pha Van San Vientiane Province	Hydrothermal Lead-Zinc deposit	Permian limestone and Carboniferous carbonate	Intermediate-felsic intrusion	Middle Triassic	NNE-and near SN-trending fault	Wang et al. (2014a,b)
14	Phou Koun	–	–	–	–	–	–
15	Phakam	Leached “oxide cap” of the Phu Kham copper-gold deposit	Paleozoic sediments, tuffs and volcaniclastics	Diorite intrusion, 299–306 Ma	Late Carboniferous, 304 Ma	A low angle fault dipping northeast at ~20°	Tate (2005))
16	Pang Kham Paklay County, Luang Prabang Province	Skarn type Cu-Au deposit	Carboniferous to Permian mudstone, bioclastic limestone, shale and siltstone. Triassic andesite and andesitic tuff	Paleozoic-Mesozoic andesite and andesitic tuff	Caledonian period	NNE-trending fault and contact zone structure	Zhao et al. (2016) Ning et al. (2017)
17	Sangthong-Bansakai (Ban Sakay) Vientiane Province	Hydrothermal and Skarn Au deposit	Carboniferous-Cretaceous and Quaternary sedimentary rocks	Late Hercynian to Indosinian granite and granodiorite	Caledonian period	NNE-trending compress-shear fault, NE-trending thrust fault and near EW-trending structural altered belt	Marutani (2006)
18	Kai So Vientiane Province	Epigenetic deposit and skarn Zn deposit	Carboniferous-Permian limestone	Intermediate-felsicintrusive rocks	Middle Triassic	Contact zone	Marutani (2006) Karinen et al. (2011)
19	Pha Luang Vientiane Province	MVT- type Zn-Pb-Ag deposit	Permian limestone	Intermediate acidic intrusive rocks	Middle Triassic	NE-trending fault	Karinen et al. (2011)
20	Vangvieng Vientiane Province	Hydrothermal Fe deposit	Paleozoic-Mesozoic sedimentary rocks	Yanshanian granite	Yanshanian period	NE-trending fault	Zhu et al. (2012)

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Table 1 (*continued*)

No.	Deposit No. location	Type of deposit	Wall rocks	Magmatic rocks	Mineralogenetic epoch	Structures	Cited references
21	Ban Houayxai Xiangkhouang Province	Epithermal Au-Ag deposit	Thick Early Permian massive calc-alkaline andesite	Early Permian aphyric mafic dyke	Early Permian	NNW-trending fault	) Manaka et al. (2008, 2014)
22	Phu Khan Xaisomboun County, Vientiane Province	Porphyry, skarn and hydrothermal Cu deposit	Rhyolitic dacite	Granodiorite-porphyry and quartz-monzonite-porphyry	Late Permian-Middle Triassic	Structural fracture belt	Zhao et al. (2015)
23	Pha Lek Xienghouang Province	Skarn and hydrothermal-type Fe deposit	Middle Devonian carbonate, shale, altered sandstone and slate	Hercynian granite, granite porphyry and granodiorite, volcanic breccias, monozogranite, 280–317 Ma	Early Permian	NW-trending fault	Karinen et al. (2011) Wang et al. (2013) Hou et al. (2019)
24	Phu Kham Xiangkhouang Province	Porphyry-related (oxide) skarn Cu-Au deposit	Early Permian volcaniclastics and interbedded limestone, red bed siltstone (Carboniferous-E. Permian) Host volcanics: U–Pb zircon 306 ± 2 Ma	Diorite intrusion, 299–306 Ma	Late Carboniferous, 304 Ma	A low angle fault dipping northeast at ~20°	Tate (2005) Kamvong (2006, 2013) Kamvong et al. (2014)
25	Na Nou	–	–	–	–	–	–
26	Phou Nhouan Xianghoang Province	Skarn-related Fe deposit	Early Permian carbonate, sandstone and shale	Yanshanian biotite granite and granodiorite	Yanshanian period	NWW-EW-trending fault	He (2004)
27	Long Vi Xianghoang Province	Porphyry Au-Cu and skarn Fe-Au deposit	Devonian-lower carboniferous calc slate and mafic tuff	Porphyric quartz diorite and quartz diorite porphyry	Early Permian	EW-trending fault	He (2004)
28	Khamthonglai (KTL) Xiengkhouang Province	Stratabound porphyry-skarn style Cu-Au deposit	Late Carboniferous to Early Permian strongly deformed and altered interbedded siltstone, sandstone, micritic limestone and carbonaceous shales	Calc-alkali stocks	Permian, with Re-Os age of 289.4 ± 1.0 Ma	Brittle-ductile and ductile shear	Merriner (2013) Hotson (2009)
29	Long Chieng Track (LCT) Phu Bia (PBCA) Xiangkhouang Province	Low-S Epithermal polymetallic Au-Ag-Cu-Pb-Zn deposit	Early Carboniferous volcaniclastics, carbonaceous sediments, sedimentary breccias, and limestones. Andesite (U–Pb zircon 286 Ma) and volcanic breccias, U–Pb zircon (283 ± 4 Ma)	Early Permian porphyritic rocks including monzonite, quartz monzodiorite and feldspar- rhyolitic dacitic porphyry	Early Permian	NNW-trending fault	Manaka (2008) Manaka et al., 2007, 2008, 2009) Leaman et al. (2019)
30	Phon Tiou (Nam Pathene) Khammouan Province	Laterite type tin deposit	Phou Tiou basin: Early Paleozoic sandstone, siltstone and limestone; Late Paleozoic and Cenozoic strata	Late Paleozoic granitic rocks	Triassic-Early Jurassic	NW-trending fold and N-trending fault	Marutani (2006)
31	Ban Nonglao Fe Khammouan Province	Skarn-type Fe deposit	Devonian, Carboniferous and Permian sedimentary rock	Granite, granodiorite and granite porphyry	Early Triassic to Middle Triassic	Contact zone	Zhu and Wu (2009)
32	Nam Muang Savannakhet Province	Hydrothermal Pb-Zn deposit	–	–	–	–	–
33	Sepon Savannakhet Province	Carlin-type Au and skarn, porphyry Cu	Ordovician sandstone and calcareous shale; Silurian carbonite- shale with interbedded little volcanics; Devonian siltstone, shale, dolomite and jasperite	Rhyodacite-porphyry, SHRIMP U-Pb zircon age 300 ± 2 Ma (Permian–Carboniferous)	Early Permian (295–288 Ma)	Steep NW and/or E-W oriented faults	Loader (1999) Manini et al. (2001) Smith et al. (2005)) Cromie et al., 2004a, 2004b, 2006a, 2006b, 2007, 2018)
34	Phunyuon Houaphanh Province	Skarn type Fe	Triassic and Carboniferous limestone	Indosinian period intermediate-felsic intrusions	Indosinian period	Contact zone	Shao et al. (2015)
35	Pingran Houaphanh Province	Mafic-ultra mafic rocks related Cu-Ni sulfide deposit	Paleozoic metamorphic rocks: greenschist and sericite schist	Serpentine rock, pyroxene peridotite, granodiorite and mafic dyke	Mesozoic-Cretaceous	Near EW, SN, NNW and NW-trending fault	Guo et al. (2011) Lei et al. (2014)

Data of deposits modified after Tien et al. (1991),Khin Khin Zaw et al., 2007, 2014), Zhu and Wu (2009), Zhao et al. (2011),), Kamvong et al. (2014), Manaka et al. (2014),), Cromie et al. (2018) and Leaman et al. (2019). Generation data of magmatic rocks are derived from Shi et al. (2015), Wang et al. (2016), Qian et al. (2016a,b, 2019) and Wang et al. (2018).

