Review

Hydrothermal ore deposits in collisional orogens

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A R T I C L E   I N F O

A B S T R A C T

Hydrothermal ore deposits at convergent plate boundaries represent extraordinary metal enrichment in the continental crust. They are generally associated with felsic magmatism in extensional settings at high thermal gradients. Although their formation is common during accretionary orogeny, more and more ore deposits have been discovered recently in the collisional orogens of China. Because collisional orogeny was operated in a compressional regime at low thermal gradients, it is not favorable for mobilization of ore-forming elements and thus for the production of hydrothermal ore deposits. Nevertheless, continental collision is generally preceded by oceanic subduction, which enables the preliminary enrichment of ore-forming elements in the mantle wedge due to chemical metasomatism by subducting slab-derived fluids. This gave rise to metal pre-enriched domains in the overriding lithosphere, which may be reactivated by extensional tectonism for hydrothermal mineralization either immediately during accretionary orogeny or at a later time during and after collisional orogeny. It is these tectonic processes that have resulted in the progressive enrichment of ore-forming elements through the geochemical differentiation of the subducting oceanic crust, the metasomatic mantle domains and the mafic juvenile crust, respectively, at different depths. Finally, the reactivation of metal pre-enriched domains by continental rifting in the orogenic lithosphere is the key to the metallogenesis of collisional orogens.

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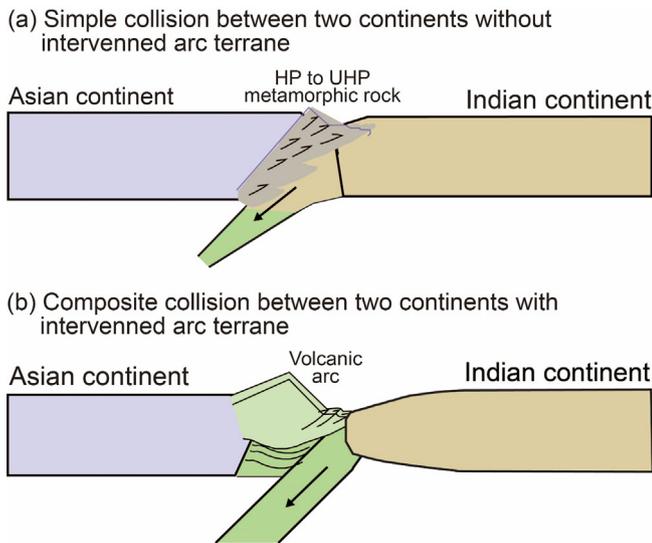
1. Introduction

Collisional orogeny generally shows a low potential for the formation of hydrothermal ore deposits [1,2]. In contrast, a large number of hydrothermal ore deposits occur in accretionary orogens such as the Tethyan orogen [3] and the circum-Pacific orogens [4,5], including porphyry Cu–Au–Mo [6], epithermal Au–Ag [7], and volcanogenic massive sulfides [8]. For this reason, collisional orogens are usually considered the unfavorable sites for significant metallogenesis relative to accretionary orogens [9,10]. As a consequence, it has been enigmatic why there is the big difference in metallogenic capacity between accretionary and collisional orogens.

Our understanding of metallogenesis in collisional orogens has dramatically changed since the finding of large ore deposits in southern Tibet [11–13]. Zhang and Hou [14] make a systematic comparison of metallogenesis in Cenozoic collisional orogens such

as Pyrenees, Alps, Zagros and Himalaya, which are all associated with northward subduction of Neo-Tethyan oceanic slab in the Mesozoic. The authors find a significant difference in their metallogenic endowment between the four orogens. They found that simple collisional orogens in Pyrenees and Alps, in which there is no intervened arc between two collided continents (Fig. 1a), only contain hydrothermal Pb-Zn and Au deposits. In contrast, composite collisional orogens in Zagros-Iranian and Himalayan-Tibetan Plateaus, in which Mesozoic arc terranes were present between two collisional continents (Fig. 1b), contain abundances of ore deposits such as hydrothermal Cu-Mo, Au, REE, Pb-Zn, and polymetallic deposits. It appears that these hydrothermal ore deposits were produced by reworking of the Mesozoic arc lithosphere in the Cenozoic. This has advanced our understanding of metallogenesis in collisional orogens. This essay aims to provide further insights into the relationship in both time and space between metallogenesis and orogenesis at convergent plate boundaries.

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(a) Simple collision between two continents without intervened arc terrane

(b) Composite collision between two continents with intervened arc terrane

Fig. 1. Schematic diagrams for two types of collisional orogeny at convergent continental boundaries.

2. Metallogenesis of accretionary orogens

It is known that arc magmatism is caused by subduction of oceanic lithosphere, leading to accretionary orogeny along continental margins [15,16]. In view of the compositional difference between the two types of collisional orogen in Pyrenees, Alps, Zagros and Himalaya [14], accretionary orogens are absent in the simple collision orogens by the direct continent–continent collision for mountain building. In contrast, accretionary orogens are present in the composite collision orogens, but they were superimposed by collisional orogeny [17]. The accretionary orogen in Zagros-Iranian Plateau is the Sanandaj-Sirjan zone and that in Himalayan-Tibetan Plateau is the Gangdese zone [14]. Both accretionary orogens were generated by subduction of the Neo-Tethyan oceanic lithosphere in the Mesozoic, and both were located in the hangwall of continental subduction zones during the collisional orogeny in the Cenozoic [18]. In this regard, the formation of these hydrothermal ore deposits in the collisional orogens is caused by reworking of the Mesozoic accretionary orogens in the Cenozoic. It is this reworking that is a key to the production of hydrothermal ore deposits at the convergent continental boundaries.

Although accretionary orogens are regarded as the favorite sites for the production of hydrothermal ore deposits, a variety of tectonic settings are cited in the literature for metallogenesis [9,10]. Inspection of these settings with reference to their temporal relationship to the subduction of oceanic lithosphere indicates that most of the hydrothermal ore deposits are not associated with mafic arc magmatism. Instead, they are associated with hydrous felsic magmatism. Nevertheless, these ore deposits were generally produced in extensional regimes, and they were substantially formed at a time variably later than the accretionary orogeny. Furthermore, there is the spatial superimposition of continental rifting on convergent continental boundaries where the collision-thickened orogenic lithosphere was thinned and then impinged by hot mantle upwellings. Thus the metallogenesis in many accretionary orogens would have occurred at a time significantly later than the cessation of active convergence by the subduction of oceanic lithosphere. Typically, orogenic Au deposits were generated at suture zones after terrane accretion [19]. The other examples include those hydrothermal Au and W–Sn deposits that develop at cratonic margins. Although hydrothermal ore deposits above active oceanic subduction zones are closely associated with

porphyry intrusions, some of porphyry Cu-Au and epithermal Au deposits were generated in the stage of post-subduction at fossil convergent plate boundaries [20,21]. So are Miocene porphyry Cu-Mo deposits in southern Tibet [3]. In addition, a diverse array of deposit types may form as part of a broad porphyry-related system with locations that vary in vertical position and/or distance from the central driving intrusion [22].

