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Mesozoic large magmatic events and mineralization in SE China: oblique subduction of the Pacific plate

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SE China is well known for its Mesozoic large-scale granitoid plutons and ore deposits. In SE China, igneous rocks with intrusion ages between 180 and 125 Ma generally become progressively younger towards the NE. More specifically, 180–160 Ma igneous rocks are distributed throughout a broad area, with mineralization ranging from Cu–Au and Pb–Zn–Ag to W–Sn; 160–150 Ma plutons are present mainly in the Nanling region and are associated with the large-scale W–Sn mineralization; younger igneous rocks occur in the NE area that has many fewer deposits. These can be plausibly interpreted as reflecting a southwestward subduction followed by a northeastward rollback of a subducted oceanic slab, in rough agreement with contemporaneous drift of the Pacific plate. Consistent with this scenario, SE China contains three Jurassic metallogenic belts distributed systematically from NE to SW: (1) a Cu–(Au) metallogenic belt in the NE corner of the South China Block, represented by the Dexing porphyry Cu deposits; (2) a Pb–Zn–Ag metallogenic belt in the middle, represented by the Lengshuikeng Ag and Shuikoushan Pb–Zn deposits; and (3) the famous Nanling W–Sn metallogenic belt in the SW. The distribution of these metallogenic belts is analogous to those in South America where Fe deposits are distributed close to the subduction zone, followed by porphyry Cu–Au deposits and Pb–Zn–Ag deposits in a medial zone, and Sn–W deposits distant from the trench. Inasmuch as quite a few late Mesozoic Fe deposits occur in the Lower Yangtze River Belt to the NE of the Cu–Au deposits in SE China, the distribution of late Mesozoic deposit belts in SE China is identical to that in South America. Therefore, southwestward subduction of the Pacific plate and the corresponding slab rollback are proposed here to explain the distributions of the late Mesozoic (180–125 Ma) magmatism and the associated metallogenic belts in SE China.

Keywords: SE China; late Mesozoic ore deposits; magmatism; metallogenic belt; Pacific plate subduction; slab rollback

Introduction

SE China is well known for its large-scale Mesozoic magmatism and mineralization, with the densest distribution of metal deposits in China (0.1 mine/km^2) (Pei *et al.* 2007). Thus,

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this region has been the subject of intensive study since the 1940s (e.g. Hsu 1943; Gilder *et al.* 1991; Zhou and Li 2000; Zhou *et al.* 2006; Li and Li 2007; Zhang *et al.* 2007a; Chen *et al.* 2008). Several tectonic models have been postulated to explain the Mesozoic evolution of SE China (Hsü *et al.* 1990; Gilder *et al.* 1991; Li 2000; Zhou and Li 2000; Wang *et al.* 2003; Zhou *et al.* 2006; Li and Li 2007; Chen *et al.* 2008; Wong *et al.* 2009). Most models can be classified into one of two types: an active continental margin related to the northwestward subduction of the Pacific plate in the Mesozoic (Jahn *et al.* 1990; Zhou and Li 2000; Zhou *et al.* 2006; Li and Li 2007; Chen *et al.* 2008); or an intraplate lithospheric event, for example, a result of the closure of an oceanic basin in the SE China interior (Hsü *et al.* 1990; Li 1998). Other models, such as wrench faulting and/or continental rifting and extension (Gilder *et al.* 1991; Li 2000; Wang *et al.* 2003, 2005c), have also been proposed based on the intracontinental lithospheric extension and thinning since the early Mesozoic (Wang *et al.* 2006). A few papers have even proposed Mesozoic mantle plume activities in South China (Xie and Tao 1996; Xie *et al.* 2001; Deng *et al.* 2004a).

Recently, scenarios emphasizing the effects on eastern China of Mesozoic Pacific plate subduction have become more prevalent. In these models, Mesozoic magmatic rocks in SE China have been interpreted as products of continental arc/back-arc activities and/or foundering of a subducted oceanic plateau. The most famous models are the low-angle subduction model (Zhou and Li 2000; Zhou *et al.* 2006) and the flat-slab subduction model (Li and Li 2007).

Based on detailed studies of Mesozoic granitoids and volcanic rocks in SE China, Zhou *et al.* proposed that SE China experienced two tectonic regimes: continent–continent collision of the Indosinian (257–205 Ma) orogeny, with a broad Tethyan orogenic domain in the early Mesozoic, giving way to a broad extension setting as a result of the Yanshanian (180–70 Ma) orogeny genetically associated with the northwest- to westnorthwestward subduction of the Pacific oceanic lithosphere in the late Mesozoic (Zhou *et al.* 2006). This low-angle subduction model explains the overall southeastward migration of magmatism. The drifting direction of the Pacific plate, however, changed several times, with a major transition at approximately 125 Ma (Sun *et al*. 2007a); therefore, late Mesozoic magmas should be separated into two groups, before and after 125 Ma, when discussing the temporal–spatial distribution of these igneous events in SE China.

A northwestward flat-slab subduction model has also been proposed to interpret the distribution of magmatism in SE China (Li and Li 2007). According to this model, the subducting oceanic slab was flattened most likely due to the underflow of an oceanic plateau of about 1000 km diameter, which migrated far into the South China Block, followed by slab foundering. It can feasibly explain the 1300 km-wide igneous lithologic belt and the series of other geological events in SE China (Li and Li 2007). This model, however, also cannot fully account for the temporal–spatial distributions of the magmatism and mineralization between 180 and 125 Ma. Moreover, it cannot feasibly explain the distribution and chemical changes of the different rock types.

Advances in isotopic dating technologies, particularly the application of sensitive high-resolution ion microprobe (SHRIMP), Cameca 1280, and LA–ICP–MS analyses in China, have promoted a dramatic accumulation of high-precision geochronological data for igneous rocks and ore deposits in SE China during the past few years, providing clearer information on Mesozoic magmatism and metallogenic formation in SE China. In this contribution, we synthesize the existing results to show that the late Mesozoic (180–125 Ma) igneous activity and the associated mineralization can be best explained by southwestward subduction of the Pacific plate and subsequent slab rollback.