3.5. The Song Da terrane

The northern part of the Song Ma suture belongs to the Song Da terrane. This terrane is mainly distributed in the north of Vietnam and covers a small area in the northeast of Laos (Trung et al., 2006; Vượng et al., 2013). The Song Ma suture zone comprises ophiolites, metabasic and metasedimentary rock assemblages, including serpentinized peridotites, gabbros, and basalts. They were emplaced by the southward subduction of the South China Block (Cai and Zhang, 2009; Faure et al., 2014). The Song Da terrane was a fragmented part from the southern margin of the South China Block at the end of late Paleozoic. Basement and cap rocks of the Song Da terrane are similar to those of the South China Block (Cai and Zhang, 2009). The intrusive rocks are mainly gabbros and granites from the late Permian to early Triassic (Fig. 1).

3.6. The Kontum block and Vientiane Meso-Cenozoic basin

The Kontum block is the oldest known continental block (Nakano et al., 2007) represented in Laos and its crystalline basement is mainly composed of Archaean mafic granulites, metabasic volcanic rocks, plagiogneisses, S-type granites, Proterozoic plagiogneisses, (gabbro) amphibolites, sillimanite schists, and migmatitic granites. The upper cap rocks are dominated by middle Triassic clastic rocks, carbonates, and a small amount of rhyolites. There are several stages of granitic magmatism from the Proterozoic to Mesozoic, felsic magmatism in the Mesozoic and pervasive basaltic volcanism in the Cenozoic. The Vientiane area consists mainly of Mesozoic-Cenozoic depression basins that are superimposed on the Kontum block. The geological formations mainly are Mesozoic to Paleogene. The sedimentary strata are mostly of Triassic-Paleogene continental salt-bearing red beds. Apart from the potassium salt-halite-gypsum deposits (Li et al., 2018), few endogenous metal deposits occur.

4. Main endogenic ore deposits

The geological and mineral exploration potentials of the endogenic deposits in Laos are gold, silver, copper, and iron, but also to a lesser extent tin-tungsten, lead-zinc and antimony-mercury (Fig. 2 and Table 1). The characteristics of the main deposits in Laos are herein described.

4.1. Gold deposits

The Xiangkok gold deposit (3): This deposit is located in Muang Long County, Luang Namtha Province. It occurs within the Houayxay terrane (Fig. 2), along a NE-trending fault zone (i.e. connected also with the Sukhothai terrane). The deposit occurs as quartz veins, formed in a middle Triassic post-collision environment, with the host rocks comprising granite and marine sedimentary rocks (Chen et al., 2009). The outcropping strata in the mining area are thin-layered massive sandstones and siltstones interbedded with silty mudstones and shales, which are rhythmically deposited. Mylonitization is found in the interbedded siltstones and shales, indicating the existence of ductile shear zones, on which brittle faults are superimposed. Intrusions are mainly biotite granodiorites and biotite diorites. The NE-trending faults control the strike of the ore bodies. Ore bodies occur mainly in the fractured zones of the granodiorites and their surrounding rocks and in the shear zones that are superimposed by brittle faults. The shape of ore bodies is vein-like and oriented along the strike of the faults. The mineralization zone is 5000 m long and 30–70 m wide, with grades ranging from is 0.5–4.0 g/t Au. Ore minerals include pyrite, pyrrhotite, chalcopyrite, galena, and sphalerite. Wall rock alteration types include silicification, pyritization, chloritization and sericitization. Mineralization occurs in multi-stages. The earliest stage has few sulfide-quartz veins penetrated along the shear zones, with a small amount of sparsely distributed and disseminated sulfides. During the main metallogenic stage, polymetallic sulfide-quartz veins were formed with pyrite, arsenopyrite and stibnite. The late metallogenic stage is present as penetrative quartz-calcite veins. This metallogenic type is interpreted to belong to shear zone type gold deposits, driven by magmatic-hydrothermal fluid circulation.

The Phapon gold deposit (10): This deposit is located in Bak Ou County, Luang Prabang Province and within the Luang Prabang terrane (Fig. 2). The outcropping strata in the mining area are Carboniferous argillaceous siltstones, marls, mudstones, lower Permian thick limestones, upper Permian andesites and basalts, middle and upper Triassic purple conglomerates, sandstones, siltstones, and arkoses (Tong et al., 2015; Hou et al., 2019). The NE-trending Luang Prabang faults cut through the lower Permian limestone. This setting also forms a group of NW-trending secondary faults, in which more than ten gold orebodies have been found. The largest is 650 m in length, 3.3 m in average thickness, 234 m in depth with an average grade of 6 g/t Au. The ore mineral is native gold and the gangue minerals are mainly calcite, followed by siderite and other carbonate minerals associated with small amounts of quartz, pyrite, realgar, and orpiment. The textures of ore mainly consist of microcrystalline textures formed by metasomatic alteration of limestone, fragmentation and mylonitization, and euhedral-granular textures in carbonate veins. Ore types include massive, breccia, and vein. The alteration of the surrounding rock is characterized by sideritization, limonitization, hematitization and weak silicification. There are two metallogenic types. Firstly, there are branch-like intrusive bodies discovered in this region. Their lithologies include monzonite, diorite, granodiorite and quartz monzonite. This metallogenic type belongs to a post-magmatic low-temperature hydrothermal gold system. The second type is non-magmatic. Although no magmatism has been found in and around the mining area, gold is associated with a structurally controlled, shear-related hydrothermal deposit type.

The Ban Sakai gold deposit (17): This deposit is located in Xanakham County, Vientiane Province within the Luang Prabang terrane (Fig. 2) and along a NE-trending tectonic magmatic belt. Carboniferous-Cretaceous and Quaternary strata are exposed in the mining area (Marutani, 2006; Tang et al., 2016). The main ore-hosting horizons are Permian black shales, gray-white argillaceous sandstones, and silicified sandstones, along with sporadic mafic to ultramafic volcanic rocks. The structures are predominantly NNE-trending compressive-tensional faults, NE-trending thrust faults and near EW-trending structural zones with alteration, the latter being the main gold ore-hosting structures. Extensive magmatic intrusions and multi-stage volcanic rocks, and also late Hercynian-Indochina granite are well developed. The Permian strata consist of tectonically modified belts, including altered cataclastic rocks together with massive quartz, limonite, pyrrhotite, disseminated pyrite and lensoidal quartz veins. More than twenty vein-type gold deposits have been discovered, which are stratiform and have lenticular veins. Ore minerals include limonite, pyrite, pyrrhotite, arsenopyrite, and a small amount of chalcopyrite and galena. Gangue minerals are mainly quartz, silicified sandstone, and tectonic breccia. The ore veins commonly include quartz and polymetallic sulfides. The textures of ores include metasomatic, euhedral–subhedral granular and cataclastic features. The ore types are mainly disseminated, brecciated, veinlet and massive in nature. The wall rock alterations include silicification, tourmalinization, sericitization, pyritization, argillization and propylitization. The gold mineralization is associated with pyrite and arsenopyrite, with metallogenic characteristics similar to orogenic gold deposits. The orebodies are located in the shear zones which were probably related to a deep magmatic activity. It is also interpreted that porphyry copper-gold deposits may also occur in the deeper part of the mining area due to the fact that the ore bodies show the transition characteristics from Au-As-Fe to Au-Cu-As from the top to the bottom.

