Recognition of a Middle–Late Jurassic arc-related porphyry copper belt along the southeast China coast: Geological characteristics and metallogenic implications

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ABSTRACT
Recent exploration has led to definition of a Middle–Late Jurassic copper belt with an extent of ~2000 km along the southeast China coast. The 171–153 Ma magmatic-hydrothermal copper systems consist of porphyry, skarn, and vein-style deposits. These systems developed along several northeast-trending transpressive fault zones formed at the margins of Jurassic volcanic basins, although the world-class 171 Ma Dexiong porphyry copper system was controlled by a major reactivated Neoproterozoic suture zone in the South China block. The southeast China coastal porphyry belt is parallel to the northeast-trending, temporally overlapping, 165–150 Ma tin-tungsten province, which developed in the Nanling region in a back-arc transtensional setting several hundred kilometers inboard. A new geodynamic-metallogenic model linking the two parallel belts is proposed, which is similar to that characterizing the Cenozoic metallogenic evolution of the Central Andes.

INTRODUCTION
Ore deposits can be used as markers of geodynamic evolution, as initially recognized for porphyry copper deposits by Sillitoe (1972), and later generalized by Mitchell and Garson (1981) and Sawkins (1984). One of the classic examples is the Central Andes, where Cenozoic porphyry copper deposits in Chile are representative of an active continental margin setting, and the Bolivian tin belt is indicative of a back-arc setting. Both metal belts formed in specific and relatively narrow time windows at the 10 m.y. scale related to the regional stress field, which was modulated by periods of flat-slab subduction (James and Sacks, 1999; Kay et al., 1999; Lehmann, 2004).

However, the tectonic setting of the major tin-tungsten province in the Nanling region of southeast China has remained puzzling. The tin and tungsten deposits are mainly of Mid-Late Triassic age, a time period locally associated with the subduction of the Izanagi plate during that time. The regional metal polarity of tin-tungsten ores in the back-arc and copper ores in the main arc integrates the mineral deposits of southeastern China into a comprehensive global metallogenic framework and reveals significant exploration potential for world-class resources.

REGIONAL GEOLOGY OF THE SOUTHEAST CHINA COASTAL BELT
The southeast China coastal area is geologically located along the edge of the Cathaysia block, which amalgamated with the Yangtze craton along the Qinhang suture zone ca. 1.1–0.9 Ga (Chen et al., 1991) to form the South China block (Fig. 1). The Cathaysia block consists of a Precambrian basement overlain by Sinian to early Mesozoic sedimentary and late Mesozoic continental clastic and volcanic cover. There are two important northeast-striking transpressive faults in the eastern part of the Cathaysia block: the Zhenge-Dapu and the Changle-Nan’ao faults. The Zhenge-Dapu fault is regarded as a transliminithspheric strike-slip fault, dividing the Cathaysia block into two units (Fig. 1), locally known as the Interior Cathaysia and the Coastal Cathaysia blocks. The newly recognized Middle to Late Jurassic southeast China coastal copper porphyry belt is located along and close to these two major fault systems. Pre-Devonian basement, late Paleozoic–Middle Triassic clastic and carbonate rocks, and late Mesozoic continental volcanic rocks are the major rock types intruded by the porphyry systems (Zhao et al., 2015). There are numerous variably eroded late Mesozoic volcanic edifices in the belt, including stratovolcanoes and volcanic domes and related intrusive rocks, which mainly formed at 140–85 Ma within an extensional regime (Chu et al., 2019). Lesser igneous activity is recorded during the time period of 170–140 Ma, which was characterized by a compressional regime (Chu et al., 2019). Local and relatively small
exposures of Jurassic volcanic and hypabyssal intrusive rocks dated at 172–152 Ma (Table S1 in the Supplemental Material) are recognized within the southern, northwestern, and western margins of the younger Cretaceous volcanic cover (Fig. 1). It is these remnant igneous centers that host the copper mineralization.

FEATURES OF THE MIDDLE–LATE JURASSIC SOUTHEAST CHINA COASTAL PORPHYRY COPPER BELT

South China is well known for the exceptionally metal-rich Late Jurassic Nanling tin-tungsten province, in what we would interpret here as a back-arc setting (Fig. 1; more detailed information is provided in the Supplemental Material; Mao et al., 2013, 2019). The discovery of the 161 Ma Xinliaodong porphyry copper deposit associated with granodiorite porphyry in eastern Guangdong Province in 2010 (Fig. 1; Wang et al., 2014) gave rise to the speculation that there may possibly be a Jurassic arc-related copper porphyry belt near the continental margin. Through detailed field investigations in the coastal area over the past 10 yr, it has been recognized that there are dozens of copper-rich porphyry, skarn, and polymetallic vein deposits associated with small magmatic centers of Middle to Late Jurassic age (Fig. 1). These discoveries put the historic giant porphyry copper district of Dexiong in a new light, where rather than an isolated ore district of uncertain tectonic affinity, it could now be viewed as part of a partly eroded Andean-style magmatic-hydrothermal metallogenic belt.

