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Geodynamic setting of Late Cretaceous Sn–W mineralization in southeastern Yunnan and northeastern Vietnam

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Abstract

The Sn–W mineralization in SE Yunnan Province, China and NE Vietnam shares many similarities. Through comparing the geological and geochronological data, we suggest the Sn–W deposits and the associate igneous rocks in the region represent one regional magmatic-mineralization event. To explore the geodynamic setting of these mineralization and magmatic activities, a geochronological dataset in the regions has been presented, containing data of this study and previously published. The dataset shows that the Late Cretaceous magmatic–mineralization–metamorphic activities widely distribute along the eastern Asian continental margin. Existing studies support that this is the product of the subduction of the Palaeo-Pacific Plate beneath the Eurasian continent, which probably formed under an Andean-type active continental margin setting. According to the exhibited data, we preliminarily conclude that the late Cretaceous magmatic and Sn–W mineralization activities in the southeast Yunnan and northeast Vietnam region is one part of this subduction activities and should have formed under the same geodynamic setting.

Keywords: Tin and tungsten mineralization; Southeastern Yunnan and northeastern Vietnam; Geochronology; Geodynamic setting

1. Introduction

The Sn and W mineral deposits in southern China were historically suggested to have formed as part of one mineralizing event (Hsu, 1943), although the W ores are mainly distributed in the eastern part of southern China, whereas most Sn deposits are in the western part (Chen et al., 1989; Chen and Zhu, 1993; Pei et al., 2001; Wang, 2010). Through extensive geochronological investigations during the past 20 years, the majority of the W deposits, some with significant Sn concentrations, in southern China (also called Nanling region) were proven to have formed at ca. 160–150 Ma (Mao et al., 2004, 2007; Hua et al., 2005a,b; Hu et al., 2012), and in an intraplate geodynamic environment, although essentially it is associated with the convergence of the Yangtze Block and Cathaysian Block (Mao et al., 2008a,b, 2013; Hu et al., 2012). But, the most economically significant of the Sn-dominant deposits, which mostly distribute in southeast Yunnan and Guangxi Provinces in the western part of southern China, including several world class deposits (i.e., Gejiu, Dachang and Dulong) are not part of Jurassic W ± Sn event. This regional Sn ± W metallogeny and its geodynamic setting in Late Cretaceous has remained poorly understood. Furthermore, several recent studies have pointed out that northeastern Vietnam, with similar Sn ± W deposits, is tectonically a part of the South China Block (Fig. 1a) (Sanematsu and Ishihara, 2011; Morley, 2012; Li et al., 2012; Goldfarb et al., 2014; Romer and Kroner, 2016). Through comparison of

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geological and geochronological data from the Sn deposits in southeastern Yunnan and northeastern Vietnam, we discovered that the Sn mineralization occurred ca. 98—78 Ma. Thus a preliminary understanding is that the Sn deposits in the southeast Yunnan and northeast Vietnam region are formed contemporaneously in Late Cretaceous and may share a same geodynamic setting.

In this paper, we focus on the Late Cretaceous tectono-magmatic—mineralization events in the southwestern part of the South China Block. We review the distribution, geological characteristics, and genesis of the Sn—W deposits and ore-related igneous rocks in southeastern Yunnan Province and northeastern Vietnam to document the extent and significance of the Late Cretaceous tectono-magmatic event. We also synthesize the reliable Late Cretaceous magmatic, mineralization, and metamorphism ages from the South China block and adjacent regions been published in the past ten years. Through plotting the ages on map, combining with published palaeo-geography data, we discovered that they present excellent distribution regularity thus give us relative clear idea on the their geodynamic background and magma affinity along the continental margin of the Late Cretaceous Eastern Asia, and we further suggest that the northeast Vietnam and southeast Yunnan region is one part of this.

2. Brief regional geological outline

The studied area is underlain by rocks of the Youjiang Basin (also called Nanpanjiang Basin) (Sanematsu and Ishihara, 2011; Mao et al., 2013; Cheng et al., 2013a,b). The southern boundary of the basin is the Red River Fault Zone (Fig. 1). Stratigraphically, five lithological units, some metamorphosed, have been recognized in this region, namely: (1) Precambrian gneiss, granulite, schist, and migmatite, with minor slate, limestone, sandstone, carbonate, and dolomite distributed in the northwestern part of the basin, which is a part of the Kangdian Massif (Li et al., 2013); (2) Cambrian to Silurian terrigenous and carbonate sedimentary rocks, deposited in a shallow marine environment (Roger et al., 2000); (3) Devonian to Permian strongly folded limestone, siliceous limestone, and terrigenous rocks; (4) Lower to Middle Triassic turbiditic sediments that include conglomerates, sandstones, tuffaceous sandstones, siltstones, and shales, with a large amount of intercalated carbonate (Chen et al., 2014); and (5) Quaternary sedimentary deposits distributes in the south-eastern part of northeastern Vietnam (Fig. 1b).