The Ban Houayxai (21) and Long Chieng Track (29) Au-Ag polymetallic deposits: The Long Chieng Track (LCT) gold deposit is located in northern Laos, on the confluence of the Loei and Truong Son fold belts (Fig. 2). The deposits are hosted within Early Permian volcano-sedimentary rocks, which are part of a Late Carboniferous-Early Permian (310–270 Ma) volcanic-plutonic sequence. The Ban Houayxai deposit is comparable to a low-sulfidation epithermal mineralization system with a resource of 76Mt at 0.82 g/t Au and 7.0 g/t Ag and mining commenced in early 2012 (Manaka et al., 2007, 2008, 2014), whereas the LCT is considered as a subvolcanic polymetallic Au-Ag-Cu-Pb-Zn deposit at the transitional zone between the porphyry and epithermal environments and has a resource of 32Mt @ 0.77 g/t Au, 4.9 g/t Ag and 0.12%Cu at a cutoff grade of 0.3 g/t Au (Leaman et al., 2019). The Ban Houayxai Au-Ag deposit is confined within the Truong Son terrane where it occurs in an Early Permian volcano-sedimentary sequence. The Early Permian is related to the emplacement of the volcanic arc sequence, resulting from the southward subduction of an oceanic crust attached to the South China block beneath the Indochina terrane during the Early Permian (Manaka et al., 2014).

4.2. Copper-gold deposits

The Pangkham gold-polymetallic deposits (16): These deposits are located Paklay County, within the Luang Prabang terrane and occurs along the NE-trending regional fault and fold zones (Fig. 2). The mining area is composed mainly of Carboniferous-Permian sandy mudstones, bioclastic limestones, mudstones, argillaceous siltstones, and a Triassic volcanic rock series. The andesites and andesitic tuffs were generally exposed to propylitization, K-feldspar, carbonation, and locally silicification and sericitization alteration types. The subvolcanic rocks are diorite porphyries which intrude the Permian limestone and mudstone as dikes, stocks, and veins. Finely disseminated and veined pyrite and chalcopyrite are common in the contact zone (Zhao et al., 2016; Ning et al., 2017). The shape of ore bodies is controlled by the contact zone between the diorite porphyries and marbles. The contact zone consists mainly of faults and interlayered fractures. Skarn-related alteration comprises marbleization, epidotization, propylitization, chloritization and pyritization together with magnetite and chalcopyrite occurring along the contact zone. The ore bodies occur in layered, lenticular and vein-like structures. The main orebody is banded, with a length of 900–1200 m, extending 100–200 m downdip with a thickness of 1.2–19 m. Grades range from 0.25 – 6.13% Cu and 0.2–14.6 g/t Au. Ore minerals include pyrite, chalcopyrite, magnetite, pyrrhotite, hematite, specularite, arsenopyrite, limonite, goethite and malachite. The main non-metallic minerals are mainly skarn assemblages, including calcium-alumina garnet, diopside, tremolite, epidote, chlorite, quartz and calcite. The ores include massive, disseminated, brecciated and veinlet types. The ore textures are predominantly micro- to fine-grained, medium to coarse euhedral and xenomorphic granular. The superficial part of the deposits comprises skarn type copper-gold mineralization related to continental subvolcanic rocks and in the deeper parts there is also a possibility of porphyry type copper mineralization.

The Phu Kham copper-gold deposit (24): The deposit is located in the southwest of Xiang Khoang on the southern margin of the Truong Son terrane and along the Thakhek-Xepon fault zone (Fig. 2). The mine has a resource of 240 Mt at 0.55% Cu, 0.24 g/t Au and 2.2 g/t Ag in 2014 and is exposed within Carboniferous and Permian carbonate and pyroclastic rocks, with skarns and porphyry veins along low angle thrust faults. Granite porphyries and fine-grained granites intruded the country rocks (Kamvong et al., 2014). The contact zones are rich in garnet and magnetite. There are strong alteration zones in the granite porphyry with potassic alteration, sericitization and silicification. Ore bodies occur in the quartz-sericite-pyrite alteration zones. Skarn occurs in the contact zone between the granite porphyry and fine-grained granite and also the surrounding carbonate rocks. The ore bodies occurring in the skarn zone are lenticular and layered. The ore-bearing country rock of the tectonic fracture zone is volcaniclastic rock while the ore bodies are lenticular and vein-like in the altered zone of hematite-carbonate-chlorite-pyrite. The porphyry type ore minerals include chalcopyrite, pyrite, azurite, and malachite. The copper ores can be divided into reticulate veins and disseminated types. Skarn-type copper (iron, gold) ores are mainly composed of chalcopyrite, cyanite, pyrite, pyrrhotite, magnetite, siderite, and malachite. Zircon U-Pb ages of granodiorite porphyry and volcanic rocks related to mineralization yielded to 310–270 Ma ages and the metallogenic epoch is late Carboniferous-early Permian as evidenced by the Re–Os molybdenite age of 304.9 ± 1.7 Ma (Kamvong et al., 2014). The deposit was initially considered to be a typical network-disseminated porphyry copper-gold deposit, but its host rocks are mainly volcanic clastic rocks and skarn, followed by granite porphyry. This deposit is interpreted to be characteristic of porphyry-skarn-epithermal copper-gold metallogenic system, which also includes the Long Chieng Track and Ban Houayxai epithermal deposits nearby.

The Long Vi porphyry gold-copper (iron) deposit (27): This deposit occurs within the Truong Son terrane (Fig. 2). Two altered and mineralized porphyritic quartz diorite and quartz diorite porphyry bodies have been found in the mining area, which intruded the Devonian-Lower Carboniferous calcareous slates with intercalated sandstones and mafic volcanic (tuffaceous) rocks (He, 2004). The contact zone of the intrusive bodies is roughly conformed with the host strata. The porphyry-type gold (copper) and skarn iron-gold ore bodies are delineated at the southern side of the Long Vi intrusion. The porphyry gold ore body is controlled by a joint-fissure zone with a length of 200–300 m and a thickness of 10–50 m. Its distribution is closely related to finely fragmented granular quartz veins and branching veins. The ore minerals are mainly limonite, minor hematite, magnetite, pyrite and chalcopyrite. The gangue minerals are mainly sericite, quartz, feldspar and kaolinite. Gold occurs as fine natural gold with a maximum particle size of 15 μm. The grade of gold ore (oxidized) is (1.5–14.6) g/t Au, and the average copper content is (0.2–0.3) % Cu. Skarn-type iron-gold ore bodies occur in a 200–400 m long and 3.9–17.1 m thick skarn zone of the upper part of the intrusion. Gold ore grade range from 2.07–9.48 g/t Au, and total iron is 35–50% Fe (He, 2004).