Geology of the Copper Belt

The porphyry copper deposits are mainly in the southern and northwestern parts of the Coastal Cathaysia block, as well as west of the extensive Cretaceous volcanic rock cover within the block. Only a few deposits, such as the Dingjiashan and Fengyan Cu-rich polymetallic deposits (Fig. 1), are exposed in a tectonic window surrounded by younger Late Jurassic–Cretaceous volcanic rocks.

The Jurassic copper deposits in the southeast China coastal belt comprise a spectrum from porphyry to skarn and to epithermal vein types. The latter veins are less abundant and economically less significant than in the well-studied Andean belt because of the greater degree of erosion in the older southeast China belt. The deposits have an age range from 171 Ma to 153 Ma (mostly Re-Os ages on molybdenite) and are coeval with the related granitic rocks ranging from 172 to 152 Ma (U-Pb on zircon; see Table S1), which include quartz diorite porphyry, granodiorite porphyry, granodiorite, and minor monzogranite.

1 Supplemental Material. Appendix S1, Figures S1–S4, and Table S1. Please visit https://doi.org/10.1130/GEOL.S.13530608 to access the supplemental material, and contact editing@geosociety.org with any questions.

Figure 1. Map showing Jurassic porphyry–skarn–hydrothermal vein copper deposits in the southeast China coastal belt (continental arc setting) and the tin-tungsten (W-Sn) province of the Nanling region (dashed red ellipse) in a back-arc setting.
Dexing porphyry copper district with a total resource of ~9.2 Mt Cu (see Table S1). The Dexing district includes three southeast-aligned, 171 Ma Cu-Mo-Au deposits, Tongchang, Fuji-awu, and Zhushahong, hosted in granodiorite porphyry intrusions. The 172 Ma Yinshan porphyry copper–epithermal Ag-Pb-Zn deposit is located 6 km southwest of the Dexing deposits, and it is hosted by both granodiorite porphyry and causative volcanic rocks. Nearby smaller Cu-Mo porphyry and polymetallic skarn/vein deposits at Yongping, Longtoufang, Tongcun, Linghou, and Dongxiang have mineralization ages of 162–154 Ma and are mainly hosted by Carboniferous carbonate and clastic rocks.

**Tectonic Control of Magmatic-Hydrothermal Mineralization**

The continental margin of southeastern China is traversed by several large margin-parallel transpressional faults, of which the Zhenghe-Dapu and Changle-Nan’ao fault zones are the largest (Fig. 1). The porphyry copper systems and related igneous rocks are controlled by these northeast-striking faults and parallel basin-margin faults that formed during the opening of northeast-trending volcanic basins between the first-order faults. The large Dexing district at the northern end of the copper belt is controlled by secondary faults that branch out from the Neo-proterozoic Qinhang suture zone, which became reactivated by the Middle Jurassic transpressive regime. At the deposit scale, the porphyry, skarn, and vein deposits are controlled by either volcanic edifices along the major faults, such as at Yinshan, Zhongguiyang, Dingjiashan, and Fengyan, or secondary basin-margin faults, such as at Honggoushan, Dongxiang, and Qiguling.

**Petrotological Nature of the Ore Systems**

The porphyry copper-related granitic rocks in the southeast China coastal belt, ranging from diorite to granite, are characterized by high-K calc-alkaline, shoshonitic, and calc-alkaline compositions, which are similar to those of the subduction-related porphyry copper systems in the North and South American Cordillera (Cook et al., 2005). Geochemically, the primitive mantle-normalized spider diagrams and chondrite-normalized rare earth element (REE) patterns (Fig. S1) of the southeast China coastal porphyry belt are similar to those of typical subduction-related continental arcs, characterized by enrichment of the large ion lithophile elements (Rb, Th, U, Ba, K) and light REEs (LREEs), and depletion of high field strength elements (Nb, Ta, P, Zr, Ti) (Pearce et al., 1984). Elevated Sr/Y ratios and “adakitic” features indicate hornblende-stable conditions in the source region, i.e., hydrated lower crust (Richards, 2011).

In tectonic discrimination diagrams (Fig. S2), all the felsic rocks in the belt plot within the volcanic-arc field. In the εHf(0) versus age diagram (Fig. S3), zircon εHf(0) data for the igneous rocks show a wide range and plot either below or along the chondritic evolution line, indicating extensive interaction between mantle and crust. Moreover, the diagram suggests that the ore-related magma systems in the southeast China coastal belt were mainly derived from mantle material with minor contributions of Neoproterozoic continental crust, as also seen in the Sr-Nd isotopic patterns (Fig. S4).