Tectonically, the accretionary orogeny means not only the vertical accretion of juvenile crust through mafic arc magmatism (Fig. 2a) but also the lateral accretion of juvenile arc terranes to continental margins (Fig. 2b). In either case, there are variable differences in time between the vertical and lateral accretions during the subduction of oceanic lithosphere. More importantly, porphyry ore deposits in the eastern Pacific rim are generally associated with felsic rather than mafic intrusives [23]. This lithochemical difference indicates that ore-forming magmas underwent significant differentiation, which may be realized through either the fractional crystallization of primary mafic arc melts or the partial melting of crystalline arc intrusives. Furthermore, these ore deposits were generally produced in extensional rather than compressional regimes, indicating that the metallogenesis postdates metamorphic dehydration of the subducting oceanic slab during its thermal coupling with the mantle wedge at subarc depths. In addition, the tectonic processes for arc magmatism above oceanic subduction zones would generally proceed in two stages [24]. The first is the generation of fertile, enriched mantle domains through chemical metasomatism of the mantle wedge by liquid phases such as aqueous solutions and hydrous melts from the subducting oceanic slab, and the second is partial melting of these mantle domains for mafic arc magmatism (Fig. 3). The two stages may be either continuous or discontinuous, depending on the geodynamics of convergent plate boundaries [25,26].

It is known that subduction zones would have low thermal gradients of <10 °C/km if the subducting oceanic slab was thermally coupled with the overlying mantle wedge [26,27]. This stage may be responsible for metamorphic dehydration and partial melting of the subducting oceanic crust (composed of seafloor sediment and mafic igneous rocks) at subarc depths, providing the liquid phases for the chemical metasomatism. However, the temperature of subduction zones was low in this stage of compression, so that the mantle domains have very low potential for partial melting to produce arc magmatism. As soon as the subducting oceanic slab was thermally decoupled with the overlying mantle wedge at subarc depths, its base can be heated by laterally flowing asthenospheric mantle [26]. As a consequence, the mantle domains can become partially melted for arc magmatism in the stage of extension. Duration for the thermal transition from coupling to decoupling between the subducting slab and mantle wedge may be short (<1 Ma) or long (>100 Ma), depending on the geodynamics of subduction zones [28]. The short duration is typical of arc magmatism above the circum-Pacific subduction zones, whereas the long duration is common for post-collisional arc-like magmatism in intracontinental regions. The intracontinental reactivation is common due to continental rifting along preexisting accretionary and collisional orogens, often showing superimposition of eclogite facies metamorphic rocks by granulite facies metamorphism at fossil convergent boundaries [27].

In accretionary orogens, hydrothermal ore deposits represent extraordinary metal concentrations that form by geological processes in tectonic environments typified by high thermal gradients at convergent plate boundaries. Although they require the conjunction of specific geological environments to form, the pre-enrichment of metals in their sources is the key to the formation of ore deposits. After examining the characteristics of some porphyry Cu-Au, epithermal Au, iron oxide Cu-Au and orogenic Au deposits worldwide, Griffin et al. [29] argue that the origin of such
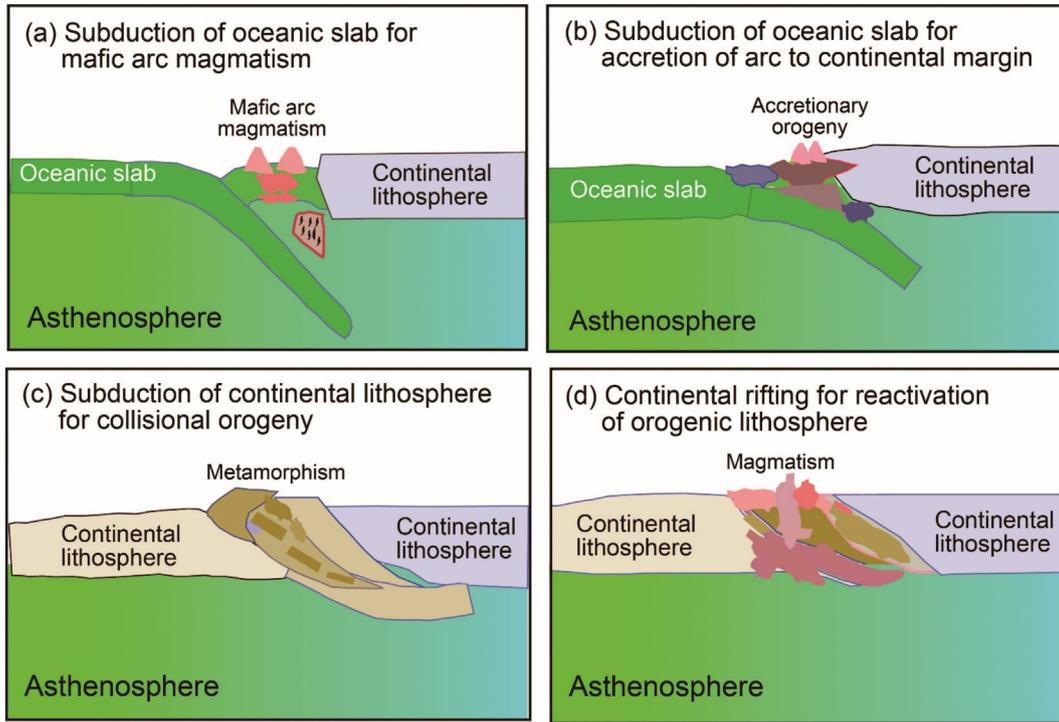
Fig. 2. Schematic diagrams showing the tectonic evolution of orogens from oceanic subduction for accretionary orogeny through continental subduction for collisional orogeny to continental rifting for rifting orogeny along convergent plate boundaries (for terminology see Supplementary Information).
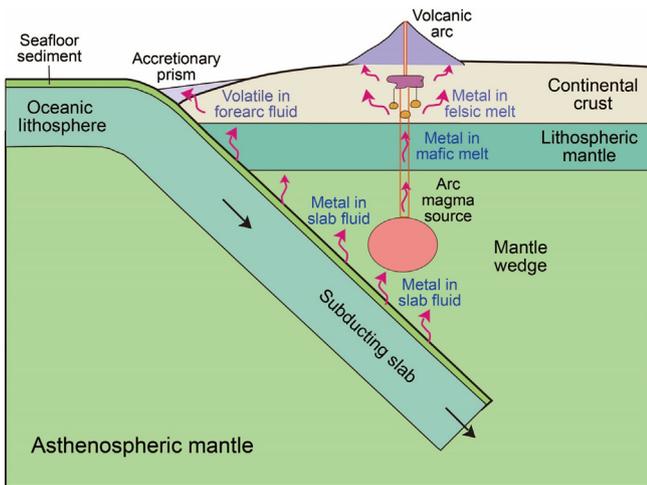
Fig. 3. Schematic diagram showing the generation of metal pre-enriched domains in the mantle wedge at first above oceanic subduction zones and then further enrichment of ore-forming elements in mafic and felsic melts through geochemical differentiation.