Geological setting

The South China Block is bounded in the N by the Qinling-Dabie orogenic belt, in the W and SW by the Tibetan and Indochina blocks, and in the NW by the Longmenshan belt (Chen and Wilson 1996; Li *et al.* 2000; Zhou *et al.* 2006; Li and Li 2007). It consists of two cratonic blocks: the Yangtze Block and the Cathaysia Block, which are separated by the Jiang–Shao (Jiangshan–Shaoxing) fault zone, which is generally taken as a major Neoproterozoic tectonic suture zone (Li *et al.* 1997; Chen and Jahn 1998; Li *et al.* 2002; Zhou *et al.* 2002) (Figure 1A). Geological, petrological, and geochronological studies have confirmed that the Yangtze and Cathaysia blocks have been a single amalgamated terrane since their Neoproterozoic collision (Li *et al.* 1997; Chen and Jahn 1998; Li *et al.* 2002; Zhou *et al.* 2002). The crust of the Yangtze Block is mainly composed of Proterozoic metamorphic rocks, which include the Banxi–Sibao Group in NW Yangtze Block, the Shuangqiaoshan–Shangxi Group (1400 Ma) in SE Yangtze Block, and the Shuangxiwu Group (∼1000–875 Ma) near the boundary between the Yangtze and Cathaysia blocks (Chen and Jahn 1998). Most of the rocks of the Shuangxiwu Group (SE of the Yangtze Block) were formed in an arc setting in the Neoproterozoic, consisting of metamorphosed arc volcanic rocks (978–875 Ma) and metasediments (Li *et al.* 2002; Zhou *et al.* 2002). The formations overlying the Proterozoic metamorphic basement in the Yangtze Block are sedimentary strata of Neoproterozoic (Sinian) to Triassic ages. Consensus is that South China experienced a Triassic compressional event, probably caused by the collision between the Indochina and South China blocks (Zhou and Li 2000; Zhou *et al.* 2006), between the South China and North China blocks (Li and Rao 1993), a combination of both (Wang *et al.* 2007), or related to a flat subduction event (Li and Li 2007). Since the Cretaceous, the South China Block has been a stable continental platform characterized by redbed sedimentation (Chen and Jahn 1998; Shu *et al.* 2009).

SE China refers to the southeastern part of the South China Block, which includes most of the Cathaysia Block and the eastern part of the Yangtze Block. Volcanic and intrusive rocks are widely exposed in SE China, distributing mostly in Zhejiang, Fujian, Jiangxi, Guangdong, and Hunan provinces with a total outcrop area of nearly 240,000 km^2 (Figure 1B) (Zhou *et al.* 2006). Four major periods have been identified from the early Palaeozoic to the late Mesozoic: the early Palaeozoic (Caledonian), the late Palaeozoic (Hercynian), the early Mesozoic (Indosinian), and the late Mesozoic (Yanshanian) periods, respectively. Caledonian granites are mainly distributed in Jiangxi and Hunan provinces, whereas Hercynian granites are rare and scattered through the whole region. The Mesozoic magmatism is widely dispersed in SE China, which covers almost 90% of magmatism therein (Zhou *et al.* 2006).

SE China is rich in mineral resources with a wide diversity of deposit types, that is, porphyry/skarn Cu–(Au), stratabound/skarn Pb–Zn–Ag, greisen/quartz-vein W–Sn, U, Nb–Ta, REE, Sb, and Hg, etc. (Chen *et al.* 1992; Pei *et al.* 1999; Jin *et al.* 2002; Hua *et al.* 2003; Li *et al.* 2004b; Jiang *et al.* 2006b; Peng *et al.* 2006; Wang *et al.* 2006; Li and Sasaki 2007; Li *et al.* 2007a, 2007d; Yao *et al.* 2007; Yuan *et al.* 2007; Zaw *et al.* 2007). Most of these deposits formed in the late Mesozoic related to the Yanshanian (Jurassic to Cretaceous) magmatism, which is generally attributed to the subduction of the

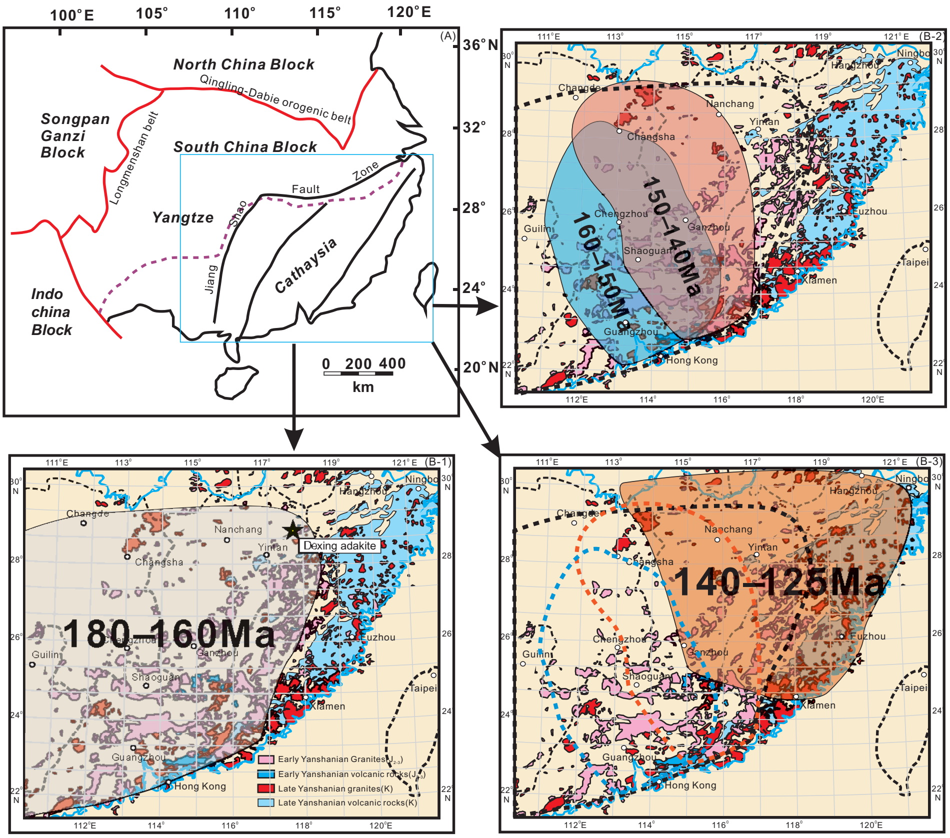

Figure 1. (A) Sketched map of the South China Block. The South China Block is surrounded by the North China Block in the north and the Songpan Ganzi Block and Indochina Block in the west. It is divided by Jiang–Shao Fault into the Yangtze and Cathysia blocks. (B) Distribution of the late Mesozoic igneous rocks in SE China (modified after Zhou *et al*. 2006). Four time interval belts are marked with different colours and become younger from the southwest towards the NE. B-1, 180–160 Ma magmatic belt in SE China including Dexing porphyry. Dexing porphyry is adakitic, related to melting of the subduction oceanic plate. B-2, 160–150 Ma (blue) and 150–140 Ma (red) magmatic belts in SE China. 180–160 Ma magmatic belt is shown as a black dotted line. B-3, 140–125 Ma magmatic belt in SE China. The black dotted line represents the 180–160 Ma belt; the blue dotted line represents the 160–150 Ma belt; and the red dotted line represents the 150–140 Ma belt.

Pacific plate (Zhou *et al.* 2006; Li and Li 2007; Zaw *et al.* 2007). Furthermore, Mesozoic–Cenozoic basins were well developed in SE China (Shu *et al.* 1998; Shu *et al.* 2004; Deng *et al.* 2004b); they include more than 100 of different sizes, with a total basinal area of $>50{,}000\ \mathrm{km}^2$ in SE China (Shu *et al.* 2007; Shu *et al.* 2009).