Plutons with ages from Proterozoic to Mesozoic have intruded parts of the sedimentary succession (Fig. 1b). Proterozoic granite is mostly developed in the Vietnam side of the

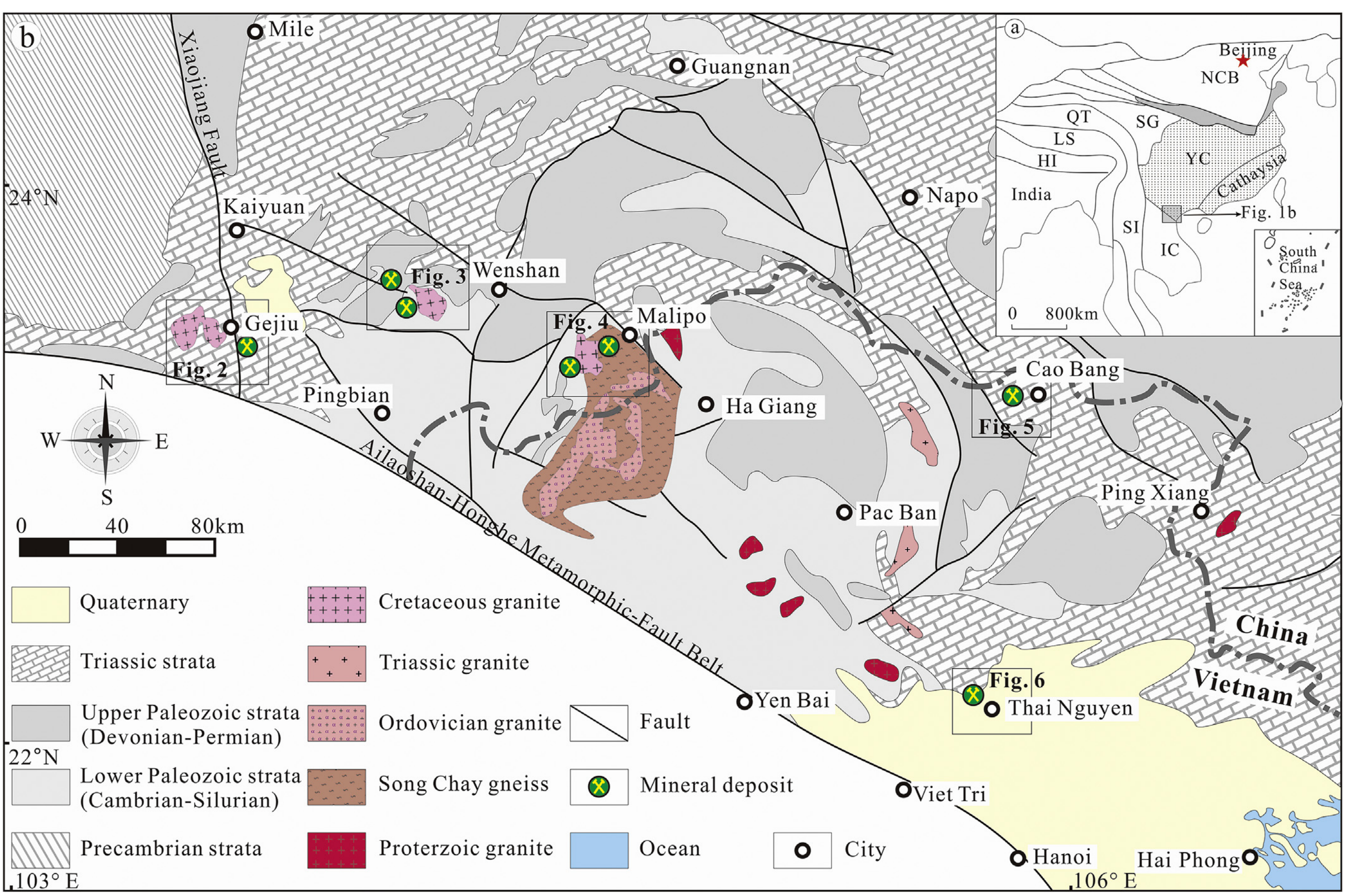

Fig. 1. a. Geological location of the studied area. b. Schematic geological map of the southeastern Yunnan and northeastern Vietnam.