The Sepon copper-gold deposits (33): The Sepon Mineral District (SMD) has copper and gold deposits that are located north of Xepon Town in Savannakhet Province and occurring nearby the Thakhek-Sepon fault along the southern margin of the Truong Son terrane (Fig. 2). The outcropping strata in the mining area comprise Ordovician sandstone-calcareous shale (Cromie et al., 2006a, 2006b, 2018; Loader, 1999; Manini et al., 2001; Smith et al., 2005), Silurian carbonate-shales and radiolarians-bearing chert (Thassanapak et al., 2018) with a small amount of volcanic rocks, and a Devonian sequence of siltstone-shale-dolomite. The intrusive rocks are early Permian rhyodacite (Loader, 1999). The strike of faults in the mining area comprise early E-W trends, cut by NW-trends and NE-trends. This is consistent with the axial direction of the fold zone. At least twenty copper and gold ore bodies have been found in a 40 km long by 10 km wide east to west corridor in the SMD. Three broad mineralisation styles are recognised in the SMD: distal sedimentary-rock hosted gold deposits (Carlin-like), proximal copper-gold skarns and quartz-stockwork porphyry copper-molybdenum. Extensive exploration and near mine resource development programs in the SMD since 2000 have significantly upgraded the indicated and inferred resources to 82.7 Mt @ 1.8 g/t Au for 4.75 million ounces of gold (at 0.5 g/t Au cut-off) in 8 separate but adjacent Carlin-like deposits, as well as a gold resource of 18 Mt @ 0.76 g/t occurring in an ironstone horizon over the Khanong copper deposit (Smith et al., 2005).

Near surface secondary copper mineralization occurs at copper-gold skarns at Khanong and in the upper levels of porphyry copper deposits at Thengkham (Smith et al., 2005, Cannell et al., 2015). Secondary supergene copper mineralization is characterized by ore zoning in order from surface to depth with: iron oxide-chalcocite-malachite-primary sulfide. Copper ore minerals include chalcocite, malachite, azurite, native copper and chalcopyrite. Porphyry-type sulphide copper mineralization mainly as chalcopyrite along with minor molybdenite and gold occurs in quartz stock-work veins, predominantly in rhyodacite porphyry. Skarn-type copper-gold mineralization typically occurs along faulted contacts between metasomatically altered rhyodacite porphyry and calcareous rocks (dolomite, limestone and calcareous shale) with massive, banded and disseminated sulphide ore types mostly with pyrite-chalcopyrite and minor gold. The surrounding rock alteration includes K-feldspar, propylitization, chloritization and silicification.

The distal sedimentary-rock hosted gold deposits (Carlin-like) occur in Silurian dolomite, Devonian shales and Permian rhyodacite, and are located approximately 1 km from the porphyry and skarn deposits (Cannell et al., 2015; Cromie et al., 2018; Smith et al., 2005). Their spatial distribution is controlled by lithologic interfaces, fault structures, folds, and other structures. Gold mineralization occurs in a micro-disseminated form (i.e. generally less than 10 μm) and is closely associated with pyrite. The gold bearing mineral assemblages include: native gold-pyrite-arsenopyrite-quartz-clay mineral and pyrite. The main types of wall rock alteration include decarbonization, argillization, and silicification.

4.3. Iron deposits

The Vangviang iron deposits (20): These iron deposits are located at Vangviang (Vang Viang) in Vientiane Province (Fig. 2), occurring within the Luang Prabang terrane and include the Ban Suan, Ti Vang, Ban San, and Ban Longkho mines (Zhu et al., 2012). The Carboniferous-Permian limestones and shales in the area are overlain by andesite and tuffaceous slates. Peraluminous calcareous granites intruded the andesites and caused sodic alteration, sericitization, silicification, carbonation, and pyritization along the contact zone. The ore bodies are layered and lenticular within andesite and at the contact zone, with an average ore grade of 40 wt% total Fe. The ore minerals are mainly magnetite with a xenomorphic granular texture and massive structure. Gangue minerals are mostly saussurite, sericite, quartz, calcite, and epidote. Metallogenesis is related to continental volcanic-granite intrusion. The ore deposit interpreted to belong to the contact metamorphic hydrothermal type and the age of iron ore mineralization is presumed to be middle Triassic.

The Phou Nhouan iron deposits (26): This iron deposit is located on the southern slope of Phou Nhouan Mountain in Mengkun County, Xieng Khoang Province (Fig. 2). The iron ore bodies occur in skarns hosted by biotite granite at the contact zones and have layered, lenticular and elliptical geometries (He, 2004). The main skarn host rocks are Carboniferous-Permian carbonates, metamorphosed sandstones, and slates. There are two ore belts along the E-W trending tectonic zone. The southern belt is 2 km long and 100–600 m wide, and the northern belt is 4 km long and 250–800 m wide. The total Fe content is more than 64 wt%. The ore minerals are mainly magnetite and include a small amount of hematite, limonite and skarn minerals. The genetic types of deposits may include hydrothermal and skarn types. The metallogenic age is inferred to be late Permian-middle Triassic, and the ore deposit appears to be a large-scale system (He, 2004).

The Pha Lek iron deposits (23): The deposit is located in the Vientiane Province and occurs at the western end of the Truong Son terrane (Fig. 2). The outcropping strata in the mining area are Devonian-Permian medium-thick layered limestones interbedded with sandstones and shales (Karinen et al., 2011). The middle-upper Devonian is the main-ore host rock sequence. Variscan granites, monzonitic granites, granodiorites and diorites intruded the Devonian system as irregular stocks. Fault structures are divided into three groups: NW, NE, and nearly E-W trending. Ore bodies occur in the outer contact zone of intermediate-felsic intrusive rocks and are layered, lenticular, and elliptical. Ore types can be divided into gravel-bearing iron ore, porous hematite and dense massive magnetite. Gravel-bearing iron ores have gravel-bearing sand, ferric silty sand, and ferric clay. The ore minerals are mainly magnetite, hematite, and limonite. The grade of iron ore is 40–50 wt% total Fe. Porous hematite ores have cavities, breccia and honeycomb textures. The ore minerals are mainly hematite and limonite with a small amount of magnetite. Dense, massive magnetite type ores have crystalline-granular and replacement textures. Magnetite is a main ore mineral, with a small amount of hematite and limonite. The metallogenic type is skarn iron ore formed by contact metasomatism. The volcanic-sedimentary type iron ores are also formed by volcanism and followed by weathering-leaching processes to form supergene iron ores. Skarn-type massive magnetite is the main ore type in the mining area which occurs as lenticular and layered forms with the metallogenic age from late Permian to early Triassic. The porous hematite of volcanic-sedimentary type is less exposed in the mining area.

The Ban Nonglao iron deposit (31): This iron deposit is located in Khammouan Province within the Truong Son terrane (Fig. 2). The strata of the deposit area are Devonian, Carboniferous and Permian sequence. Skarns were formed within the Permian carbonate (Zhu and Wu, 2009). The intrusive rocks are granites, granodiorites, and granite porphyries. The ore bodies are layered, vein-like and lenticular, occurring at the contact between the intrusive bodies and surrounding rocks. The exposed area is 530 m long and 360 m wide. The grades of the main ore range from 45.35 – 55.62 wt% total Fe. The ore minerals are mainly hematite and magnetite with microcrystalline textures and are massive. The genetic type of the deposit is contact metasomatic (skarn type). The metallogenic period is inferred from the early Triassic to middle Triassic, and the deposit may be a large-scale system.