ore deposits is related to enrichment of these ore-forming elements in the subcontinental lithospheric mantle that underwent metasomatism by liquid phases from subducting oceanic slabs. For porphyry Cu deposits in the Gangdese orogen, Hou et al. [30,31] link metallogenesis to pre-enrichment of the ore-forming element in the mantle wedge above the Neo-Tethyan oceanic subduction zone. Similar arguments are also shared for the genesis of REE-rich carbonatite at Mianning-Dechang in Southwest China [32] and Au-rich porphyry deposits at Beiya along the western margin of the South China Block [33]. In this regard, the temporal and spatial distributions of hydrothermal ore deposits at convergent plate boundaries are the result of spectacular metallogenic processes.

In view of the tectonic processes above oceanic subduction zones, their metallogenesis would experience at least three steps of geochemical differentiation (Fig. 4). The first is the preliminary enrichment of incompatible elements, including ore-forming elements, in the liquid phases by metamorphic dehydration and/or partial melting of the subducting oceanic crust at subarc depths (Fig. 4a). The second is the further enrichment of the ore-forming elements in mafic melts by partial melting of the metasomatic domains in the mantle wedge (Fig. 4b). This leads to mafic arc magmatism that is either modal for volcanic eruption on the surface or
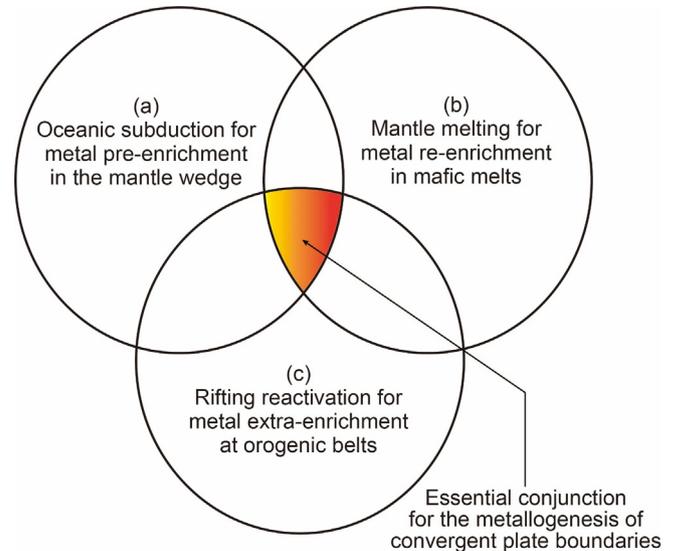
Fig. 4. Schematic diagram showing the conjunction of three independent steps for progressive enrichment of ore-forming elements in the mantle wedge, the mafic melt and the felsic melt, respectively, with the final mineralization at convergent plate boundaries.

cryptic for igneous intrusion below the surface. The third is the extraordinary enrichment of those metals in hydrothermal fluids for ore deposition during felsic magmatism (Fig. 4c), which may be realized either through the fractional crystallization of mafic arc melts during their ascent or through the partial melting of mafic arc intrusives in the lower crustal level. While there may be variable differences in time between the first and second steps, it is generally short between the second and third steps. Because the second step would be caused by lithospheric rifting, the extensional regime prevails for metallogenesis at convergent plate boundaries. In other words, the rifting orogeny is responsible for reactivation of both accretionary and collisional orogens [27] and thus for the final deposition of ore minerals.

3. Metallogenesis of collisional orogens

In order to produce numerous giant or large ore deposits at convergent plate boundaries, it is necessary to have the reactivation of metal pre-enriched domains by later tectonism. It is known that subduction of the Neo-Tethyan oceanic slab beneath the Asian continent for accretionary orogeny in the Mesozoic was followed by the collisional orogeny between the Indian and Asian continents in the Cenozoic [18]. With respect to the age of 55 ± 10 Ma for the continental collision between India and Asia [17,34], the majority of hydrothermal ore deposits in the Gangdese orogen of southern Tibet would have formed in the syn- and post-collisional stages [14]. In this regard, their formation can be attributed to reactivation of the Mesozoic accretionary orogens not only by the collisional orogeny in the Early Cenozoic (Fig. 2c) but also by the rifting orogeny in the Late Cenozoic (Fig. 2d). Therefore, the metallogenesis of collisional orogens would be generally achieved by reactivation of the metal pre-enriched domains in the hangwall of continental subduction zones. This provides a generic model for the origin of hydrothermal ore deposits in collisional orogens (Fig. 4). It is applicable to the metallogenesis of collisional orogens elsewhere in the world, which is illustrated below by Mesozoic ore deposits in the Central Orogenic Belt of China, such as hydrothermal Mo deposits at Shapinggou in the Dabie-Hong'an orogen, and hydrothermal Au deposits at Jiaodong and Xiaoqinling in the southern margin of the North China Block.

The Shapinggou Mo deposit is located in the Shang-Ma fault zone between the Dabie and Hong'an orogens in east-central China. It is one of the largest Mo-only porphyry deposits in the world [35–39]. It has a total reserve of approximately 2.37 Mt Mo with ore grades of ∼0.14 wt% Mo in average, and Mo is present in the form of molybdenite. Porphyry magmatism dominantly occurred in the Early Cretaceous and can be divided into two stages at 125–138 Ma and 111–118 Ma, respectively [40]. The Mo ore-bodies are mainly hosted in the late-stage granitic porphyry and syenite, whose exposure area is much smaller than the early-stage intrusions. The ore-bearing granitoids are located in the Bei-huaiyang zone, a lithotectonic unit that looks like the hangwall of the Triassic continental subduction zone [41]. Molybdenite Re–Os dating yields an isochron age of 111.1 ± 1.2 Ma for the mineralization, and zircon U–Pb dating gives ages of 111.7 ± 0.8 Ma for the granitic porphyry and 111.9 ± 0.6 Ma for the quartz syenite [42]. In comparison with the Triassic age of 245–215 Ma for the continental collision to build the Hong'an-Dabie-Sulu orogenic belt between the North and South China Blocks [43,44], the porphyry Mo mineralization postdates the collisional orogeny at least 100 Ma. Nevertheless, it is only slightly later than the emplacement age of 112–115 Ma for mafic dykes, which are also located in the Shang-Ma fault zone but show oceanic island basalts (OIB)-like trace element geochemistry and relatively depleted radiogenic isotope compositions with consistently high $\varepsilon_{Nd}(t)$