basin (Li et al., 2013). Paleozoic, mainly Silurian, granites are exposed in the Song Chay massif that lies on the boundary between China and Vietnam. They include an augengneiss derived from a porphyritic monzogranite emplaced at 428 ± 5 Ma (Roger et al., 2000), and the Phan Ngame orthogneiss dated at 438.7 ± 3.5 Ma. Permian to Triassic plutons include the Phia Bioc granite and the Cao Bang mafic intrusive rocks. The Phia Bioc granite is porphyritic and undeformed, contains microdioritic enclaves, and yielded zircon LA-ICP-MS U–Pb ages scattered from 247 Ma to 242 Ma (Roger et al., 2012). Late Cretaceous igneous rocks are widespread throughout the basin margin. Gabbro, syenite, mafic enclaves, mafic dikes, porphyritic granite, and equigranular granite in the Gejiu district in southeastern Yunnan yield ages from 85 to 78 Ma (Cheng et al., 2013a,b). Various types of granites in the Bozhushan stock yield ages from 87 to 84 Ma (Cheng et al., 2010; Li et al., 2013). The Laojunshan complex of southeastern Yunnan, which contains porphyritic granites, equigranular granite, and granite porphyry, yield ages from 89 Ma to 83 Ma (Feng et al., 2013). The Pia Oac leucocratic monzonitic granite of northeastern Vietnam yields zircon U–Pb SIMS and LA-ICPMS ages of 94–87 Ma (Wang et al., 2011a,b; Roger et al., 2012). A group of Sn–W polymetallic deposits distribute around these late Cretaceous granitic plutons. A detailed geological description on these deposits has been complied in Appendix 1.

3. Late Cretaceous magmatism–mineralization geochronological frameworks in southeast Yunnan and northeast Vietnam

The tin polymetallic mineralization and related igneous rocks in the western South China Block have attracted some interests in past decades (Tu et al., 1984; Xie et al., 1984; 308 Geological Party, 1984; Wu et al., 1984; Wu and Liu, 1986; Luo, 1995; Mao et al., 2008a,b). However, the pioneering data are controversial as it indicates that these igneous rocks and ore deposits mostly formed during the Devonian to Late Oligocene (Wang, 1983; Yan et al., 2005). Another aspect, previous studies on the geology and timing of the Sn–W polymetallic deposits and related tectono-magmatic activities in northeast Vietnam were relatively limited, which led the understandings on the ore genesis and regional metallogeny are limited.

Fifteen high precise SHRIMP or LA-ICP-MS zircon U–Pb dating results, comprising ages of the gabbro, mafic microgranular enclaves (MMEs), syenite, mafic dykes, porphyritic granite and equigranular granite, demonstrate that all the igneous rocks in the Gejiu district formed between 78 Ma and 85 Ma (Cheng and Mao, 2010; Cheng et al., 2013a,b) (Appendix 3). Another 13 Ar–Ar muscovite/phlogopite dating results on different mineralization styles in the Gejiu district ranging from 77 Ma to 95 Ma. These similar ages between intrusions ore deposits indicate a genetic relationship between mineralization and magmatism.

Cheng et al. (2010) and Li et al. (2013) reported the ages of three phases from Bozhushan granitic intrusions in SE Yunnan province are 86.5 ± 0.5 Ma, 87.5 ± 0.7 Ma and 87.8 ± 0.9 Ma. As mentioned before, the Bozhushan granitic complex is considered to be genetically associated the periphery Ag–Sn–W polymetallic mineralization (Appendix 1), including the Bainiuchang Ag–Sn deposit.

Laojunshan is another Sn–W polymetallic ore related large granitic complex in SE Yunnan province (Fig. 1b). Three samples collected from Nanyangtian W polymetallic deposit, which locates in the eastern side of the Laojunshan complex, representing three phases of the Laojunshan granites yield ages of 87.2 ± 0.6 Ma, 86.8 ± 0.4 Ma and 85.9 ± 0.4 Ma, respectively (Feng et al., 2013) (Appendix 1). Li et al. (2013) analyzed the LA-ICP-MS zircon U–Pb ages of granites from Dulong Sn–Zn deposit, which locates in the western part of the Laojunshan complex (Appendix 1), yielding 84.3 Ma to 91.7 Ma. These results are consistent with the data reported by Liu et al. (2007), which are ranging from 86.9 Ma to 92.9 Ma. For the timing of mineralization in this district, Liu et al. (1999, 2000) reported the sphalerite Rb–Sr age of Dulong deposit is 76.7 ± 3.3 Ma to 79.8 ± 9.11 Ma, and Liu et al. (2007) further analyzed the TIMS cassiterite U–Pb age of 82.0 ± 9.6 Ma. The above data are consistent with the new molybdenite Re–Os and muscovite Ar–Ar dating results presented in this study (Appendix 2). All these data suggest the late Cretaceous is a major mineralization and magmatism period in the Laojunshan complex and periphery areas.