The Bulao iron deposits (4): The iron deposits are located in Bulao Village, Bokeo Province (Houayxay- Sukhothai terrane, Fig. 2). The strata in the mining area are mainly lower Silurian (S_1b) and middle-lower Triassic ($T_{1\text{-}2}dw$). The former are mostly terrestrial fine-grained clastic rocks, which are epimetamorphic rocks of their protolith. The latter are mainly intermediate-felsic volcanic-subvolcanic rocks and sedimentary rocks associated with gray andesites, tremolite-epidote, epidote, and tremolite-garnet skarns and dacite and andesitic pyroclastic rocks (Zhu and Wu, 2009). Fault structures are divided into N-S and NW trends. The distribution of ore bodies is mainly controlled by the N-S trending faults, which coincide with the axis of syncline folds. The intrusive rocks are predominantly granites, diorites, and monzonite porphyries. Amphibole-bearing granites occur as stocks. The monzonite porphyries are of the late Indosinian-Yanshanian period. The ore bodies occur in the fractured zone of gray-green skarn and altered andesite of the Dange Formation. The main ore bodies are lenticular or layered. Together they are 446 m long, 32–56 m thick and have 20.96–54.38 wt % total Fe (Zhu and Wu, 2009). Ore minerals are dominated by primary massive magnetite and hematite, with a small amount of limonite and mixed ores that are exposed on the surface. Gangue minerals include biotite, tremolite, garnet, epidote and clay minerals. Ore texture is mainly xenomorphic granular. Ore types include dense massive, mesh-vein, banded and disseminated. Wall rock alterations and skarn assemblages include tremolite-garnet skarn, tremolite-epidote skarn, and epidote skarn. The Dange Formation consists of a tuff and andesite emplaced in the island arc-back arc basin, and the metamorphic-metasomatic skarn and magnetite were formed at the contact zone by later granite porphyry related magmatic hydrothermal process. The metallogenic type belongs to the skarn type system.

4.4. Copper deposits

The Phu Khan copper (iron) deposits (24): These copper (iron) deposits are located in Vientiane Province and occur in the transition zone between the Luang Prabang terrane and Truong Son terrane (Fig. 2). The outcropping strata in the mining area are Carboniferous carbonate rocks, which were intruded by granodiorite porphyry, quartz monzonite porphyry, and are overlain by the rhyolitic and dacitic volcanic complex. Copper ore bodies occur in porphyry, skarn and hydrothermal alteration zones (Zhao et al., 2015). Porphyry copper ore bodies occur in granodiorite porphyry, quartz monzonite porphyry, and the rhyolitic dacite volcanic complex. The main ore bodies are 500–1200 m in length, 15–75 m in thickness and more than 200 m in vertical extent. Copper-bearing minerals are chalcopyrite, azurite, bornite, and malachite. Wall rock alteration includes K-feldspar alteration, silicification and sericitization. Skarn-type copper (iron) deposits occur in the outer contact zone of the intrusions of felsic rocks. The larger ore bodies are 250–700 m in length and 5–50 m in thickness. The mineral compositions are chalcopyrite, azurite, bornite, magnetite, siderite, and malachite. The ore-bearing host rock is felsic volcanic rock with lenticular and vein-like ore bodies, with a length of 50–200 m and a thickness of 3–5 m. The metallogenic period is inferred to be late Permian-early Triassic.

The Ban Namthong copper deposit (22): The deposit is situated in Vientiane Province, which may be the same ore field that also hosts the Phu Kham Copper mine (Fig. 2). Currently a small copper deposit (Zhao et al., 2015) and the strata of the mining area are mainly Carboniferous carbonates. Intermediate-felsic intrusive rocks are common in the mining area (Zhao et al., 2015). Skarn zones and hydrothermal alteration zones with uneven widths are developed at the edge of the intrusions. Ore minerals are mainly chalcopyrite, and associated minerals are arsenopyrite, molybdenite, galena, and sphalerite, with local tin and gold mineralization. Based on the age of the intermediate-felsic intrusive rocks, the metallogenic period is interpreted to be late Carboniferous-middle Triassic.

The Ban Namo copper deposit (6): The deposit is located in the Namo County, Oudomxay Province and within the Phongsaly-Simao terrane (Fig. 2). The outcropping strata are upper Triassic red terrigenous clastic sedimentary sequences (Zhao et al., 2015). The structural features are predominantly faulting, and the strata are mostly block faulted. The fracture zones range up to tens of meters in width. The ore bodies have vein-like and lenticular geometries. Primary ore minerals are mainly chalcopyrite and pyrite. Secondary ore minerals are malachite, azurite, and native copper. The metallogenic type is primarily hydrothermal, and the ore-bearing hydrothermal fluids may have been originated from saline brine in sedimentary basins.

The Phu Thung copper deposit (8): This copper deposit is located in Oudomxay Province within the Phongsaly terrane (Fig. 2). The outcropping strata are mainly upper Triassic red terrigenous clastic sedimentary sequences (Zhao et al., 2015). The intrusive rocks are diorites and felsic porphyries and occur as branches and veins. The ore bodies are layered and veined within the structural fracture zone. The primary ore minerals are chalcopyrite, chalcopyrite with native copper, and the secondary ore minerals are malachite, covellite and azurite. Low-grade copper mineralization is common in the upper Triassic rocks. The ore bodies appear to be controlled by stratigraphic setting, and the genesis of the deposits may be of sedimentary-reworked type. Ore-forming materials may be sourced from red mudstone beds or buried igneous rocks beneath them.

4.5. Lead and zinc deposits

The Pha Luong lead-zinc deposit (19): The deposit is located in the northwestern part of Vangviang (Van Viang) County, Vientiane Province (Fig. 2). The outcropping strata in the mining area are mainly thick-bedded Carboniferous to Permian limestone and dolomitic limestone (Khin Zaw et al., 2014; Karinen et al., 2011). The strike of faults is mostly NE-trending and similar to the regional faults. The mineralization zone is about 10 km long, and the orebodies occur in veins in the structural fracture zone with a maximum thickness of 30 m. The ore minerals are mainly of galena and sphalerite. The gangue minerals are mainly calcite and barite with a small amount of pyrrhotite and pyrite. Fluorite occurs locally. The deposit was probably formed as a basin-system related to the opening of the Palaeo-Tethys from northern Gondwana during the Early Palaeozoic (Khin Zaw et al., 2014). The ore with higher lead grade contains 50% − 60% galena and 17% − 22% Pb. Brittle-ductile shear zones with a width of about 20 m are found on the south side of the mining area, in which lead-zinc mineralization was also discovered.

The Kai So lead-zinc deposit (18): The deposit is located near Vientiane within the Loei terrane (Fig. 2). The outcropping layers are light gray, gray-white medium thick crystalline limestones, and subordinate dolomitic limestone of Carboniferous-Permian age (Karinenet al., 2011). Ore bodies occur as veins and lenses along structural fracture zones, with the characteristics of clustering occurrence and zoning distribution. The size of ore deposits may reach large scale and a systematic exploration is required (Karinen et al., 2011).