Mesozoic igneous rocks in SE China

Mesozoic igneous rocks are abundant in SE China with increasing density towards the ocean (Table 1). Most of the igneous rocks are granites. Early Mesozoic granites are distributed in Hunan, Guangdong, Hainan, and parts of Jiangxi and Fujian provinces (Zhou *et al.* 2006).

Table 1. Igneous rock outcropped in SE China in Mesozoic and associated deposits.

No.	Locality	Lithology	Igneous classification	Age (Ma)	Error (Ma)	Related Deposits	Method	Reference
1	Tong'an, Guangxi	Syenite	Shoshonitic	163	1	Sn	Ar–Ar hornblende	Li *et al*. (2004a)
2	Niumiao, Guangxi	Syenite	Shoshonitic	161	1	Sn	Ar–Ar hornblende	Li *et al*. (2004a)
3	Yangmei, Guangxi	Syenite	Shoshonitic	162	1	Unknown	Ar–Ar hornblende	Li *et al*. (2004a)
4	Qinghu, Guangxi-Guangdong border	Syenite	Shoshonitic	156	6	Unknown	LA–ICPMS U–Pb zircon	Li *et al*. (2001a)
5	Huashan, Guangxi	Two-mica granite	Fractionated I-type	161	1	Sn	SHRIMP U–Pb zircon	Zhu *et al*. (2006)
6	Guposhan, Guangxi	Biotite-granite	I-type	163	4	Sn	SHRIMP U–Pb zircon	Zhu *et al*. (2006)
7	Fogang, Guangdong (N23°56′31″, E113°37′02 ″)	Biotite-granite	Fractionated I-type	159	2	W, Sn	SHRIMP U–Pb zircon	Li *et al*. (2007)
8	Fogang, Guangdong (N23°33′18, E113°17′30)	Biotite-granite	Fractionated I-type	163	3	W, Sn	SHRIMP U–Pb zircon	Li *et al*. (2007)
9	Fogang, Guangdong (N23°42′26, E113°28′14)	Biotite-granite	Fractionated I-type	165	2	W, Sn	SHRIMP U–Pb zircon	Li *et al*. (2007)
10	Nankunshan, Guangdong (N23°35′49; E113°48′21)	Alkaline-granite	A-type	157	5	Unknown	SHRIMP U–Pb zircon	Li *et al*. (2007)
11	Jiufeng, Guangdong (113°22′28″, E25°17″19″)	Biotite-granite	Fractionated I-type	160	1	Mo	LA–ICPMS U–Pb zircon	Xu *et al*. (2005)
12	Mashan, Guangdong	Monzonite	Shoshonitic	164	2	Unknown	Ar–Ar hornblende	Li *et al*. (2001b)
13	Ejinao, Guangdong	Syenite	A-type	137	2	Unknown	SHRIMP U–Pb zircon	Wang *et al*. (2005)

14	Qianlishan, Hunan	Biotite-granite	Fractionated I-type	152	2	W, Sn, Cu, Mo *et al*.	SHRIMP U–Pb zircon	Li *et al*. (2004b)
15	Qitianling, Hunan	Biotite-granodiorite	I-type	161	2	W, Sn, Cu, Mo *et al*.	TIMS U–Pb zircon	Zhu *et al*. (2003)
16	Xishan, Hunan	Granitic intrusive-volcanic complex	A-type	156	2	Mo	SHRIMP U–Pb zircon	Fu *et al*. (2004)
17	Baoshan, Hunan	Granodiorite	I-type	173	2	W, Sn, Cu, Mo *et al*.	TIMS U–Pb zircon	Wang *et al*. (2002)
18	Shuikoushan, Hunan	Granodiorite	I-type	172	2	Pb, Zn, Ag *et al*.	TIMS U–Pb zircon	Wang *et al*. (2002)
19	Tongshanling, Hunan	Granodiorite	I-type	179	2	W, Sn, Cu, Mo *et al*.	TIMS U–Pb zircon	Wang *et al*. (2002)
20	Xitian (mineralization), Hunan	Granite		155.5	1.7	Sn	SHRIMP U–Pb zircon	Ma *et al*. (2005)
21	Xiangzikou granite, Weishan, Hunan	Two-mica granite	Fractionated I-type?	187	4	Unknown	LA–ICPMS U–Pb	Ding *et al*. (2006)
22	Ningyuan, Hunan	Alkaline basalt		175	1	Unknown	Ar–Ar whole rock	Li *et al*. (2004a)
23	Daoxian, Hunan	High-Mg basalt		152	2	Unknown	Ar–Ar whole rock	Li *et al*. (2004a)
24	Jinjiling, Hunan	Biotite-monzonitic granite	A-type	156	2	Unknown	SHRIMP U–Pb zircon	Fu *et al*. (2004)
25	Sanziling, Hunan	Biotite-monzonitic granite/granodiorite	A-type	157	1	Unknown	SHRIMP U–Pb zircon	Fu *et al*. (2004)
26	Xishan, Hunan	Volcanic intrusive complex		156	2	Unknown	SHRIMP U–Pb zircon	Fu *et al*. (2004)
27	Huangshaping, Hunan	Granodiorite		161.6	1.1	W, Sn, Pb, Zn, Nb, Ta	LA–ICPMS U–Pb zircon	Yao *et al*. (2005)
28	Baoshan, Hunan	Biotite-granite		173.3	1.9	Pb, Zn	SHRIMP U–Pb zircon	Wang *et al*. (2002)
29	Keshubei, Jiangxi (N24°08′29″; E115°16′28″)	Alkaline granite	A-type	189	3	Unknown	SHRIMP U–Pb zircon	Li *et al*. (2007)
30	Zhaibei, Jiangxi	Alkaline granite	A-type	172	5	Unknown	SHRIMP U–Pb zircon	Li *et al*. (2003)

(*Continued*)

Table 1. (*Continued*)