Late Cretaceous magmatic and mineralization ages have been reported in the northeast Vietnam in recent years. Wang et al. (2011a,b) reported the age of the Tinh Tuc Sn–W deposits in the east of Piaoac pluton in northeast Vietnam is 93.9 ± 3.0 Ma. By using of TIMS and LA-ICP-MS zircon U–Pb and mica Ar–Ar methods, Roger et al. (2012) and Chen et al. (2014) reported the ages of Piaoac granite are ranging from 83.5 Ma to 90.6 Ma. Another example in northeast Vietnam is the Nui Phao W polymetallic ore district (Fig. 1b), Sanematsu and Ishihara (2011) analyzed the ore-related granites by mica $^{40}Ar–^{39}Ar$ method and obtained four ages, which yielding from 81.5 ± 0.3 Ma to 82.8 ± 0.3 Ma. These two ages are quite consistent and are believed to represent the solidification of granite and the formation of associated Sn–W mineralization occurred in the Late Cretaceous (Sanematsu and Ishihara, 2011).

In summary, it is clear that the Late Cretaceous is a major episode of magmatic activities and the related large scale Sn–W mineralization distribute throughout the southeast Yunnan and northeast Vietnam. Combining the new data of this study and published igneous rocks and mineralization ages (Appendix 3), the histogram of these dating results demonstrating 100–80 Ma is the most important period of the mineralization and magmatism activities in the southeast Yunnan and northeast Vietnam region with a peak of 83–90 Ma (Fig. 2).

4. Distribution of Late Cretaceous magmatism–mineralization activities along Eastern Asian continental margin and the possible geodynamic links

4.1. Distribution of Late Cretaceous magmatism–mineralization activities along eastern Asian continental margin

A number of techniques have been applied to date the igneous rocks and ore deposits in eastern Asian continental margin, which have recognized one major episode of Sn–W mineralization and associated magmatic event in the Late Cretaceous. This mineralization event lasted for about 20 million years, ca. ~78 Ma to ~98 Ma, but with peaks of activities at 85–95 Ma (Appendix 3 and Figs. 2 and 3, and the appendix in Jiang and Li, 2014). The north-most late Cretaceous tectono-magmatic activities occurs in South Korea and southwest Japan. In the South Korea, a number of granites were dated at ca. 94–71 Ma (Jiang and Li, 2014, and the reference therein), and the basalts in this area with similar age are thought to be the products related to the same geodynamic