The Pha Van San lead-zinc deposit (13): The deposit is situated in the Vientiane Province within strata of the Permian light gray terrigenous clastic rocks and Carboniferous gray carbonate rocks (Fig. 2). There are two groups of faults, one SE-trending and the other N-S trending (Wang et al., 2014a,b). The ore bodies form with vein and lenticular to irregular geometries, with lengths from 30 to 50 m and a thickness of up to 3 m. The ore minerals are mainly galena, minor stibnite and arsenopyrite. The silver in the ore is as high as 525 g/t Ag.

4.6. Tin and tungsten deposits

The Nam Pathene tin-tungsten deposit (30): The deposit is located in the Ban Nakham, Khammouan Province (Fig. 2), within a depression basin in the south of the Truong Son terrane (Marutani, 2006). Large NW-trending faults and anticlinal folds are developed in the mining area. Indosinian aged biotite monzonitic granites intruded the Devonian sandstones and Carboniferous-Permian limestones in the fold axis. The ore bodies are layered and bedlike in siltstone and skarn altered limestone at the contact zone. The main ore minerals are cassiterite, pyrrhotite, pyrite, arsenopyrite, and sphalerite, followed by chalcopyrite, galena, chalcopyrite, and covellite. The main gangue minerals are feldspar, quartz, epidote, and chlorite, followed by sericite, calcite, ilmenite, diopside, tremolite, tourmaline, a small amount of amphibole and biotite. Ore textures include xenomorphic-granular, phenocrystic and colloidal types. The ores occur as massive, disseminated and reticular in nature. The types of ores include altered sandstone-hosted type, skarn type, and greisen type. Among them, altered sandstone-hosted type and skarn type ores have heteromorphic granular to massive structure, and the disseminated greisen type ores are mesh-vein structure. Wall rock alteration includes silicification, and skarnization, followed by greisenization, chloritization, and sericitization. The metallogenic stage can be divided into early cassiterite-quartz formation and late cassiterite-sulfide formation. In the central fault zone of the mining area, there are many stages of intrusive magmatism, including Permian syenite porphyry veins, fine-grained granite vein and Triassic subvolcanic rock (containing tin). The main rock types of the Triassic subvolcanic rocks are granite porphyry, diorite porphyrite, which occur as cap and wall rocks. Sanematsu et al. (2011) reported Ar/Ar ages of granites from 253 to 199 Ma in the deposit area and the age of the granites are comparable to those in the Sn-bearing belt of SE Asia. It is concluded that the metallogenic types can be classified into skarn type and medium-high temperature hydrothermal filling type tin deposits.

5. Discussion

5.1. Paleo-Tethys converge and multi-terrane amalgamation

Laos and its adjacent areas are composed of three main crustal blocks (also regarded as microcontinents), including Indochina block, Sibumasu block, and South China block (Metcalfe, 1988). They have a similar tectonic history as Gondwana-derived allochthonous blocks, and they are thought to have been developed through four major geological and tectonic stages involving rifting, drifting, amalgamation and post-amalgamation (Sengör and Hsü, 1984; Lepvrier et al., 1997;

Metcalfe, 1999; Charusiri et al., 2002; Hall, 2002; Hisada et al., 2004). The marginal fold belts around the Indochina block include Sukhothai fold belt, Loei fold belt, and Truong Son fold belt, all of which are characterized by the emplacement of volcano-intrusive rocks (Khositanont et al., 2008; Khin Zaw et al., 2007; Khin Zaw and Meffre, 2007). The Sukhothai fold belt and the Loei fold belt are considered to be related to the westward and eastward subduction of a branch of the Paleo-Tethys oceanic crust, respectively, which followed by the closure of the ocean and the development of the Nan-Uttaradit suture. More geological processes and events were formed by the collision between the Indosinian and the Sibumasu blocks (Bunopas, 1981; Srichan et al., 2006), i.e., the eastward subduction of the oceanic crust of the Paleo-Tethys (Chiang Mai suture). The eastward subduction time of the latter is later than that of the former westward subduction. In recent years, many attempts have been made to define a relationship between these blocks and fold belts (Ueno and Hisada, 2001; Sone and Metcalfe, 2008; Barr and Charusiri, 2011). It is considered that the Indochina block is a composite block formed by the core of the Kontum continental nucleus and its multiphase marginal hyperplasia or amalgamation of terranes. The Upper Carboniferous-Triassic terrigenous clastic rocks, limestones and volcanic rocks are identified in the Houayxay structural belt, which contain Permian-Triassic arc volcanic rocks and continental basement (Miyahigashi et al., 2017; Thassanapak al., 2017; Ueno et al., 2018) and can be connected regionally with the Sukhothai belt (Metcalfe, 2011; Panjasawatwong et al., 2003; Sone and Metcalfe, 2008). Therefore, it is considered as a composite terrane on the eastern edge of the Sibumasu block. The Carboniferous back-arc basins and multi-stage arc magmatic activities (Qian et al., 2016b; Rossignol et al., 2016, 2018; Yang et al., 2016) are identified in the Luang Prabang tectonic belt, and is regionally connected with the Loei tectonic belt forming as a terrane accreting on the western margin of the Indochina block. In comparison, the Truong Son fold belt was formed due to the Paleozoic subduction and collision of the Indochina block and the South China block (Hutchison, 1989; Khin Zaw et al., 2014).

The Truong Son fold belt is a terrane attached to the north of Kontum Massif. The Tam Ky-Phuc Son suture (Lepvrier et al., 2004; Tran et al., 2014) was identified on the southern margin of Truong Son. It is therefore considered that there may have been an oceanic crust between the Truong Son belt and the Kontum Massif and that they may have been formed at the result of the late Paleozoic amalgamation. The Song Ma suture is recognized on the northern margin of the Truong Son belt, and a large number of granitoids were emplaced on the southern side. The tectonic environments were identified by rock types including arc granite, arc-continental collision granite, collisional orogenic granite, and post-collisional granite. Their formation is related to the southward subduction of the Song Ma oceanic plate which resulted the Song Ma suture (Liu et al., 2012; Shi et al., 2015; Qian et al., 2019). To the north of the Song Ma, there is another suture zone which belongs to the Song Da mirco-terrane (Trung et al., 2006; Vượng et al., 2013). It is a fragment separated from the southern margin of South China block at the end of Late Paleozoic. Its basement and caprock are similar to those of the South China block (Cai and Zhang, 2009). In the Phongsaly-Muong Say area, geological formations are largely represented by Mesozoic-Cenozoic basin deposits (Wang et al., 2017b), which can be connected with the Simao terrane from the north of Laos to China (Chonglakmani and Helmcke, 2001). Since its basement is carbonate-clastic sediments above the late Paleozoic oceanic crust, the Paleo-Tethys formed an inland basin. The closure of the Paleo-Tethys due to the mountain-basin transformation resulted in the formation of the Phongsaly-Simao terrane. Therefore, the geological-tectonic units in the northern part of Laos can be divided into five terranes, including the Houayxay-Sukhothai terrane, the Phongsaly-Simao terrane, the Luang Prabang-Loei terrane, the Truong Son terrane, and the Song Da terrane, which are sandwiched between the Indochina block, the Sibumasu block and the South China block (Fig. 1).