values of −1.8 to 4.5 and low $(^{87}Sr/^{86}Sr)i$ ratios of 0.7040 to 0.7050 [45]. In view of the known tectonism for subduction of the Paleo-Tethyan oceanic slab beneath the southern margin of the North South Block in the Late Paleozoic [46], it is inferred that these mafic dykes have their mantle source to be generated by metasomatic reaction of the mantle wedge peridotite with hydrous melts derived from dehydration melting of the subducting Paleo-Tethys oceanic crust [45]. This period of oceanic subduction would have also given rise to a fertile, Mo pre-enriched domain in the mantle wedge. During the collisional orogeny in the Triassic, nevertheless, the domain was not reactivated for the porphyry Mo mineralization. In the Early Cretaceous, however, the collision-thickened orogenic root was foundered for underplating of the asthenospheric mantle due to the continental rifting [47]. It is this episode of rifting orogeny that would have resulted in reactivation of the Mo pre-enriched domain for the porphyry Mo mineralization at the collisional continental boundary (Fig. 5).

The Jiaodong Au ore district is located in the southeastern margin of the North China Block. It consists of >100 gold deposits, including seven world-class giants [48–52]. These deposits have a total gold reserve of >4,000 t, making Jiaodong the largest gold producer of China. The Jiaodong Au deposits are hosted by Neoarchean to Paleoproterozoic amphibolite facies metamorphic rocks, which were intruded by a large volume of Mesozoic granitoids with a small volume of mafic igneous rocks. All these rocks are located in a lithotectonic unit north of the Sulu orogen and east of the Tanlu Fault. This unit is part of the Paleoproterozoic Jiao-Liao-Ji orogen and served as the hangwall of the Triassic continental subduction zone [53,54]. The majority of Au deposits there are hosted by the NE-trending ductile–brittle faults traversing some granitoids and, less commonly, the basement rocks. The ore-bearing granitoids were emplaced episodically at ca. 160–150 Ma, 130–126 Ma, and 125–90 Ma, respectively. Gold mineralization occurs either as extensional massive gold–quartz–pyrite veins that can continue for >1 km along strike or as shear zone-hosted disseminated sulfides in fractured granitoids. Various geochronological approaches were used to date the hydrothermal Au mineralization at Jiaodong, yielding a range of ages from 100 to 138 Ma [55]. After examination of all available dates for Au ore bodies and their host rocks, Goldfarb and Santosh [49] conclude that the vast majority of the gold ore was deposited over a relatively short time interval between 120 and ca. 126 Ma. This range of metallogenic ages falls within a peak age range of
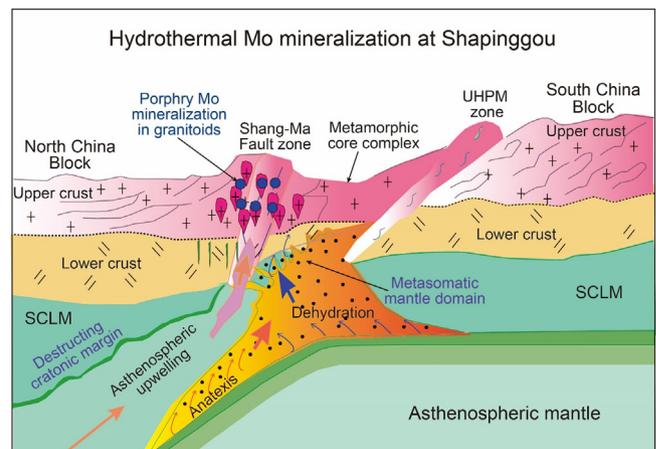
Fig. 5. Schematic diagram showing the formation of the porphyry Mo deposit at Shapinggou in the Shang-Ma fault zone between the Dabie and Hong'an orogens. SCLM, subcontinental lithospheric mantle; UHPM, ultrahigh-pressure metamorphic.

120–130 Ma for intense magmatism in the eastern part of the North China Block [56,57]. Its youngest age is also close to an age of ~121 Ma for the geochemical transformation in the composition of mantle sources between two types of mafic igneous rocks [58], suggesting that the hydrothermal Au mineralization is temporally associated with a dramatic demarcation in mantle composition at the fossil convergent boundary.

There have been hot debates on the origin of hydrothermal Au deposits in the Jiaodong district [49–52]. Because these Au deposits are hosted in the Precambrian metamorphic basement, they resemble many features of common orogenic Au deposits [19,59]. In general, typical Phanerozoic orogenic Au deposits were generated by regional metamorphism of oceanic igneous rocks in accretionary orogens surrounding Precambrian cratons [60]. However, there was no accretionary orogen of Phanerozoic age along the convergent continental boundary between the North and China Blocks in the Dabie-Sulu orogenic belt [61]. On the other hand, the Jiaodong Au deposits have their metallogenic ages consistent with the peak age of cratonic destruction in North China, so that they were termed as decratonic gold deposits [51]. Although they do occur in the hangwall of the collisional orogen between the North and South China Blocks, the metallogenic ages of 120–126 Ma in the Early Cretaceous are significantly later than the continental collision to build the Dabie-Sulu orogenic belt at 215–245 Ma in the Triassic [61]. This makes their formation irrelevant to the collisional orogeny itself. Nevertheless, there was northward subduction of the Paleo-Tethyan oceanic slab beneath the southern margin of the North China Block in the Late Paleozoic before the continental collision in the Triassic to build the Dabie-Sulu orogenic belt [46,61]. This period of oceanic subduction would generate a series of fertile, Au pre-enriched domains in the mantle wedge. Nevertheless, these domains were not reactivated for the hydrothermal Au mineralization during the collisional orogeny in the Triassic. Instead, they were reactivated by the continental rifting in the Early Cretaceous subsequent to foundering of the orogenic root [47]. This rifting orogeny would serve as the geodynamic mechanism for the hydrothermal Au mineralization in the collisional orogen.

The Xiaoqinling Au deposits are located in the southern margin of the Trans-North China Orogen in the North China Block. They constitute the second largest gold producer of China [51,62,63]. Compared with the hydrothermal Au deposits at Jiaodong, the Au deposits at Xiaoqinling are mostly hosted in the Precambrian metamorphic rocks of the Taihua Group (2.2–2.9 Ga) and the volcanic rocks of the Xiong'er Group (~1.78 Ga), rather than the Mesozoic intrusions, in the southern margin of the North China Block. This ancient craton was subducted by the North Qinling microcontinent for continental collision at 490–500 Ma in the Cambrian [46]. Afterwards its southern margin was laterally grown southwards through more one episodes of accretionary orogeny during the Paleozoic till the final collision of its newly accreted margin with the northern margin of the South China Block in the Triassic. The Au ore bodies in the Xiaoqinling district dominantly occur in Au-bearing quartz veins and to a lesser extent in auriferous altered rocks hosted in the Taihua Group [51,62,63]. The Au mineralization mostly took place at a range of ages from 135 to 120 Ma [62], which are basically contemporaneous with those of the Jiaodong Au deposits. However, it is significantly later than the continental collision between the North China Block and the North Qinling terrane in the Cambrian. Nevertheless, the North China Block was subducted by the ancient oceanic slab in the Ediacaran before colliding with the North Qinling terrane in the Cambrian [46]. In this regard, there would be not only chemical metasomatism of the mantle wedge but also accretionary orogeny before the collisional orogeny by the continental subduction in the Cambrian. This enables the preliminary Au enrichment in metasomatic domains

of the mantle wedge, which were reactivated for the final Au mineralization in the Early Cretaceous.