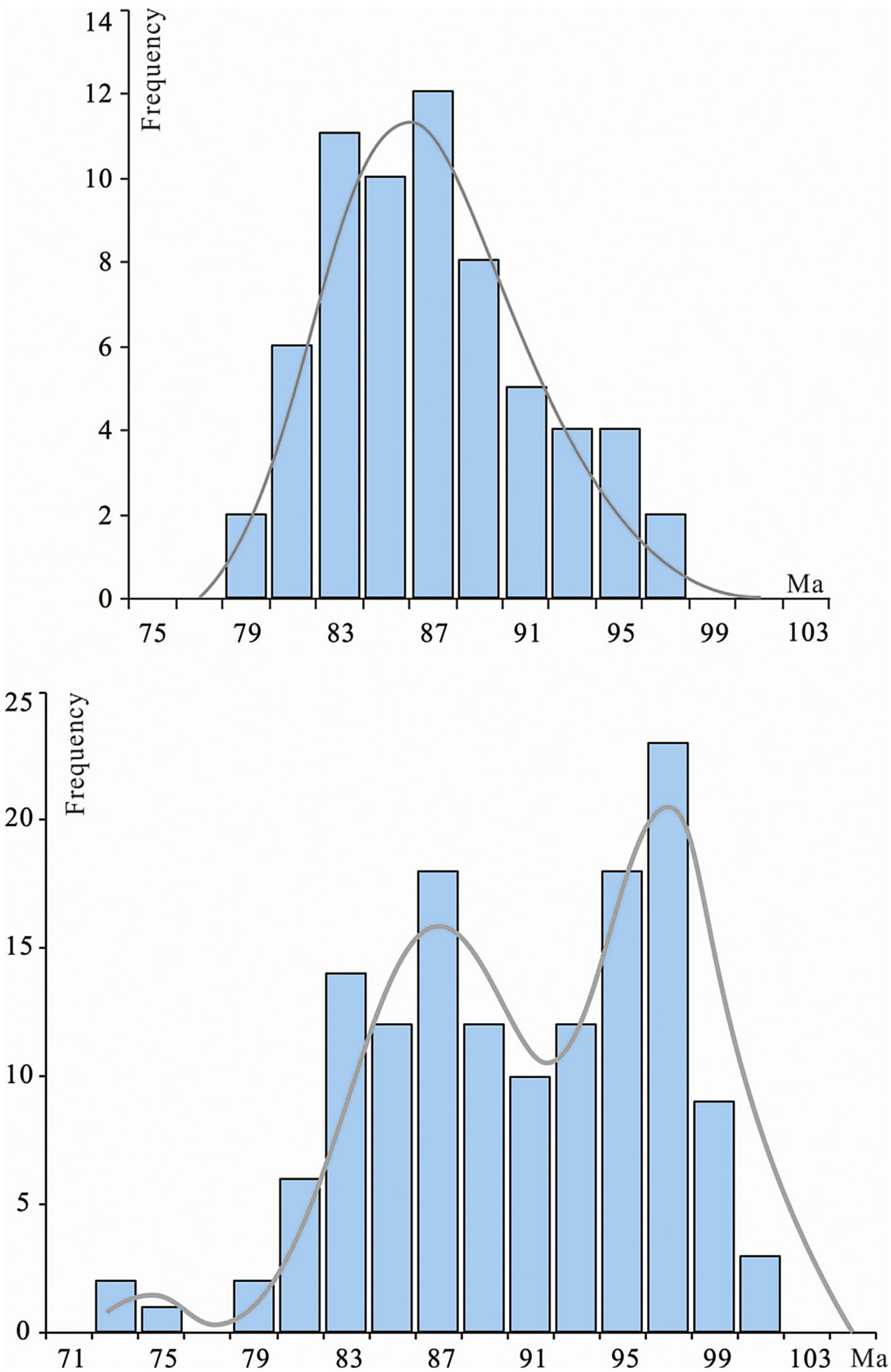

Fig. 2. Geochronological framework of the magmatic activities and Sn–W polymetallic mineralization in the southeastern Yunnan and northeastern Vietnam.