No.	Locality	Lithology	Igneous classification	Age (Ma)	Error (Ma)	Related Deposits	Method	Reference
31	Chebu, Jiangxi	Gabbro		173	4	Unknown	SHRIMP U–Pb zircon	Li *et al*. (2003)
32	Quannan, Jiangxi	Syenite	A-type	165	3	Unknown	SHRIMP U–Pb zircon	Li *et al*. (2003)
33	Tabei, Jiangxi	Syenite	A-type	162	2	Unknown	Ar–Ar hornblende	Li *et al*. (2003)
34	Dexing, Jiangxi	Diorite-granodiorite-porphyries	Adakitic	171	3	Cu, Au	SHRIMP U–Pb zircon	Wang *et al*. (2006)
35	Antang, Jiangxi	Alkaline basalt		168	1	Unknown	Ar–Ar whole rock	Wang *et al*. (2004)
36	Tianmenshan (main body), Jiangxi	Biotite-granite		152	2	Unknown	SHRIMP U–Pb zircon	Liu *et al*. (2007)
37	Tianmenshan (minor body), Jiangxi	Biotite-granite		152	2.6	Unknown	SHRIMP U–Pb zircon	Liu *et al*. (2007)
38	Tianmenshan, Jiangxi	Granite-porphyry vein (dike)		150.8	1.8	W, Sn, Nb, Ta	SHRIMP U–Pb zircon	Liu *et al*. (2007)
39	Dajishan (minor body), Jiangxi	Mica-granite		151.7	1.6	W	SHRIMP U–Pb zircon	Zhang *et al*. (2006)
40	Sanqingshan-III, Jiangxi	Biotite-alkaline granite	A-type	123	2.2	Unknown	SHRIMP U–Pb zircon	Zhang *et al*. (2007)
41	Tai Po, H.K.	Granodirorite	I-type	165	1	Unknown	TIMS U–Pb zircon	Davis *et al*. (1997)
42	Lan Tau, H.K.	Monzogranite	Fractionated I-type	162	1	Unknown	TIMS U–Pb zircon	Davis *et al*. (1997)
43	Chek Lap Kok, H.K.	Leucogranite	Fractionated I-type?	162	1	Unknown	TIMS U–Pb zircon	Davis *et al*. (1997)
44	Tsing Shan, H.K.	Biotite-monzogranite		160	1	Unknown	TIMS U–Pb zircon	Davis *et al*. (1997)
45	Tai Lam, H.K.	Monzogranite	Fractionated I-type	159	1	Unknown	TIMS U–Pb zircon	Davis *et al*. (1997)
46	Needle Hill-Sha Tin, H.K.	Leucogranite/biotite-monzogranite		146	1	Unknown	TIMS U–Pb zircon	Davis *et al*. (1997)

47	Kowloon, H.K.	Biotite	Fractionated I-type	140	1	Unknown	TIMS U–Pb zircon	Davis *et al*. (1997)
48	Chinmen, Fujian	Gneiss-granite	I-type	139	1	Unknown	TIMS U–Pb zircon	Yui *et al*. (1996)
49	Dongshan, Fujian	Gneissic-granite	I-type	122	3	Unknown	TIMS U–Pb zircon	Tong and Tobisch (1996)
50	Pingtan, Fujian	Biotite-granite	I-type	125	1	Unknown	TIMS U–Pb zircon	Dong *et al*. (1997)
51	Honggong, Zhejiang	Quartz-syenite	A-type	124	1	Unknown	Ar–Ar biotite	Qiu *et al*. (1999)
52	Huashan, Anhui	Granite		125	2	Cu, Fe	SHRIMP U–Pb zircon	Wang *et al*. (2005)
53	Sucun, Zhejiang	K-feldspar granite		133.42	0.24	Unknown	Ar–Ar	Wang *et al*. (2005)

Note: Although more than 2000 radiometric age data have been accumulated for igneous rocks in SE China since the early 1960s, previously published age data needs to be re-examined largely due to limitations of the early dating techniques and complications caused by multiple magmatic and tectonothermal activities in this region. Ages listed in this table are regarded as good-quality data obtained in reputable laboratories using the new generation of mass spectrometers. Among them, most are U–Pb zircon ages by SHRIMP or single-grained zircon TIMS methods. High precision Ar/Ar and K–Ar ages were obtained from well-established laboratories.

Late Mesozoic granitic rocks are often associated with equivalent silicic volcanic rocks with some basalt (10%). It has been proposed that late Mesozoic igneous rocks are closely related to the subduction of the Pacific plate (Gilder *et al.* 1991; Zhou and Li 2000; Zhou *et al.* 2006; Li and Li 2007). According to previous studies, late Mesozoic igneous rocks fall into two main age groups: 180–125 Ma and 125–90 Ma (Zhou *et al.* 2006). The 180–125 Ma igneous rocks are mainly distributed in the interior of SE China (Zhou *et al.* 2006), whereas the 125–90 Ma magmatism exhibits an obvious ocean-ward migration towards the SE (Chen and Jahn 1998; Zhou *et al.* 2006; Wong *et al.* 2009).

To better understand the formation of late Mesozoic magmatisms, we focus on magmatisms between 180 and 125 Ma, before the Pacific plate changed its drifting direction (Sun *et al.* 2007a). The distribution of these magmatisms is further classified using refined time intervals of 180–160 Ma, 160–150 Ma, 150–140 Ma, and 140–125 Ma. Four overlapping regions are identified, with the regions becoming progressively younger towards the NE (Figure 1B), similar to that described by Zhou *et al.* (2006):

(1) Early Jurassic (180–160 Ma) igneous rocks are mainly distributed in the Nanling Range (Li *et al*. 2007b; Wang *et al.* 2005b and papers therein; Wang *et al.* 2002; Yao *et al.* 2005; Zhou *et al.* 2006; Zhu *et al.* 2006), with some adakitic porphyries (Wang *et al.* 2006) in Dexing, Jiangxi Province.

(2) Slightly younger (160–150 Ma) igneous rocks outcrop mainly in SE Hunan, SW Jiangxi, and northern Guangdong provinces (Li *et al.* 2004b, 2007c; Wang *et al.* 2005b; Zhao *et al.* 2006), and were probably formed in an intracontinental rift region like those in the Nanling Range.

(3) The Late Jurassic to Early Cretaceous (150–140 Ma) igneous rocks mainly outcrop in Jiangxi province with some part of Guangdong and Hunan provinces.

(4) The Early Cretaceous (140–125 Ma) igneous rocks are widespread in Jiangxi, Anhui, Fujian, Zhejiang, and Jiangsu provinces, and are mainly volcanic rocks (Zhou and Li 2000; Wang *et al.* 2003; Jiang *et al.* 2005) with some intrusive rocks, such as Honggong pluton (128 Ma) and Sucun granite (133 Ma) in Zhejiang, Da'an A-type granite (139 Ma) in Fujian (Wang *et al.* 2005b). The compositions of the rocks are mainly I-type or S-type granites (Zhou and Li 2000; Wang *et al.* 2005b; and references therein) with some A-type granites (Zhu *et al.* 2006; Wong *et al.* 2009). Moreover, there are huge amounts of intrusive rocks between 140 and 125 Ma along the Lower Yangtze River Belt (Chang *et al.* 1991; Yang *et al.* 2007; Xie *et al.* 2008; Xie *et al.* 2009; Li *et al.* 2011), which are likely associated with a ridge subduction and the associated slab window (Ling *et al.* 2009).