The above documents indicate that the formation of hydrothermal ore deposits in the hangwall of collisional orogens requires the conjunction in time and space of three essential steps (Fig. 4): (1) the subduction of oceanic lithosphere before continental collision, generating the metal pre-enriched domains in the mantle wedge (Fig. 4a), (2) the further enrichment of ore-forming elements in mafic melts through partial melting of the metal pre-enriched mantle domains (Fig. 4b), and (3) the reactivation of metal pre-enriched crustal domains by continental rifting for hydrothermal mineralization above continental subduction zones (Fig. 4c). In this regard, it is necessary to have the three steps of metal enrichment together in the orogenic lithosphere in order to make the hydrothermal ore deposits in either of accretionary, collisional or rifting orogens. However, it remains to be resolved which step has played a central role in the extraordinary enrichment of metals for orogenic metallogenesis.

## 4. Metallogenesis of granitic rocks

In addition to the hydrothermal ore deposits in I-type granites of the Gangdese orogen [11–14], there are a number of potential Be, Nb-Ta and Sn mineralizations in S-type granites of the Himalayan orogen. This is indicated by the occurrence of rare-metal bearing minerals such as beryl, columbite-group minerals, tapiolite, pyrochlore-microlite, fergusonite, rutile, and cassiterite in leucogranites [64]. These leucogranites were emplaced in the Late Cenozoic [65] and contemporaneous with adjacent migmatites and granulites [66], indicating their petrogenetic link to rifting orogeny [17]. With respect to the tectonic architecture along the convergent continental boundary between India and Asia [18], the Himalayan orogen is composed of metasedimentary rocks derived from the subducting Indian continent, and the leucogranites herein were derived from partial melting of the metasedimentary rocks [67,68]. Therefore, the extraordinary enrichment of ore-forming elements in the S-type granites has no bearing on the chemical metasomatism of the mantle wedge during the Neo-Tethyan oceanic subduction in the Mesozoic. It may result from geochemical differentiation of the metasedimentary rocks through both partial melting and fractional crystallization. In contrast, the Gangdese orogen is composed of igneous rocks that were produced by continental arc magmatism in the Mesozoic [18] and then reworked by continental rifting in the Cenozoic for the geochemical differentiation in the *syn*-collisional and post-collisional stages, respectively [17]. As a consequence, the ore-forming elements were pre-enriched in the mantle wedge by the chemical metasomatism in the Mesozoic and then re-enriched in the I-type granitic melts that underwent the geochemical differentiation for the final ore deposition in the Conozoic. In either case, the metallogenesis at the convergent continental boundary is caused by continental rifting for the reactivation of metal pre-enriched domains.

There are also very important hydrothermal ore deposits of Mesozoic age in South China. These include not only granite-related Sn, W, and Sb deposits, but also porphyry Cu–Mo, vein-type Pb–Zn–Ag, and epithermal Au–Ag–(Cu) deposits [69,70]. As one of the most important metallogenic provinces in the world, South China has been the focus of research for more than a half of century [71–74]. However, the metallogenic province of South China did not experience either accretionary orogeny or collisional orogeny in the Mesozoic [61]. Nevertheless, there was the Jiangnan orogen of Neoproterozoic age in South China. This is a composite orogen that was built through two episodes of convergent tectonism. The first is subduction of the Cathaysian oceanic slab beneath the Yangtze Craton for accretionary orogeny in the Early Neopro-

terozoic [75], resulting in the generation of metal pre-enriched domains in the mantle wedge. It was followed by collisional orogeny to build a unified continent of South China. Afterwards, this composite accretionary-collisional orogeny was superimposed by two episodes of continental rifting in the Middle Neoproterozoic. The first episode occurred at 800–830 Ma in response to the attempting breakup of supercontinent Rodinia and thus was a failed one. The second was successful to run into supercontinental rupture for separation of South China from Rodinia at 740–780 Ma [76,77]. As a consequence, the ore-forming elements would have achieved sufficient enrichment in the orogenic lithosphere, which was susceptible to reactivation for hydrothermal mineralization. In the Paleozoic, South China was an independent continental region till its collision with the North China Block in the Triassic [61]. It was variably reactivated due to westward subduction of the Paleo-Pacific slab beneath eastern Asian continent in the Jurassic to Cretaceous [61,70], resembling the effect on Mesozoic magmatism in North China [78]. For this reason, the hydrothermal ore deposits of Mesozoic age in South China would be primarily generated by reworking of the metal pre-enriched domains in the Jiangnan orogen. Contemporaneous magmatism is abundant in South China and mostly in granitic composition [79], indicating the multistages of geochemical differentiation through partial melting and fractional crystallization since the Neoproterozoic. While the differentiation of sedimentary rocks results in the Sn-W-Sb and Pb–Zn–Ag deposits in S-type granites, the differentiation of igneous rocks leads to the Cu–Mo and Au–Ag deposits in I-type granites. In either case, the metallogenesis is achieved by the reactivation of metal pre-enriched domains in the crustal rocks of fossil accretionary orogens.

In view of the above arguments, it appears that the tectonic mechanism for metallogenesis of collisional orogens can be clarified by linking the metal pre-enrichment to modal or cryptic arc magmatism in accretionary orogens at first and then linking the final mineralization to hydrothermal reactivation by rifting orogeny (Figs. 3 and 4). However, the problem has been encountered in distinguishing contributions not only between crustal and mantle materials but also between material and heat from the asthenospheric mantle to both petrogenesis and metallogenesis in continental regions. This has resulted in a lot of mistakes in interpreting geochemical data for orebodies and their wallrocks in various types of orogens. Regardless of the composition of major elements in magmatic rocks, typically, positive $\varepsilon_{Nd}(t)$ or $\varepsilon_{Hf}(t)$ values were erratically ascribed to material contributions from the depleted mantle (the ordinary asthenospheric mantle), and arc-like trace element distribution patterns were erratically ascribed to primary arc magmatism [24]. As a consequence, various hypotheses and models were put forward for the origin of hydrothermal ore deposits in continental regions, leading to considerable confusion and misconception in petrogenetic and metallogenic studies. Because the metallogenesis requires at least the three steps of metal enrichment in lithospheric domains (Fig. 4), the incompatibility of ore-forming elements is the key to the geochemical differentiation of both crustal and mantle materials above subduction zones (Fig. 3).