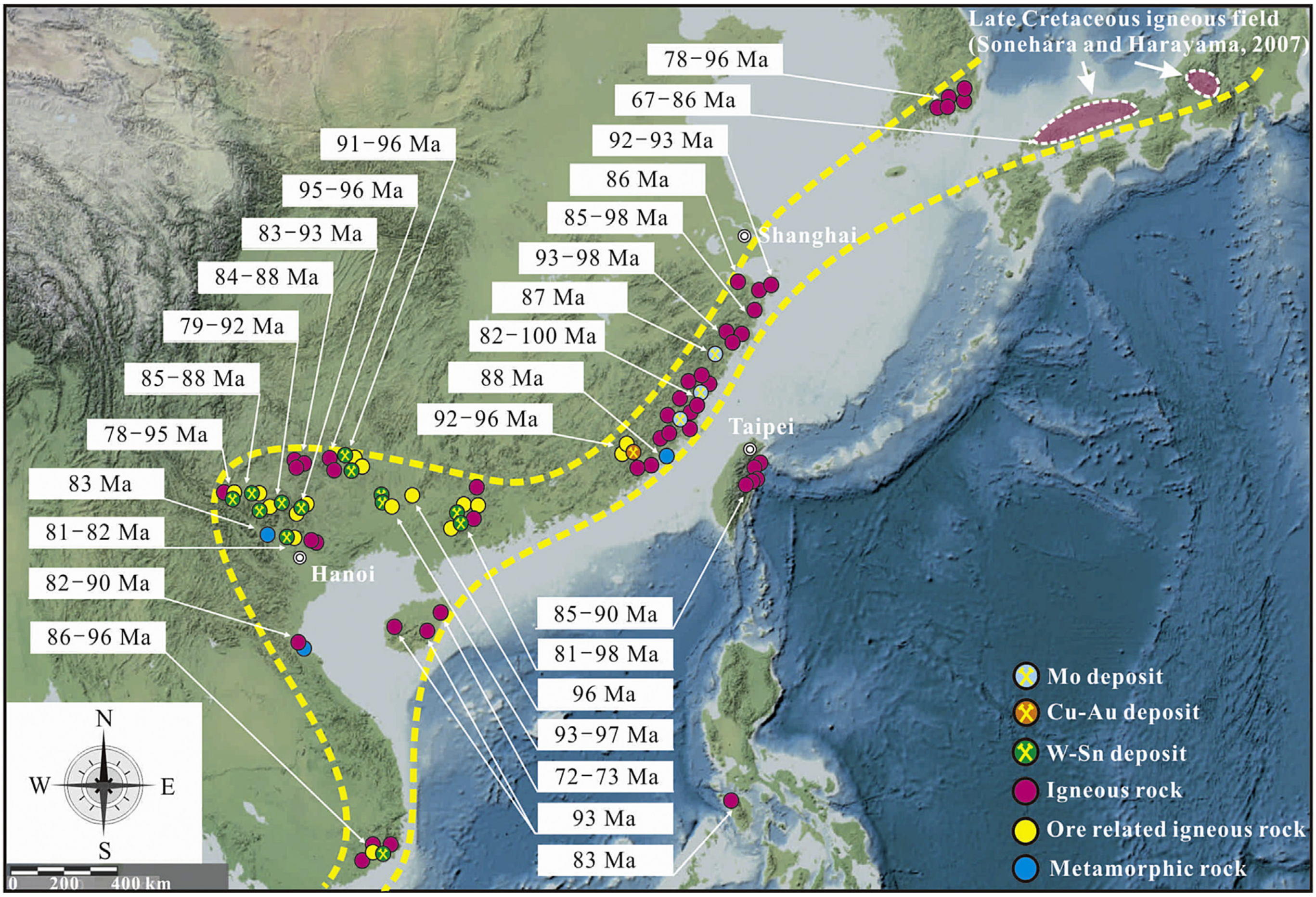

Fig. 3. Distribution of Late Cretaceous ages along the eastern margin of Asian continent.

setting. In southwestern Japan, large amounts of Late Cretaceous magmatic activities continued around 70 Ma (Sonehara and Harayama, 2007; Jiang and Li, 2014). The syenites, gabbro, granites and the bimodal volcanic rocks in the southeast coastal area of South China formed during 82 Ma–99 Ma with mostly younger than 90 Ma (Xu et al., 1999; Qiu et al., 2012; He and Xu, 2012; Chen et al., 2012a,b,c; Li et al., 2014). Several granites and metamorphic rocks with ages from 86 Ma to 88 Ma were reported in the northeast Taiwan (Yui et al., 2009; Wintsch et al., 2011). A group of Sn and Cu ores and intrusive rocks occur in Western Guangdong and Eastern Guangxi provinces with ages of 81 Ma–100 Ma, with most of them lie in 90–100 Ma (Appendix 1). As presented in the former section, the Sn–W mineralization and associated igneous rocks in southeast Yunnan and northeast Vietnam are formed during 100–80 Ma with a peak of 83–90 Ma. While in the southeast Vietnam, a series of granites and associated Sn mineralization formed during 87–94 Ma in the Dalat Zone (Shellnutt et al., 2013; Nguyen et al., 2004a,b). The Late Cretaceous magmatic activities also discovered in the western Borneo Island and the Mindoro Island in Philippines, with ages of ~83 Ma. The above data clearly demonstrate that the late Cretaceous magmatism & mineralization activities are widespread along the continental margin of eastern Asia, as listed in Appendix 3 and plotted in Fig. 3, which are from southwestern Japan, via South Korea, southeast margin of China and southwest South China, eastern Vietnam, Borneo island, to Mindoro in Philippine, all of which possibly are the products of the same geodynamic setting.

4.2. The possible geodynamic links

Studies have demonstrated that mantle–crust interaction is widely developed throughout the whole eastern Asian continental marginal belt, including the contemporaneous I- and S-type granite in Dalat zone of southern Vietnam, and the contemporaneous mafic-, felsic- and alkaline intrusive rocks in southeast Yunnan and northeast Vietnam, the contemporaneous I- and S-type granite in Yangchun Basin western Guangdong, the contemporaneous gabbro-syenite-granite-diorite association and I- and/or A-type granites in coastal Fujian, and the contemporaneous felsic volcanic rocks and alkaline rocks in coastal Zhejiang province (Fig. 3), as well as the volcanic analogues exposed in the southeast China coastal area (Li and Li, 2007; Zhou and Li, 2000; Zhou et al., 2006; Jiang and Li, 2014), all of which may represent the result of interaction between lithospheric mantle derived melt and crustal derived melt in the similar extensional geodynamic setting (Xu et al., 1999; Qiu et al., 2008; Nguyen et al., 2004a,b; He et al., 2009; He and Wu, 2012; Wang et al., 2011a,b; Shellnutt et al., 2013; Cheng et al., 2013a,b; Chen et al., 2014; Li et al., 2014). Moreover, in South Korea, mafic microgranular enclaves (MMEs) are hosted by the contemporaneous Yangsan porphyritic granite, and large amount of contemporary granites, diorite, tonalite, and gabbro occur in the SW part of Japan (reference as listed by Jiang and Li, 2014) (Fig. 3). One possible interpretation, as mentioned above, is that the large scale interaction of coeval mantle- and crust-derived melt with close spatial—temporal links along the whole eastern Asian continental margin (Nguyen et al., 2004a; Cheng et al., 2012a,b,c, 2013a,b; Xu et al., 1999; He and Xu, 2012). However, the contemporaneous I-S-A-type granites may also be obtained by crustal melting in a heterogeneous crust, as the entire variation may be obtained by crustal melting without melt input from the mantle if the crust already contains the required heterogeneity, but a heat source to induce crustal melting is essential, which still needs the input of mantle material (Sato, 2012).