5.2. Relationship between ore deposit distribution and terrane attributes

A variety of the endogenetic metallic deposits (mainly including lead, zinc, copper, gold, silver, iron, tin and tungsten) are recognized in mainland SE Asia (Fan, 2000; Gatinsky, 2005; Khin Zaw et al., 2006, 2007, 2014). The occurrence of the endogenetic deposits is mostly confined to either the Sukhothai terrane, the Loei terrane or the Truong Son terrane, and thus an intimate relationship between the tectonic processes and ore formation within these terranes is reasonably attributed and considered (Khositanont et al., 2007; Khin Zaw et al., 2007). Comparatively, nearly all of the large endogenetic metallic deposits are distributed within the Luang Prabang-Loei terrane, and the Truong Son terrane in northern Laos, and only a few endogenetic metallic deposits are recognized in the Houayxay-Sukhothai terrane, the Phongsaly-Simao terrane and the Song Da terrane (Fig. 2, Table 1).

Several endogenetic ore deposits are discovered within the Luang Prabang-Loei terrane, closely associated with the occurrence of the late Palaeozoic to Triassic volcano-plutonic rocks (Khin Zaw et al., 2006, 2007, 2014). The deposits in the Loei district are characterized by diverse types, such as the Phu Thap Fah porphyry-related reduced skarn gold deposit, the Phu Lon oxidized skarn copper-gold deposit and the Chatree epithermal gold-silver deposit in Thailand. However, the types of deposits in the Luang Prabang region of northern Laos are different from the former; there are mainly the structurally controlled orogenic type gold deposits at Phapon, Phakam and Sakay, and the magmatic hydrothermal-type copper-gold deposit at Pangkuam, as well as hydrothermal lead-zinc deposit in Pan Van San. Although there are no volcano-plutonic rock outcrops in these mining areas, it is speculated that there are hidden porphyry bodies in certain areas. It implies that the formation of these deposits is related to the concealed intrusions (Tien et al., 1991). Based on geological characteristics of deposits (Table 1), the Phapon gold deposit and the Pan Van San lead-zinc deposit were formed in a collisional orogenic environment, while the Pangkuam, the Phakam and the Sakay gold (copper) deposits were formed in a post-collisional extensional environment. This assembly of the endogenetic metallic deposits in the Luang Prabang-Loei terrane mainly include gold, silver, copper and lead-zinc deposit, and the mineralization styles are classified as skarn, porphyry, structurally modified types, and sediment-hosted types.

Comparatively, a number of endogenetic ore deposits have been discovered within the Truong Son terrane, are closely associated with the occurrence of the Permian to Triassic volcano-plutonic rocks (Cromie et al., 2018; Khin Zaw et al., 2014; Liu et al., 2012; Qian et al., 2019; Roger et al., 2012; Shi et al., 2015). The Sepon mineral district includes both gold and copper deposits, and their metallogenic types are classified as the Carlin-like gold deposits and porphyry-skarn copper-gold-molybdenum deposits. The former occurs within decalcified and silicified calcareous shale and mudstone associated with fine-grained pyrite (Cromie et al., 2004a, 2004b, 2006a, 2006b, 2007, 2018), where the intrusions of rhyodacite porphyry dikes are thought to be closely related to the genesis of the gold mineralization. It is inferred to be an adakite-like intrusion by partial melting in the subduction of oceanic crust (Kamvong et al., 2014). The latter mineralized system is also recognized in the Sepon district including quartz stockwork porphyry molybdenum, skarn copper-gold, and carbonate replacement copper-gold, where the intrusions of quartz porphyry are thought to be related to late Carboniferous-early Permian (Cromie et al., 2006a, 2006b, 2007, 2018). The Phu Kham mineral district with granite porphyry and fine-grained granite occurrences are 306–299 Ma in age (Backhouse, 2004; Tate, 2005; Kamvong et al., 2014). There are many deposits related to the arc-continental collision environment, mainly including the Pha Lek, the Phou Nhouan iron deposits, the Ban Houayxai gold-silver deposit, and the Tharkhek copper-gold deposit (Hotson, 2009), as well as the Xam Nua copper-iron deposits. There are a large number of granites in the collisional orogenic environment, and they are mainly associated with the Lakxao gold deposit in Laos and the

Phuoc Son and the Bong Mieu gold deposits in the Phuoc Son area of Vietnam (Manaka et al., 2010). The deposits related to the post-collisional extensional environment are mostly distributed in the Mesozoic depression basin, the Song Ca tensional fault zone and the Sam Nua rift zone in the south of the Truong Son terrane, and mainly include the Nam Pathene tin-tungsten deposits and the Quy Hop tin deposit, as well as some lead-zinc deposits. An assembly of the endogenetic metallic deposits in the Truong Son terrane mainly include iron, copper-gold (silver), and lead-zinc deposit, and the mineralization styles are classified as skarn, porphyry, orogenic and sediment-hosted types.

The number of mineral deposits in the Sukhothai terrane are less than those in Luang Prabang-Loei terrane and the Truong Son terrane in northern Laos. The deposit types formed by arc collision related magmatic hydrothermal processes are mainly distributed in the Sukhothai terrane, including the Xiangkok gold deposit, the Pha Yinshui copper deposit, and the Bulao iron deposit, and the mineralization styles are classified as skarn and hydrothermal types. The deposit type related to the development of the Mesozoic basins are mainly distributed in the Phongsaly terrane, including the Ban Nateuy, the Houay Khayai, and the Na Thong lead-zine deposits, as well as the Ban Namo and the Phu Thung copper deposits, whose mineralization styles are classified as hydrothermal and sediment-hosted types.

5.3. Tectonic-magmatic stage and intermediate-felsic magmatic metallogenic system

Intermediate-felsic volcanic-intrusive rocks are widely distributed in northern Laos. In addition to a small amount of magmatic rocks formed in the pre-Devonian and post-Jurassic, a large number of rocks were formed in the Permian-Triassic, which is the main stage of tectonic transformation during the Paleo-Tethys convergence (Wang et al., 2018). According to the structural framework of the tectonic evolution of convergent margin (Groves and Bierlein, 2007; Hou, 2010), the tectonic transformation process in the study area can also be divided into four tectonic-magmatic stages (Qian, 2016; Qian et al., 2016a, 2016b, 2019; Shi et al., 2015; J. L. Wang et al., 2014; Wang et al., 2018; X. Y. Wang et al., 2017; Y. Wang et al., 2017; Z. C. Wang et al., 2014), i.e. initial subduction of oceanic crust, arc-continent collision, intracontinental orogeny and post-collisional extension, which lead to different mineralization and metallogenic assemblages respectively (Fig. 3).

Initial subduction stage: The calc-alkaline magmatic and adakitic rocks in subduction zones were formed by partial melting and assimilation of subducting plates penetrating into the hot mantle. The identified rocks in norther Laos include Phu Kham and Puthep adakites (e.g., Kamvong et al., 2014). The Phu Kham adakites in the Truong Son terrane were emplaced during Late Carboniferous (ca. 306 to 304 Ma), which were most likely formed during the initiation of subduction of the Ailaoshan–Song Ma ocean plates (Song Ma suture). The Puthep adakites in the Loei terrane were formed during the middle Triassic (ca. 244 to 241 Ma) (Kamvong et al., 2014), and they were most likely formed during the initiation of subduction of the Paleo-Tethys ocean plates (Chiang Mai suture?). These rock formation ages are largely coeval to Re–Os molybdenite ages (Phu Kham: ca. 304 Ma; Puthep 1: ca. 246 Ma) and suggest a close temporal links between the adakite formation and the copper-gold mineralization (Kamvong et al., 2014). Hence, the related metallogenic types in northern Laos are mainly porphyry Cu-Au deposit, skarn, and epithermal Au-Ag deposits, and the typical skarn deposits are the Phu Kham Cu-Au deposit and the Puthep Cu-Au deposit (Kamvong et al., 2014) as well as the Sepon Carlin-like and skarn Cu-Au deposits (Cromie et al., 2018). The epithermal Au-Ag polymetallic deposits are mainly of the Long Chieng Track, Ban Houayxai and Chatree (Salam et al., 2014; Manaka et al., 2014; Leaman et al., 2019).