In addition, orogens at convergent plate boundaries would have evolved from accretionary through collisional to rifting with respect to their genetic relationship to subduction zones in both time and space (Fig. 6). Thus, it is critical to distinguish the collisional orogeny from both pre-collisional accretionary orogeny and post-collisional rifting orogeny in given orogens [17,27,28,47]. While a heat supply from the asthenospheric mantle is prominent during continental rifting [27,28], the proportion of material supply has decreased from the maximum during the accretionary orogeny (Fig. 4a) to the minimum during the collisional orogeny (Fig. 4c). Both heat and material can be supplied
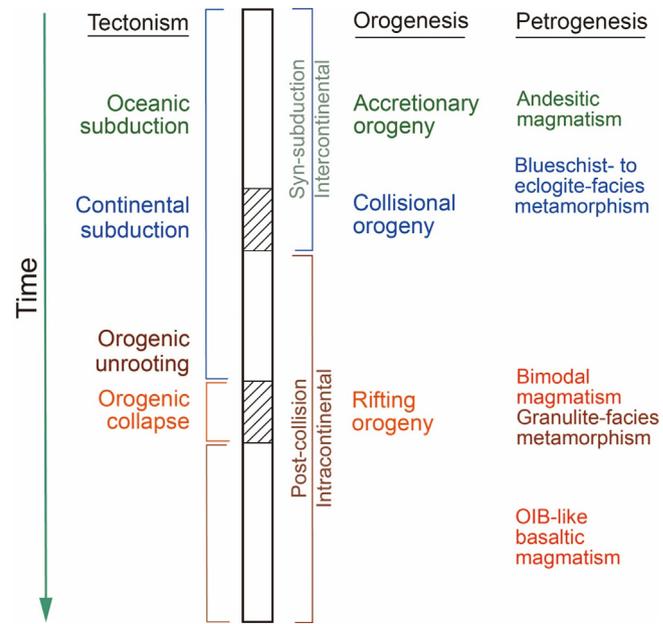
Fig. 6. (Color online) A schematic flowchart illustrating the tectonic evolution of orogens from accretionary through collisional to rifting along convergent plate boundaries with respect to their genetic relationship to subduction zones in both time and space (for terminology see Supplementary Information).

by the asthenospheric mantle through the rifting orogeny, but only volatiles are susceptible to transport together with the high heat flow into orogenic crust. In this regard, ore-forming elements were not originated from the asthenospheric mantle. Instead, they would be derived from the subducted crustal rocks that could be locally enriched in ore-forming elements. This is indicated by the common occurrence of crust-like isotopic signatures in mafic igneous rocks. Nevertheless, these crustal signatures were incorporated by recycling of crustal material at subduction zones into the mantle source of mafic magmas in the form of liquid rather than solid phases with very small amounts [24]. Otherwise the mantle source would change its lithochemistry from ultramafic to mafic, making its melting products intermediate to felsic in composition [78,80]. On the other hand, the mafic magmas would undergo significant geochemical differentiation in two ways to produce felsic melts. One is the fractional crystallization during accretionary orogeny, and the other is that their crystalline products in the lower crust underwent partial melting during collisional or rifting orogenesis. In either case, the hydrothermal fluids were produced together with the felsic melts. It is the fluids that can eventually have the sufficient enrichment of ore-forming elements for ore deposition.

5. Concluding remarks

Collisional orogens host many of the important hydrothermal ore deposits in the world, but their building itself has the limited metallogenic endowment with respect to mountain building by either pre-collisional accretionary orogeny or post-collisional rifting orogeny. This is the reason why previous studies disfavor the production of hydrothermal ore deposits by collisional orogeny. However, more and more observations indicate that the metallogenesis of collisional orogens is pre-conditional by the pre-enrichment of ore-forming elements in the orogenic crust and mantle, respectively. Heterogeneous fertilization of the mantle wedge by the subduction of oceanic lithosphere generates the metasomatic domains with variable enrichment of ore-forming

elements. This process provides metal pre-enriched reservoirs that can be reactivated by continental rifting for felsic magmatism, resulting in the formation of hydrothermal ore deposits either immediately during accretionary orogeny or later on during collisional and rifting orogenesis. Such ore deposits are common in the hangwall I-type granites of both oceanic and continental subduction zones. In this regard, the generation of metal pre-enriched domains in the mantle wedge is the key step to the metallogenesis of either accretionary or collisional orogens. By doing so, the geochemical differentiation of crustal and mantle rocks at different depths plays a substantial role in causing the progressive enrichment of ore-forming elements in the overriding lithosphere above continental subduction zones. On the other hand, the subducted crustal rocks may be locally enriched in ore-forming elements, which may be further enriched by geochemical differentiation to form rare-metal minerals in the footwall S-type granites of fossil subduction zones. Nevertheless, the mantle contribution to both petrogenesis and metallogenesis at crustal depths is overwhelmed by heat rather than material, which is most favorable in the sites of continental rifting along previously subducted zones.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2019.01.007.