It is generally accepted that the East Asian margin has experienced successive oceanic subduction since the Paleozoic (Maruyama and Seno, 1986; Isozaki, 1996; Lapierre et al., 1997; Maruyama et al., 1997; Xu et al., 1999; Zhou and Li, 2000; Zhou and Chen, 2001; Isozaki et al., 2010). The East Asian margin was characterized by large-scale sinistral strike-slip movements during the early Late Cretaceous, and one of most pronounced phenomenon is that a series of small NE—SW trending intraplate pull-apart basins developed in southeast China during the Late Cretaceous (Charvet et al., 1994; Lapierre et al., 1997; Shu et al., 2004; Suo et al., 2013; Yang, 2013), which occurred contemporaneously with a series of abrupt changes in the drifting direction of the subducting Pacific Plate (Sun et al., 2007; Mao et al., 2013). For the extensive Late Mesozoic magmatic activities in southeast China, a consensus about their tectonic background is that subduction of the paleo-Pacific plate played a significant role, which generated a large volume of subduction associated magma (Li and Li, 2007; Wong et al., 2009; Mao et al., 2013; Li et al., 2012; Roger et al., 2012; Hu et al., 2012). Furthermore, since there were relatively scarce magmatic activities during the early stage of the Early Cretaceous (145—125 Ma), Li et al. (2014) suggested that the paleo-Pacific oceanic subducting slab break-off occurred in the coastal area of SE China after ca. 125 Ma, and a roll back of the subducting slab after ca. 115 Ma, ultimately resulted in the widespread bimodal magmatism and the lithospheric extensional geodynamic regime. This model may interpret the magmatic & mineralization events along the eastern Asian continental margin presented in this study (Fig. 3), and the widespread mantle—crust interaction in this belt, as well as the presence of a series of Cretaceous extensional basins (Gilder et al., 1991; Zhou et al., 2006; Shu et al., 2009).

On another aspect, the voluminous intrusive rocks and contemporary volcanic rocks in the eastern Asian continental margin are thought to be formed at an Andean-type active continental margin setting during the Cretaceous (Nguyen et al., 2004a; Li et al., 2012; Li ZX et al., 2012; Morley, 2012; Roger et al., 2012; Jiang and Li, 2014). In the north part of this belt, the Late Cretaceous tectono-magmatic activities in the southwest margin of Japan, as well as the large amounts of Late Cretaceous granitoids and volcanic rocks distributed in Gyeongsang Basin in southeast Korean Peninsula, show subduction affinity in petrology and geochemistry. To the south, this subduction is considered to have significant influence on the tectonic evolution in SE China from the middle Jurassic through early Cretaceous (Jahn et al., 1976, 1990; Gilder et al., 1991). This influence extended to southern Vietnam during the Mid-late Cretaceous and pursued to southwest Borneo in Indonesia and northern Mindoro in Philippines through the late Cretaceous (Nguyen et al., 2004b; Knittel, 2011; Morley, 2012; Shellnutt et al., 2013). However, the Andean-type continental margin setting of the Mesozoic eastern Asia, which accompanied by developing many sinistral strike-slip faults and pull-apart basins, is thought that underwent a transition from Andean-type (continental arc) to West Pacific-type or Japanese-type (trench-arc-back arc) continental margins (Suo et al., 2013). For the timing of the eastern Asian Andean-arc type active continental margin geodynamic regime been terminated, Jiang and Li (2014) proposed that the tectonic transition took place at ~70 Ma, rather than the previously believed that the Andean-active continental margin existed until ca. 90—85 Ma (Jahn et al., 1990; Zhou and Li, 2000; Li et al., 2012).

4.3. Any other possibility for the Late Cretaceous magmatism—mineralization events in SE Yunnan and NE Vietnam geodynamic regime?