Remarkably, A-type granites of different ages are much more abundant in SE China than previously thought (Wang *et al.* 2005a,b; Wong *et al.* 2009). A-type granitic magma is generally taken as an indication of lithospheric extension (Collins *et al.* 1982; Whalen *et al.* 1987). A-type granites or alkaline intrusive rocks, for example, Sucun geode-like Kf-granite in Zhejiang (133 Ma) (Wang *et al.* 2005b), Qianlishan Sn/W-bearing A-type granites in southwestern Hunan (Li *et al.* 2004b), Pitou granite in Jiangxi (171 Ma) (Chen *et al.* 2002), Fogang (159–165 Ma) and Nankunshan alkaline granites (158 Ma) in northern Guangdong (Li *et al.* 2007c) with the occurrence of the early Yanshanian bimodal volcanic rock associations (Ningyuan, 173 Ma) (Li *et al.* 2004a) in western Hunan, southern Jiangxi (Baimianshan, 172 Ma) (Wang *et al.* 2003), and eastern Guangxi (Huilongyu, 161–163 Ma) (Li *et al.* 2004a), suggest that SE China was periodically in an extensional environment from approximately 180 Ma to the Cenozoic.

Major metallogenic belts

SE China is famous for W–Sn deposits, with more than 50% of the world's total W reserves. There are also a large number of large ore deposits of precious metals (Au and Ag), base metals (Cu, Pb, Zn), and rare metals (Nb, Ta, Y, etc.) in this region (Table 1). Most of the ore deposits are spatially and temporally associated with igneous rocks. Over the last century, many studies have focused on these ore fields, including petrological and mineralogical research on the geological settings of metallogenesis, geological features of the deposits, sources of ore-forming materials, and the signatures of ore-forming fluids. In particular, some large ore deposits, such as the Dexing porphyry Cu deposit in Jiangxi Province, the Shuikoushan Pb–Zn polymetallic deposits in Hunan Province, the Shizhuyuan–Xianghualing–Furong W–Sn polymetallic deposits in South Hunan Province, etc., have been studied by many researchers (Hua *et al.* 2003; Li *et al.* 2006, 2007d; Wang *et al.* 2006; Li and Sasaki 2007; Mao *et al.* 2007, 2009; Zhang *et al.* 2007b). Three metallogenic belts are recognized from NE to SW (Figure 2A): (1) Cu–(Au) belt in the NE; (2) Pb–Zn–Ag belt in the middle; and (3) W–Sn belt in the SW.

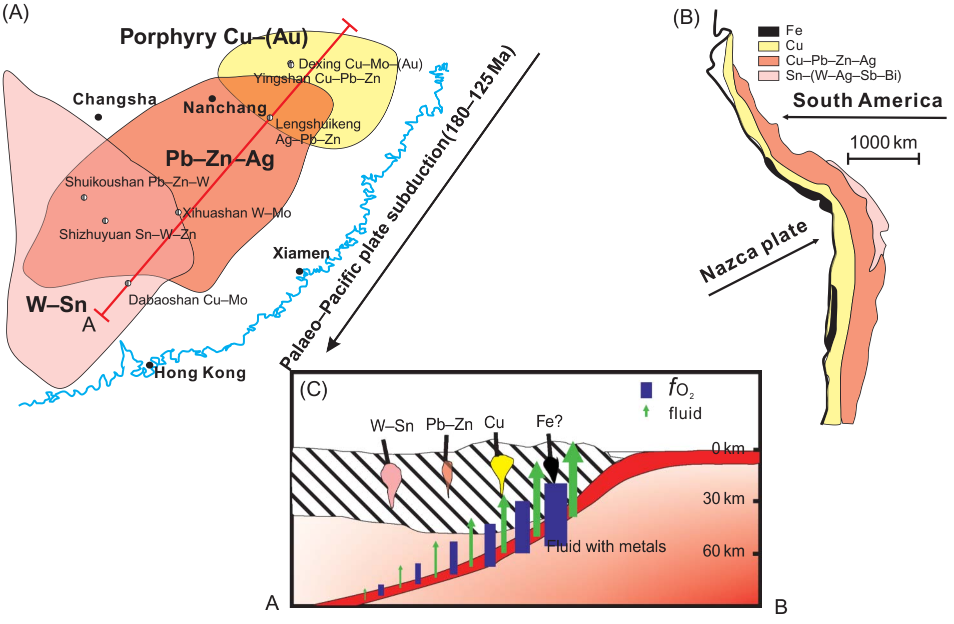

Figure 2. (A) Three Mesozoic metallogenic belts are identified in SE China with different colours where the representative deposits are located. From the NE to the SW are the porphyry Cu–(Au) belt distributed mainly in Jiangxi, Anhui Provinces; the centre Pb–Zn–Ag belt located mainly in Hunan, Jiangxi, and north Guangxi Provinces; and the inner W–Sn belt covered mainly in Hunan, Guangxi, and Guangdong provinces. This is consistent with the Pacific plate drifting southwestward during 180–125 Ma. (B) Metallogenic belts distributed in South America, with Fe oxide, porphyry Cu–Au deposits close to the subduction zone, followed by Pb–Zn–Ag deposits and then Sn–W deposits, analogous to SE China. (C) A model explaining the connection between metallogenic belt formation and subduction depth and oxygen fugacity. Green upward lines represent fluids released during subduction. The thickness and length of the lines represent the amount of fluid. Blue bars represent the oxygen fugacity in subduction zone. Thicker and longer bars represent higher oxygen fugacity.

(1) The Cu–(Au) metallogenic belt is mainly located in the NE corner of the South China Block. The Dexing porphyry Cu–(Au) deposit in Jiangxi province is one of the largest porphyry Cu deposits in China and contains 150 Mt of ores at 0.43% Cu, 0.02% Mo, 0.16g/t Au, and 1.9g/t Ag, approximately equivalent to 6.45 Mt Cu, 0.25 Mt Mo, 24 t Au, and 285 t Ag (Zhu *et al.* 1983). It is associated with granodiorite porphyries of Yanshanian age (171 Ma) (Wang *et al.* 2006) that intruded in slate and phyllite of the Mesoproterozoic Shuangqiaoshan Group. The granodiorite porphyries lie along the intersection of a NW-trending fault and a NE-trending anticlinal axis. It consists of three major porphyries: Tongchang (0.7 km^2) in the central part of the region, Fujiawu (0.2 km^2) to the SE, and Zhushahong (0.06 km^2) in the NW (Zhu *et al.* 1983; He *et al.* 1999; Wang *et al.* 2006).