References

[1] Kerrich R, Goldfarb RJ, Richards JP. Metallogenic provinces in an evolving geodynamic framework. Econ Geol 2005;100th Anniversary Volume: 1097–136.
[2] Groves DI, Bierlein FP. Geodynamic settings of mineral deposit systems. J Geol Soc 2007;164:19–30.
[3] Richards JP. Tectonic, magmatic, and metallogenic evolution of the Tethyan orogen: from subduction to collision. Ore Geol Rev 2015;70:323–45.
[4] Sawkins FJ. Metal deposits in relation to plate tectonics. Berlin Heidelberg New York: Springer Verlag; 1984. p. 261.
[5] Nelson EP. Suprasubduction mineralization: metallo-tectonic terranes of the southernmost Andes. Geophys Monogr 1996;96:315–30.
[6] Seedorff E, Dilles JH, Proffett Jr JM. Porphyry deposits: characteristics and origin of hypogene features. Econ Geol 2005;100th Anniversary Volume:251–98.
[7] Simmons SF, White NC, John DA. Geological characteristics of epithermal precious and base-metal deposits. Econ Geol 2005;100th Anniversary Volume:485–522.
[8] Franklin JM, Gibson HL, Jonasson IR, et al. Volcanogenic massive sulfide deposits. Econ Geol 2005;100th Anniversary Volume:523–60.
[9] Bierlein FP, Groves DI, Cawood PA. Metallogeny of accretionary orogens — the connection between lithospheric processes and metal endowment. Ore Geol Rev 2009;36:282–92.
[10] Hronsky JMA, Groves DI, Loucks RR, et al. A unified model for gold mineralisation in accretionary orogens and implications for regional-scale exploration targeting methods. Mineral Deposit 2012;47:339–58.
[11] Rui ZY, Hou ZQ, Qu XM, et al. Metallogenetic epoch of Gangdese porphyry copper belt and uplift of Qinghai-Tibet Plateau. Mineral Deposit 2003;22:217–25 (in Chinese).
[12] Hou ZQ, Cook NJ. Metallogenesis of the Tibetan collisional orogen: a review and introduction to the special issue. Ore Geol Rev 2009;36:2–24.
[13] Hou ZQ, Zhang H. Geodynamics and metallogeny of the eastern Tethyan metallogenic domain. Ore Geol Rev 2015;70:346–84.
[14] Zhang HR, Hou ZQ. Metallogenesis within continental collision zones: comparisons of modern collisional orogens. Sci China Earth Sci 2018;61:1737–60.
[15] Windley BF. The evolving continents. 3rd ed. New York: Wiley; 1995. p. 526.
[16] Cawood PAC, Kröner A, Collins WJ, et al. Accretionary orogens through time. Geol Soc Spec Pub 2009;318:1–36.
[17] Zheng YF, Wu FY. The timing of continental collision between Indian and Asia. Sci Bull 2018;63:1649–54.
[18] Yin A, Harrison TM. Geologic evolution of the Himalayan-Tibetan orogen. Ann Rev Earth Planet Sci 2000;28:211–80.
[19] Goldfarb RJ, Baker T, Dube B, et al. Distribution, character, and genesis of gold deposits in metamorphic terranes. Econ Geol 2005;100th Anniversary Volume:407–50.
[20] Richards JP. Postsubduction porphyry Cu-Au and epithermal Au deposits: products of the remelting of subduction-modified lithosphere. Geology 2009;37:247–50.
[21] Wang GG, Ni P, Yao J, et al. The link between subduction-modified lithosphere and the giant Dexing porphyry copper deposit, South China: constraints from high-Mg adakitic rocks. Ore Geol Rev 2015;67:109–26.
[22] Sillitoe RH. Porphyry copper systems. Econ Geol 2010;105:3–41.
[23] Lee CTA, Luffi P, Chin EJ, et al. Copper systematics in arc magmas and implications for crust-mantle differentiation. Science 2012;336:64–8.
[24] Zheng YF, Chen YX, Dai LQ, et al. Developing plate tectonics theory from oceanic subduction zones to collisional orogens. Sci China Earth Sci 2015;58:1045–69.
[25] Zheng YF, Chen YX. Continental versus oceanic subduction zones. Nat Sci Rev 2016;3:495–519.
[26] Zheng YF, Chen RX, Xu Z, et al. The transport of water in subduction zones. Sci China Earth Sci 2016;59:651–82.
[27] Zheng YF, Chen RX. Regional metamorphism at extreme conditions: implications for orogeny at convergent plate margins. J Asian Earth Sci 2017;145:46–73.
[28] Zheng YF, Zhao ZF. Introduction to the structures and processes of subduction zones. J Asian Earth Sci 2017;145:1–15.
[29] Griffin W, Begg G, O'Reilly SY. Continental-root control on the genesis of magmatic ore deposits. Nat Geosci 2013;6:905–10.
[30] Hou ZQ, Zheng YC, Yang ZM, et al. Contribution of mantle components within juvenile lower-crust to collisional zone porphyry Cu systems in Tibet. Mineral Deposit 2013;48:173–92.
[31] Hou ZQ, Yang ZM, Lu YJ, et al. Subduction- and collision-related porphyry Cu deposits in Tibet: possible genetic linkage. Geology 2015;43:247–50.
[32] Hou ZQ, Liu Y, Tian SH, et al. Formation of carbonatite-related giant rare-earth-element deposits by the recycling of marine sediments. Sci Rep 2015;5:10231.
[33] Hou ZQ, Zhou Y, Wang R, et al. Recycling of metal-fertilized lower continental crust: origin of non-arc Au-rich porphyry deposits at cratonic edges. Geology 2017;45:563–6.
[34] Zhu DC, Wang Q, Zhao ZD. Constraining quantitatively the timing and process of continent-continent collision using magmatic record: method and examples. Sci China Earth Sci 2017;60:1040–56.
[35] Zhang HD, Wang BH, Hao YJ, et al. Geological characteristics and comprehensive ore-prospecting information of Shapinggou porphyry-type molybdenum deposit in Anhui Province. Mineral Deposit 2012;31:41–51 (in Chinese).
[36] Wang GG, Ni P, Yu W, et al. Petrogenesis of Early Cretaceous post-collisional granitoids at Shapinggou, Dabie Orogen: implications for crustal architecture and porphyry Mo mineralization. Lithos 2014;184:393–415.
[37] Gao Y, Mao JW, Ye HS, et al. A review of the geological characteristics and geodynamic setting of the late Early Cretaceous molybdenum deposits in the East Qinling-Dabie molybdenum belt, East China. J Asian Earth Sci 2015;108:81–96.
[38] Chen YJ, Wang P, Li N, et al. The collision-type porphyry Mo deposits in Dabie Shan, China. Ore Geol Rev 2017;81:405–30.
[39] Ren Z, Zhou T, Hollings P, et al. Magmatism in the Shapinggou district of the Dabie orogen, China: implications for the formation of porphyry Mo deposits in a collisional orogenic belt. Lithos 2018;308–309:346–63.
[40] Ren Z, Zhou TF, Yuan F, et al. The Ssages of magmatic system in Shapinggou molybdenum deposit district, Anhui Province: evidence from geochronology and geochemistry. Acta Petrol Sin 2014;30:1097–116 (in Chinese).
[41] Zheng YF, Zhou JB, Wu YB, et al. Low-grade metamorphic rocks in the Dabie-Sulu orogenic belt: a passive-margin accretionary wedge deformed during continent subduction. Int Geol Rev 2005;47:851–71.
[42] Zhang H, Li CY, Yang XY, et al. Shapinggou: the largest Climax-type porphyry Mo deposit in China. Int Geol Rev 2014;56:313–31.
[43] Li SG, Jagoutz E, Lo CH, et al. Sm/Nd, Rb/Sr, and ^{40}Ar/^{39}Ar isotopic systematics of the ultrahigh-pressure metamorphic rocks in the Dabie-Sulu belt, Central China: a retrospective view. Int Geol Rev 1999;41:1114–24.
[44] Liu FL, Liou JG. Zircon as the best mineral for P-T–time history of UHP metamorphism: a review on mineral inclusions and U–Pb SHRIMP ages of zircons from the Dabie-Sulu UHP rocks. J Asian Earth Sci 2011;40:1–39.
[45] Dai LQ, Zhao ZF, Zheng YF. Tectonic development from oceanic subduction to continental collision: geochemical evidence from postcollisional mafic rocks in the Hong'an-Dabie orogens. Gondwana Res 2015;27:1236–54.
[46] Wu YB, Zheng YF. Tectonic evolution of a composite collision orogen: an overview on the Qinling-Tongbai-Hong'an-Dabie-Sulu orogenic belt in central China. Gondwana Res 2013;23:1402–28.