**GENETIC MODEL FOR THE MIDDLE TO LATE JURASSIC SOUTHEAST CHINA COASTAL PORPHYRY COPPER BELT**

The continental blocks in East Asia were amalgamated by the end of the Triassic after rising away from the Gondwana supercontinent in the late Paleozoic (Zhao et al., 2018). Zhou et al. (2006) recognized a period of relative tectonomagmatic quiescence from ca. 205 to 180 Ma (Early Jurassic) in the South China block. The dominant tectonic regime gradually changed from a Tethyan domain to a Pacific domain in the Middle Jurassic, which was triggered by the oblique subduction of the Izanagi plate (Maruyama et al., 1997). There is widespread agreement that the Izanagi plate subducted beneath the Eurasian continent at a low angle, occasionally even close to flat, although the precise ages of changes in trajectories are still very debated (e.g., Zhou et al., 2006; Li and Li, 2007; Wang et al., 2011; Mao et al., 2013; Chu et al., 2019).

Our recognition of a Middle to Late Jurassic, southeast China coastal magmatic arc associated with a ca. 171–153 Ma porphyry copper belt, coupled with the 165–150 Ma tin-tungsten province in the Nanling region within an associated back-arc setting (Mao et al., 2013), provides convincing evidence for a subduction-related tectono-magmatic regime throughout the Middle–Late Jurassic. We propose a comprehensive metallogenic-geotectonic model based on previous data and our own new work (Fig. 2). When the oceanic plate subducted obliquely beneath South China at a low angle, it formed a group of regional northeast-trending transpressional faults, opened a series of northeast-trending basins between the major transpressional structures, and reactivated the Neoproterozoic Qinhang suture zone. During the Middle and Late Jurassic, the slab dipped at a relatively flat angle to the northwest and reached more than 1000 km inward from the Izanagi trench, located a few hundred kilometers seaward of the edge of the continental margin. Subduction was accompanied by strong interplate coupling and concomitant compression and crustal thickening. The 300 km section of the South China block closest to the continental margin was uplifted to form a high plateau (Chen, 2000; Zhang et al., 2016), hosting the copper ores along coast-parallel fault systems. The porphyry copper ore systems with an age range of 171–153 Ma and related calc-alkaline magmatism formed along the northeast-trending transpressive faults and associated structural zones.

The association of porphyry copper systems with subduction settings is well documented from the Andes and southwestern North America, with recurrent short-lived metallogenic epochs occurring during a long-lived history of subduction on the 100 m.y. scale (Sillitoe, 2012). The world-class Dexing porphyry district, coupled with the Dongxiang, Yongping, Longtoufang, Linghou, and Tongcun magmatic-hydrothermal copper systems in the northern part of the belt, occurs east of the Qinhang suture (Fig. 1). Reactivation of the suture strands to the east during the Middle–Late Jurassic transpressive regime focused the ascent of mantle and lower-crustal melt from previously subduction-metasomatized lithosphere in a general regime close to flat-slab subduction. Such melts with adakitic features pick up the metal inventory from the hydrated and metasomatized lower continental crust and are favorable for copper mineralization, different from the usual calc-alkaline main arc magmatism generated during normal subduction (Kay et al., 1999; Haschke et al., 2002).

By contrast, the original northeast-trending transpressional faults gradually changed to a transtensional style in the back-arc in the Nanling Range. The back-arc region was dominated by intracrustal melting and fractionation, as shown by the Late Jurassic S-type or ilmenite series peraluminous granitic rocks, which reflect large-scale crustal melting of chemically reduced pelitic rock sequences. The necessary high heat flow above the slab region was likely induced by upwelling mantle flow through a slab window, and associated lithospheric delamination, similar to the Miocene magmatic flare-up in the central Andes (Kay and Coira, 2009). The highly evolved granites and related tin-tungsten deposits are spatially located along several northeast-trending faults, particularly at the intersection areas between northeast-trending and preexisting east-west-trending faults (Mao et al., 2019).

In contrast to the Miocene Bolivian tin province (Sillitoe et al., 1975; Lehmann, 1990), there are no volcanic rocks genetically associated with the tungsten- and tin-related granites in the Nanling region, indicating a relatively deeper emplacement position. This is therefore more similar to the Triassic tin-tungsten mineralization in the northern Bolivian tin province. Extreme fractionation processes there produced world-class tin-tungsten deposits in the apical portions of much larger granite systems and in the country rocks around the cupolas.

In light of the newly recognized model, it is likely that there are as-yet undiscovered economically significant Middle to Late Jurassic porphyry copper systems beneath the Cretaceous volcaniclastic cover along the southeast China
Figure 2. Genetic model for coupling of Middle–Late Jurassic southeast China coastal porphyry copper belt along the continental margin, and Middle–Late Jurassic Nanling tin-tungsten province in a back-arc terrane. The relatively flat subduction setting allowed lithospheric metasomatism and formed porphyry copper systems by melting/assimilation/storage in the lower continental crust (Hildreth and Moobath, 1988). S-type peraluminous granitic rocks in the Nanling tin-tungsten province formed by partial melting of pelitic source material, possibly induced by asthenospheric mantle upwelling through the slab window in the back-arc region.