(2) Pb–Zn–Ag deposits are mainly distributed in Jiangxi, Hunan provinces, and northern Guangdong province, with the Lengshuikeng deposit in Jiangxi (Zuo *et al.* 2008), Shuikoushan deposit in south Hunan province (Zhang *et al.* 2007b), and Fuwang Ag, Songxi Ag (Sb), and Chadong As–Ag–Au deposits in Guangdong province (Zhang *et al.* 2001; Liang *et al.* 2005, 2007). The Lengshuikeng Ag deposit, Jiangxi Province, is one of the most important Ag deposits in China. It is a polymetallic deposit with 6000 t Ag, 0.1 Mt Pb, and 0.2 Mt Zn (Bureau of Geology and Mineral Resources of Jiangxi Province 1984). There are two types of mineralization in Lengshuikeng district: the first type mainly occurred in porphyry granites, represented by Yinluling, Yinzhushan, and Baojia deposits; the other type is strata-bounded mineralization, which occurred in the volcanic rock of Upper Jurassic strata, represented by Baokeng, Linkeng, and Yinglin deposits (Yan *et al.* 2007). The SHRIMP zircon age of porphyry granite is 162 Ma and sericite $^{40}Ar/^{39}Ar$ age is 162.8 Ma (Zuo 2008). The Shuikoushan deposit is a polymetallic deposit, with 0.5 Mt of Pb and Zn each, and 1400 t Ag and 28 t Au (Zeng *et al.* 2000; Zhang *et al.* 2007b). It contains two major deposits: the Kangjiawan Au–Ag–Pb–Zn and the Shuikoushan Pb–Zn–Au–Ag deposits. Ore body–host rock contact relationships differ between the Kangjiawan and Shuikoushan deposits. At Kangjiawan, ore bodies are mainly hosted in the brecciation zones developed in the silicified section of the Permian limestone. In the Shuikoushan deposit, ore bodies are mainly hosted in the breccia contact zones between the granodiorite intrusive body, the Permian limestone, and shale–marl unit, or in faults situated in the core of an overturned anticline (Zhang *et al.* 2007b). The mineralization of both deposits is related to Yanshanian magmatic intrusions, and mineralizing fluids are at least partially derived from the associated intrusive bodies. The age of the Shuikoushan granodioritic intrusions is approximately 163.2 Ma (Ma *et al.* 2006a).

(3) SE China hosts more than half of the world's W–Sn reserves, mostly concentrated in southern Hunan and Jiangxi, northern Guangdong, and Guangxi provinces (Chen *et al.* 1992; Li *et al.* 1993; Shen *et al.* 1994; Mao and Li 1995; Yin *et al.* 2002; Lu *et al.* 2003; Li *et al.* 2004b, 2007d; Mao *et al.* 2004, 2007; Zhao *et al.* 2005; Peng *et al.* 2006; Gu *et al.* 2007; Hua *et al.* 2007; Yuan *et al.* 2007; Zaw *et al.* 2007). The W–Sn deposits are represented by Shizhuyuan W–Sn and Furong Sn polymetallic deposits in south Hunan, both of which are among the largest and economically important skarn–greisen–vein tungsten–polymetallic deposits in China (Mao and Li 1995; Yin *et al.* 2002; Lu *et al.* 2003). The Shizhuyuan W–Sn deposit occurs along the contact between a Late Devonian dolomitic limestone and a Jurassic to Cretaceous granitoid pluton (Lu *et al.* 2003). This deposit contains

> 750,000 t WO_3, 490,000 t Sn, 300,000 t Bi, 130,000 t Mo, and 200,000 t Be with combined WO_3 grades ranging from 1 to 5% (Wang *et al.* 1987; Zhang *et al.* 1998; Lu *et al.* 2003). In addition, the deposit is rich in fluorine with a reserve of 76 Mt at 2% fluorite, making it one of the largest fluorite deposits in China (Liu *et al.* 1995; Lu *et al.* 2003). The Shizhuyuan deposit is thought to be related to the Qianlishan granite complex, which consists of medium- to coarse-grained biotite-granite (locally porphyritic), fine-grained biotite-granite, granite-porphyry, and quartz-porphyry. Geochemical and chronological investigations of the granitic rocks have been carried out by many geologists (Yin *et al.* 2002; Li *et al.* 2004b). Porphyry biotite-granite related to the deposit is approximately 152 Ma (Li *et al.* 2004b).

Remarkably, the distribution of mineralization belts in SE China is analogous to metallogenic belts in South America (Sillitoe 1972a, 1972b; Mlynarczyk and Williams-Jones 2005) (Figure 2B). South America hosts a succession of roughly parallel, N–S-trending metallogenic belts, which comprise four overlapping zones from W to E: the iron deposits of the Coastal Belt; the porphyry Cu–Mo–Au deposits of the Western Cordillera; the polymetallic vein- and replacement-type Cu–Pb–Zn–Ag deposits, and sedimentary Cu deposits of the Altiplano; and finally the vein and porphyry Sn–W–(Ag) deposits of the Eastern Cordillera (Sillitoe 1976; Mlynarczyk and Williams-Jones 2005). This distribution of deposit types was explained as the result of a sequential incorporation of different metal suites in magmas generated at progressively greater depths above a shallow-dipping subduction zone below the Andean orogen (Sillitoe 1972b). It may also be related to oxygen fugacity (Liang *et al.* 2006; Sun *et al.* 2007b) and element mobility (Bebout *et al.* 1999; Bebout 2007; Ding *et al.* 2009), both of which are sensitive to subduction.

Oblique subduction model

The special distributions of magmatism and metallogenic belts between 180 and 125 Ma in SE China can be best interpreted by southwestward oblique subduction of the Pacific plate. The southwestward subduction of the Pacific plate may have started sometime between 180 and 200 Ma during the 'magmatic gap' in SE China (Zhou and Li 2000; Zhou *et al.* 2006). Consequently, eastern China became an active continental margin (Maruyama 1997; Zhou and Li 2000; Scotese 2002). This marked the transformation of the tectonic regime from Indosinian to Pacific in SE China. Adakites and other magmatism, as well as associated ore deposits, for example, the Dexing porphyry Cu–(Au) deposit, were probably formed during the early stage of the subduction. As the subduction continued, slab rollback of the Pacific plate started, resulting in back-arc extension and associated magmatism and mineralization. The slab-rollback-induced magmatism started from the far end of the subducted slab and became younger towards the subduction zone (Figure 2). Meanwhile, mineralization belts change from W–Sn deposits in the far end, to Pb–Zn–Ag deposits in the middle, and to porphyry Cu deposits close to the subduction zone (Figure 2C).

According to our model, the southwestward subduction of the Pacific plate in the Early Jurassic can feasibly interpret major Mesozoic geologic observations in SE China, including (a) the age distribution of Mesozoic magmatisms and (b) the distribution of the Jurassic polymetallic deposits belts in SE China. It is also consistent with the drifting history of the Pacific plate before 125 Ma (Sun *et al.* 2007a).