Continent-arc collision stage: Subduction plates are continually modified and activated to form collision-related marginal arc calc-alkaline rocks and alkaline rocks at back-arc extensional backgrounds, and the identified rocks include subvolcanic-plutonic rocks at Phu Long, Pha Lek, Pha Yinshui and Bulao within the Luang Prabang-Loei terrane, the Truong Son terrane, and the Houayxay-Sukhothai terrane (Shi et al., 2015; Qian et al., 2016b; Wang et al., 2018). The main ore-forming assemblages are porphyry-skarn type Fe-Cu-Au deposits and epithermal Au-Ag polymetallic deposits (Hou et al., 2019; Kamvong and Khin Zaw, 2009; Leaman et al., 2019; Manaka et al., 2014; Salam et al., 2014). Among them, the Pha Lek iron deposit is a skarn type magnetite deposit. Its ore-forming parent rock is monzonitic granite formed in 280 Ma, whose tectonic setting is presumed to be a continental margin metallogenic system developed in the early stage of arc-continent collision (Wang et al., 2013; Hou et al., 2019). The Bulao iron deposit occurs in intermediate-felsic volcanic-subvolcanic rocks and pyroclastic sedimentary rocks of the middle-lower Triassic. Its tectonic setting is limited to island-arc-back-arc basin sedimentary environment. It is affected by magmatic hydrothermal metasomatism related to late granite porphyry intrusion to form skarn magnetite deposit of contact zone metamorphism (Yang et al., 2016). The Fe-Cu-Au metallogenic association mainly includes the Pang Kham Cu-Au (Fe) deposits, the Long Vi Au-Cu (Fe) deposits, and the Phu Lon Cu-Fe (Au) deposits (He, 2004; Kamvong and Khin Zaw, 2009; Zhao et al., 2016).

Collisional orogenic stage: During this process, the crust melted and formed collisional granitoids (Hou, 2010). The syn-collisional high-alumina magmatic rocks (Shi et al., 2015; Qian et al., 2016b; Wang et al., 2018) predominantly developed in northern Laos, forming Au-Pb-Zn(Ag)-Fe-Cu deposits related to orogenic types associated with lithophile elements and tectonically altered rock types as well as hydrothermal vein type. Among them, the most important type is the orogenic gold deposit, mainly including the Xiangkok gold deposit, the Phapon gold deposit, and the Ban Sakai gold deposit. This metallogenic type belongs to the post-magmatic low-temperature hydrothermal gold deposits controlled by tectonic alteration process (Tang et al., 2016; Chen et al., 2017; Guo et al., 2019). Also, hydrothermal Pb-Zn (Ag) deposits were formed due to basin-mountain transformation and thermally driven by magmatism. Typical deposits include the Pha Luang Pb-Zn (Ag) deposits and the Pha Van San Pb-Zn deposits (Karinen et al., 2011; Wang et al., 2014a,b), as well as the Phou Thung and the Ban NaMo sedimentary-Cu-Pb-Zn deposits (J. L. Wang et al., 2014; Z. C. Wang et al., 2014).

Post-collisional extension stage: During this process, the heat flow from asthenosphere rises up due to disintegration and lost of orogenic root or mantle subsidence (Hou, 2010). The formation of Sn-W deposits and alkaline porphyry and epithermal Au-Ag deposits were related to the late Triassic-early Jurassic calc-alkaline magmatism emplaced in the post-collisional extensional tectonic setting. Similarly hydrothermal, stratabound deposits related to subalkaline volcanic-intrusive complexes and also Carlin-like Cu-Pb-Zn and Au-Sb-Hg deposits were also formed. The extensional tectonic types are mainly occurred in the Sukhothai extensional basin, the Song Ca extensional tectonic basin, the Truong Son terrane marginal depression belt and the Sam Nua rift belt in the Triassic (Thassanapak et al., 2017; Rossignol et al., 2018). The main rock types are A-type granite, and quartz porphyry (Wang et al., 2017a, b; Cromie et al., 2018) and their related deposits include the Nam Pathene Sn-W deposits, the Ban Namthong Pb-Zn deposits (Marutani, 2006), the Sepon quartz stockwork Cu-Mo and sedimentary-hosted deposits (Cromie et al., 2018). The mineralization styles are classified as skarn, porphyry, hydrothermal, and sediment-hosted types.

6. Conclusions

Geotectonic trajectories in northern Laos indicate a composite crustal block including the NE-trending Sukhothai terrane, the Loei terrane, the NW-trending Truong Son terrane and the Song Da terrane, together with the Simao terrane and the Kontum block in the middle, which constitute a “λ-shape” structural framework. The Truong Son terrane has an older basement and overlying caprock while the Loei terrane is a tectonic group built upon a continental margin. The Sukhothai terrane is a Paleo-Tethyan arc terrane, and the Simao terrane is a sedimentary fold belt consisting of the late Paleozoic oceanic crust and a Mesozoic fault basin, whereas the Song Da terrane is a crustal fragment originally from the South China block margin. The amalgamation of these terranes is due to the convergence and closure of the Paleo-Tethyan ocean, and the multiple metallogenic assemblages are caused by their related geological attributes and tectonic processes.

During the convergence of the Paleo-Tethys, the intermediate-felsic magmatic-metallogenic systems were developed from the initial subduction, arc-continent collision, intracontinental orogeny to the post-collision extensional tectonic stage, in which porphyry Cu-Mo-Au deposits, skarn and epithermal copper-Au deposits related to adakite rocks that were formed by the initial subduction stage. During an arc-continent collision, Fe-Cu-Au deposits related to calc-alkaline arc volcanic-intrusive rocks were formed as well as the alkaline porphyry and epithermal Cu-Au-Ag deposits in the back-arc extensional setting. During the intracontinental collisional orogenesis stage, Au-Pb-Zn(Ag)-Fe-Cu deposits related to collisional granitoids and tectonically altered rocks and hydrothermal veins were formed. Epithermal Au-Ag deposits and Sn-W deposits related to calc-alkaline-meso-alkaline intrusive rocks and hydrothermal, stratabound deposits and Carlin-like Au-Sb-Hg deposits related to subalkaline volcanic-intrusive complexes were occurred during the extension stage after the collision. Due to the differences of the initial stage of subduction of the different terranes, the longevity and timing of arc magmatic activities are also different during the Paleo-Tethys convergence. It is apparent that the collisional orogenic stage of the Truong Son terrane is earlier than that of Luang Prabang-Loei terrane. But in general, different tectonic-magmatic stages have apparent distinctive relationships with the metallogenic assemblages. Further detailed investigations are required to further develop a better understanding of the timing, tectonics and metallogenesis towards a broader regional context which will increase interest in geology, ore deposit research and mineral exploration in the region.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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