The tectonic affiliation of the southeast Yunnan and northeast Vietnam region is a long confusion, probably its special tectonic location makes it is not easy to have its tectonic affinity defined. Except the geochronological data presented in this study shows that the characteristics of Sn—W mineralization and magmatism activities in NE Vietnam are similar to the western South China block, the stratigraphic sequence architecture of northeastern Vietnam and Chinese southeast Yunnan and western Guangxi provinces are also comparable (Chen et al., 2014). However, it remains not convincing enough to category this region to the South China tectonic domain. Here we try to further evaluate the possible factors influenced the geological evolution of this region in late Cretaceous from a boarder scale through reviewing the palaeo-graphical/tectonic patterns of the adjacent tectonic units. Geographically, two potential candidates may contribute influence: the Neo-Tethys, typically represented by the collision of India Plate and the Eurasian Continent in the western sector, and the subduction of Paleao-Pacific plate to the Eastern Eurasia continental margin in the eastern part.

For the first possibility, according to Ali and Aitchson (2008), the India—Seychelles separated from Madagascar during 90—85 Ma (Storey et al., 1995; Torsvik et al., 2000) then migrated rapidly northwards eventually colliding with the part of Asia now known as Tibet in the Paleogene at 50—55 Ma (Lee and Lawver, 1995; Rowley, 1996; Hodges, 2000; DeCelles et al., 2002; Leech et al., 2005; Najman, 2006; Zhu et al., 2004). There are also researchers proposed that the initial collision time was earlier (65–70 Ma) (Klootwijk et al., 1992; Rage et al., 1995; Yin and Harrison, 2000). Anyway, in ca. 99 Ma a substantial ocean separated India–Seychelles–Madagascar from Australia–Antarctica (Coffin, 1992; Frey et al., 2000; Mohr et al., 2002), and by 83.5 Ma, India plate was appreciably more isolated in the middle of ocean. In the 55 Ma reconstructions, Schettino and Scotese (2005) motion path shown that the India continent have not collided with the Eurasian continent, which may not be able to provide enough geodynamic influence on the tectonic evolution of the SE Yunnan and NE Vietnam area. For the second possible factor, Yang (2013) proposed a tectonic model for the evolution of the East Asian margin during the Late Cretaceous that the collision of the Okhotomorsk Block with the East Asian margin during 100–89 Ma and the oblique strike-slip motion during 89–83 Ma, which is one part of the Izanagi Plate northwest-warding immigration along the eastern Eurasia continental margin (Mao et al., 2013), leading the extension and magmatism following the transpressional regime. This process may be responsible for the intense basin evolution, magmatism–mineralization and metamorphism activities along the eastern Asian continental margin.

5. Concluding remarks and future considerations

The data reported and summarized in this study show a group of Sn–W deposits with many similarities developed in the SE Yunnan and NE Vietnam region, which likely represent one regional metallogenic event. Most of these Sn–W deposits formed contemptuously in Late Cretaceous (ca. 80–100 Ma), and all of these ore deposits are genetically related with the coeval regional magmatic activities. From the regional mineralization–magmatism–metamorphism geochronological dataset, we suggest that the Late Cretaceous tectono-magmatic event widespread along the eastern Asian continental margin, including the region of this paper. Previous studies have shown that this maybe the product of the subduction of the Palaeo-Pacific Plate beneath the Eurasian continent, which probably formed under an Andean-type active continental margin setting. For the Late Cretaceous magmatism and mineralization activities in the SE Yunnan and NE Vietnam region, it is reasonable to suggest they are parts of this event and formed under the same geodynamic setting. However, because of the special location of this region, the data in this study just a framework that provides skeletal understandings on this issue to some extent, it is necessary to have more studies to make these understandings more clear. Here we list several suggestions, in our view they are important for studying the Sn–W mineralization in SE Yunnan and NE Vietnam region in the future. (1) As the question rose by Morley (2012), how are these granitic plutons in SE Yunnan and NE Vietnam, SW Borneo, northern Mindoro and northeast Taiwan associate to the tectonic evolution of SE Asia? The answer of this question will be helpful to figure out the nature of the Late Cretaceous tectono-magmatism in this region. (2) The existing data also indicate the Triassic granitic magmatism and the related Sn–W mineralization activities widely occurred in the whole region, which possibly are the responses to the Indosinian tectonic movement. In this case, characterizing the two episodes of mineralization and magmatic activities in this region and raveling out their relationship are significant. (3) Although the current opinion favors the paleo-Pacific plate NW-direction subduction model for the late Cretaceous geodynamic evolution in the eastern Asian continent (e.g. Honza and Fujioka, 2004; Metcalfe, 2009; Zhang et al., 2010; Wang et al., 2011a,b), how this process influenced the geological evolution in the southeast Yunnan and northeast Vietnam remains need more details.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.sesci.2016.12.001.

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