The distribution and ages of island chains on the Pacific plate indicate that the Pacific plate was drifting towards SW in the Early Cretaceous (Sun *et al.* 2007a). Consistent with

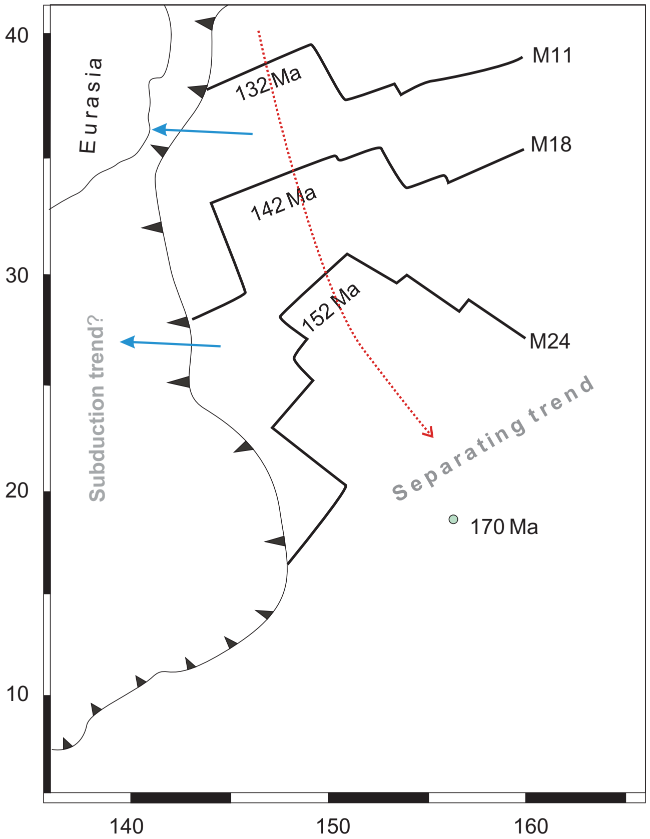

Figure 3. The magnetic anomalies in the Pacific Ocean floor, showing the drifting direction of the Pacific plate between 132 and 175 Ma (modified after Ludden *et al*. 2006). The dotted line is the apparent drifting direction, which was likely bent by the opening of the South China sea (Morley 2002) and/or seaward jumping of the subduction zone (Shimamura 1989), as well as slower subduction rate near SE China. The solid line is the estimated drifting direction before 125 Ma.

this theory, the magnetic anomalies in the ocean floor show that the Pacific plate was drifting roughly southward between 130 and 170 Ma (Figure 3) (Ludden *et al.* 2006), instead of northwestward as previously proposed (Zhou and Li 2000; Li and Li 2007). Interestingly, the drifting direction is not fully consistent with the distribution of deposits and magmatic rock in SE China. The apparent drifting direction was likely bent by the opening of the South China sea (Morley 2002) and, more importantly, the seaward jumping of the subduction zone (Shimamura 1989). Taking all of the above into consideration, the drifting direction of the Pacific plate was roughly consistent with the subduction direction defined by the distribution of the mineralization belts.

Iron deposits in the Lower Yangtze River Belt have been well studied (Zhai *et al.* 1996; Yu and Mao 2004, 2005; Jiang *et al*. 2006a; Ma *et al.* 2006b; Yu *et al.* 2007; Yu *et al.* 2008); however, the forming mechanism is still unclear. Apatite from the Washan and Dongshan iron deposits indicated a high fO_2 environment. The initial Sr isotopic compositions of the apatite from the iron deposits are similar to that of the volcanic rocks in the Ningwu basin and deposits in the basin, suggesting that the iron deposit has magmatic origination (Yu *et al.* 2007; Yu *et al.* 2008). The ages of iron deposits, however, are difficult to determine.

Limited ^{232}Th–^{208}Pb isotopic data of apatite yield an age of 124 ± 41 Ma, similar to the age of host volcanic rocks (127 Ma) (Jiang *et al.* 2006a). This age marginally predates the transformation of Pacific drifting (Sun *et al.* 2007a), and may well be due to ridge subduction (Ling *et al.* 2009). Nevertheless, if the metallogenic belts in SE China are indeed comparable to those in South America, there should be more Ningwu-type iron deposits, possibly of older ages, along the Lower Yangtze River Belt, closely related to the oblique subduction of Pacific plate in the late Mesozoic.

The oxygen fugacity (fO_2) of Jurassic magmatic rocks and related deposits in SE China decreases gradually from NE (Ningwu Fe deposits, Dexing porphyry Cu–Au deposit) to SW (Nanling W–Sn deposits), changing from magnetite-type to ilmenite-type. More precisely, apatite in the iron deposit in the Ningwu basin shows the highest fO_2 environment, with the Dexing porphyry Cu deposit as the second highest. It has long been recognized that most Cu–Au deposits are formed at convergent margins (Sillitoe 1997; Mungall 2002), and are closely associated with high fO_2 rocks (Sillitoe 1997; Sun *et al.* 2004; Liang *et al.* 2006). As the plate subducted to deeper depths, oxygen fugacity decreased, likely because of lower amounts of dehydration-released fluids. Correspondingly, Pb–Zn and then W–Sn ore deposits formed. Tin is dominantly in 4+ valence in high fO_2 silica melts (Linnen *et al.* 1995). Sn^{4+} ion radii similar to that of Ti^{4+}, as allomerism are formed minerals such as hornblende, biotite, ilmenite, etc. (Jiang *et al.* 2006b). Therefore, tin is not enriched in the late fluids or melts in high fO_2. By contrast, in reducing silica melts, Sn is mainly present as Sn^{2+} with a larger ion radius, which is not concentrated in early formed minerals and enriched in later silica liquids to form tin deposits (Linnen *et al.* 1995; Webster *et al.* 1997; Thompson *et al.* 1999; Muller *et al.* 2001). This is consistent with our oblique subduction model (Figure 2). Oxygen fugacity in convergent margin magmas is usually considerably higher than in mid-ocean ridge and other geological settings (Brandon and Draper 1996; Parkinson and Arculus 1999; Sun *et al.* 2007b), likely due to subduction-released fluids (Brandon and Draper 1996; Sun *et al.* 2007b). Therefore, oxygen fugacity decreases gradually with increasing distance from the trench.

Discussions

SE China has undergone multiple tectonic and magmatic events and related metallogenic processes since the early Proterozoic, making it hard to study the ore formation processes. In addition, different kinds of deposits have usually been studied separately by different groups; little attention has been paid to the relationship among all deposits and associated igneous rocks.

As a result, polymetallic deposits in SE China have been attributed to a number of different tectonic environments. The Dexing Cu deposits have been related to the partial melting of the delaminated lower continental crust in an extensional tectonic regime in the intracontinent (Wang *et al.* 2003; Hou *et al.* 2007), whereas Pb–Zn metallogenic deposits in SE China have been attributed either to melting of sedimentary crust, for example, Huangshaping Pb–Zn–W–Sn deposits and Lengshuikeng Ag–Pb–Zn deposits (Yao *et al.* 2005, 2007; Zuo 2008; Zuo *et al.* 2008) or to I-type granite, for example, Shuikoushan Pb–Zn deposit (Wang *et al.* 2002; Yao *et al.* 2005) or taken as manganic skarn-type around or on some W–Sn deposit, for example, Nanfengao, Congshuban, and Shexing Pb–Zn deposits around Shizhuyuan W–Sn polymetallic deposit (Mao *et al.* 2009). By contrast, W–Sn deposits are usually associated with S-type granites (Jiang *et al.* 2008) with some mantle input (Zhu *et al*. 2006; Li *et al*. 2009), or highly evolved I/S-type granites (Ĉerny *et al.* 2005; Li *et al.* 2008). It has also been argued that W–Sn deposits formed in high oxygen fugacity and post-magmatic hydrothermal alteration of the granite (Jiang *et al.* 2006b, 2008). Deposits in SE China in the Mesozoic were usually considered to be formed in an intracontinental rifting regime (Wang *et al.* 2002, 2006; Hua *et al.* 2003; Mao *et al.* 2004; Ma *et al.* 2006a; Hou *et al.* 2007). Other geologists proposed that these deposits were related to westward subduction of the Pacific plate (Niu 2005; Pei *et al.* 2007; Zaw *et al.* 2007).

Our model shares many common ideas with previously proposed Pacific subduction models (Zhou *et al.* 2006; Li and Li 2007). Previous models, however, proposed northwestward Pacific plate subduction, whereas the actual subduction direction was southwestward before approximately 125 Ma, as indicated by island chains (Sun *et al*. 2007a).

The flat subduction model (Li and Li 2007) can plausibly explain the present distribution of Mesozoic magmatism in SE China; however, this model does not consider the transformation in subduction direction of the Pacific plate and the rotation of the continent. SE China had experienced a clockwise rotation of about 70–90° from the Triassic to the Jurassic (Zhu *et al.* 1998) (Figure 4). From the model of Li and Li (2007), the subduction of the Pacific plate would be northwestward since the Triassic, which is not consistent with the magnetic abnormity in the present Pacific oceanic plate (Figure 3). Meanwhile, there are no Late Triassic adakitic rocks reported in the Cathaysia Block, and syenitic and A-type granitic intrusions (Wang *et al.* 2005b) also cannot support the conclusion that the granitic magmatic evolution during the Mesozoic followed such a pattern (Chen *et al.* 2008).

Others have proposed that the Pacific subduction system started at 101 Ma, and that the E–W-trending basalt array extending from the Cathaysia interior to the Cathaysia Folded Belt, which decreases in age from 175 to 98 Ma, is related to the post-orogenic (Indosinian) extension based on different sources (Chen *et al.* 2008). This model, however, cannot explain the decreasing of the magmatic ages and the ore deposit belts illustrated in this study (Figures 1 and 2). We propose that the southwestward subduction of the Pacific plate may have started sometime between 180 and 200 Ma, during the ‘magmatic gap’ in SE China (Zhou and Li 2000; Zhou *et al.* 2006). Consequently, eastern China became an active continental margin (Maruyama 1997; Zhou and Li 2000; Scotese 2002; Sun *et al.* 2007a). This marked the transformation of the tectonic regime in SE China from the Indosinian to the Pacific.

Conclusions

We propose an oblique subduction model to explain the distribution of late Mesozoic (180–125 Ma) magmatism and metallogenic events in SE China. We infer that the Pacific plate was subducting southwestward during this period. This model can plausibly explain the temporal–spatial distribution of mid-Mesozoic large-scale igneous events and associated mineralizations in SE China. Granitoid plutons are mainly Jurassic (180–160 Ma) in the Nanling region in the SW, and become progressively younger northeastward to approximately 140–125 Ma in the Lower Yangtze River Belt, which is consistent with southwestward subduction followed by a northeastward slab rollback. The spatial distribution of the three Jurassic metallogenic belts is analogous to that in South America.

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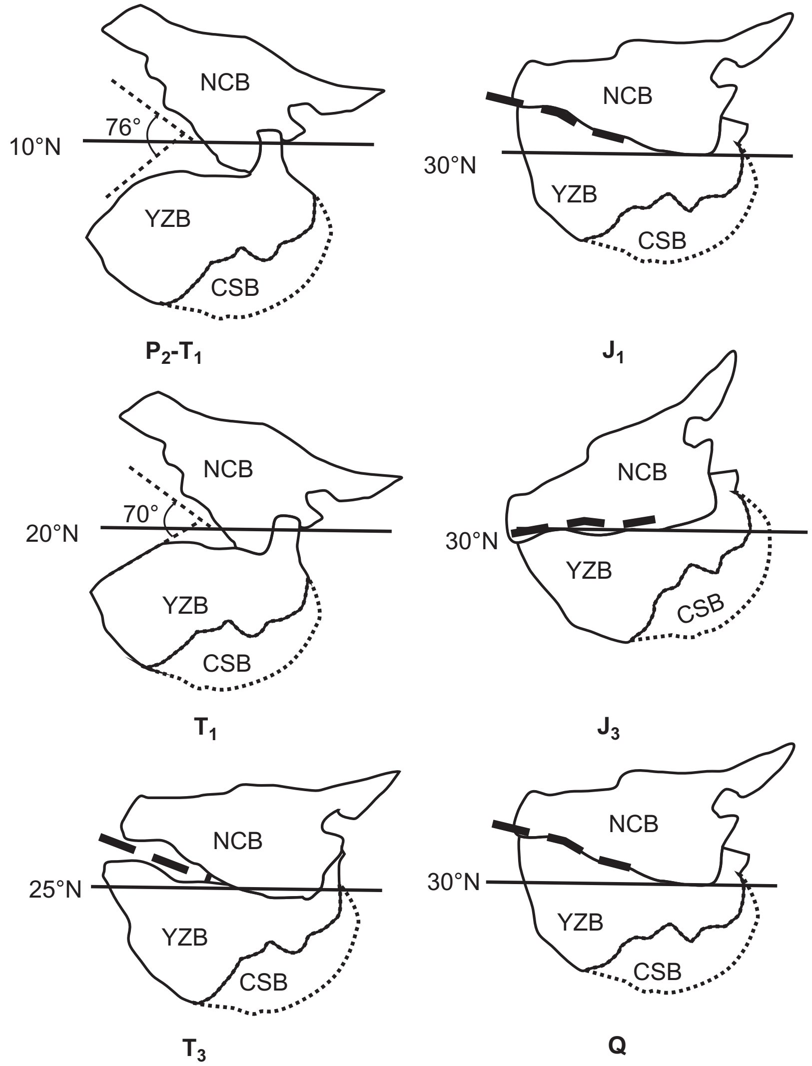

Figure 4. Docking and rotation between North China Block (NCB) and South China Block [composed by the Yangtze Block (YZB) and Cathaysia Block (CSB)] from Triassic to Jurassic (modified after Zhu *et al.* 1998). The dotted line between the two blocks is speculative. The black solid line represents the latitude. The YZB and NCB docked in P_2–T_1 at 10°N and drifted to the north till T_3–J_1. The YZB and NCB joined together completely in the Early Jurassic. After that, they rotated anticlockwise by approximately 30° in the Late Jurassic and then rotated clockwise by approximately 30° in the Quaternary. This has influenced the present distribution of magmatic rocks and tectonic features in the SE China.

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