[47] Zheng YF, Zhao ZF, Chen RX. Ultrahigh-pressure metamorphic rocks in the Dabie-Sulu orogenic belt: compositional inheritance and metamorphic modification. Geol Soc Spec Pub 2019;474. https://doi.org/10.1144/SP474.9.

[48] Guo P, Santosh M, Li SR. Geodynamics of gold metallogeny in the Shandong Province, NE China: an integrated geological, geophysical and geochemical perspective. Gondwana Res 2013;24:1172–202.

[49] Goldfarb R, Santosh M. The dilemma of the Jiaodong gold deposits: are they unique? Geosci Front 2014;5:139–53.

[50] Mao JW, Wang YT, Li HM, et al. The relationship of mantle-derived fluids to gold metallogenesis in the Jiaodong Peninsular: evidence from H-O-C-S isotope systematics. Ore Geol Rev 2008;33:361–81.

[51] Zhu RX, Fan HR, Li JW, et al. Decratonic gold deposits. Sci China Earth Sci 2015;58:1523–37.

[52] Groves DI, Santosh M. The giant Jiaodong gold province: the key to a unified model for orogenic gold deposits? Geosci Front 2016;6:409–17.

[53] Tang J, Zheng YF, Wu YB, et al. Geochronology and geochemistry of metamorphic rocks in the Jiaobei terrane: constraints on its tectonic affinity in the Sulu orogen. Precambrian Res 2007;152:48–82.

[54] Tang J, Zheng YF, Wu YB, et al. Zircon U-Pb age and geochemical constraints on the tectonic affinity of the Jiaodong terrane in the Sulu orogen, China. Precambrian Res 2008;161:389–418.

[55] Yang JH, Wu FY, Wilde SA. A review of the geodynamic setting of large-scale Late Mesozoic gold mineralization in the North China Craton: an association with lithospheric thinning. Ore Geol Rev 2003;23:125–52.

[56] Wu FY, Lin JQ, Wilde SA, et al. Nature and significance of the Early Cretaceous giant igneous event in Eastern China. Earth Planet Sci Lett 2005;233:103–19.

[57] Zhang SH, Zhao Y, Davis GA, et al. Temporal and spatial variations of Mesozoic magmatism and deformation in the North China Craton: implications for lithospheric thinning and decratonization. Earth Sci Rev 2014;131:49–87.

[58] Dai LQ, Zheng YF, Zhao ZF. Termination time of peak decratonization in North China: geochemical evidence from mafic igneous rocks. Lithos 2016;240–243:327–36.

[59] Groves DI, Goldfarb RJ, Gebre-Mariam M, et al. Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types. Ore Geol Rev 1998;13:7–27.

[60] Goldfarb RJ, Groves DI. Orogenic gold: common or evolving fluid and metal sources through time. Lithos 2015;233:2–26.

[61] Zheng YF, Xiao WJ, Zhao GC. Introduction to tectonics of China. Gondwana Res 2013;23:1189–206.

[62] Li JW, Bi SJ, Selby D, et al. Giant Mesozoic gold provinces related to the destruction of the North China Craton. Earth Planet Sci Lett 2012;349–350:26–37.

[63] Mao JW, Goldfarb RJ, Zhang ZW, et al. Gold deposits in the Xiaoqinling-Xiong'er region, Qinling Mountains, central China. Mineralium Deposits 2002;37:306–25.

[64] Wang RC, Wu FY, Xie L, et al. A preliminary study of rare-metal mineralization in the Himalayan leucogranite belts, South Tibet. Sci China Earth Sci 2017;60:1655–63.

[65] Wu FY, Liu ZC, Liu XC, et al. Himalayan leucogranite: petrogenesis and implications to orogenesis and plateau uplift. Acta Petrol Sin 2015;31:1–36 (in Chinese).

[66] Weinberg RF. Himalayan leucogranites and migmatites: nature, timing and duration of anataxis. J Metamorph Geol 2016;34:821–43.

[67] Gao LE, Zeng LS, Asimow PD. Contrasting geochemical signatures of fluidabsent versus fluid-fluxed melting of muscovite in metasedimentary sources: the Himalayan leucogranites. Geology 2017;45:39–42.

[68] Liu XC, Li XH, Liu Y, et al. Insights into the origin of purely sediment-derived Himalayan leucogranites: Si-O isotopic constraints. Sci Bull 2018;63:1243–5.

[69] Hu RZ, Zhou MF. Multiple Mesozoic mineralization events in South China — an introduction to the thematic issue. Miner Deposit 2012;47:579–88.

[70] Mao JW, Cheng YB, Chen MH, et al. Major types and time-space distribution of Mesozoic ore deposits in South China and their geodynamic settings. Miner Deposit 2013;48:267–94.

[71] Hua RM, Chen PR, Zhang WL, et al. Metallogenesis related to Mesozoic granitoids in the Nanling Range, South China and their geodynamic settings. Acta Geol Sin 2005;79:810–20.

[72] Zaw K, Peters SG, Cromie P, et al. Nature, diversity of deposit types and metallogenic relations of South China. Ore Geol Rev 2007;31:3–47.

[73] Hu RZ, Bi XW, Zhou MF, et al. Uranium metallogenesis in South China and its relationship to crustal extension during the Cretaceous to Tertiary. Econ Geol 2008;103:583–98.

[74] Mao JW, Pirajno F, Lehmann B, et al. Distribution of porphyry deposits in the Eurasian continent and their corresponding tectonic settings. J Asian Earth Sci 2014;79:576–84.

[75] Zhang SB, Zheng YF. Formation and evolution of Precambrian continental lithosphere in South China. Gondwana Res 2013;23:1241–60.

[76] Li ZX, Li XH, Kinny PD, et al. Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze Craton, South China and correlations with other continents: evidence for a mantle superplume that broke up Rodinia. Precambrian Res 2003;122:85–109.

[77] He Q, Zhang SB, Zheng YF. Evidence for regional metamorphism in a continental rift during the Rodinia breakup. Precambrian Res 2018;314:414–27.

[78] Zheng YF, Xu Z, Zhao ZF, et al. Mesozoic mafic magmatism in North China: implications for thinning and destruction of cratonic lithosphere. Sci China Earth Sci 2018;61:353–85.

[79] Zhou XM, Sun T, Shen WZ, et al. Petrogenesis of Mesozoic granitoids and volcanic rocks in South China: a response to tectonic evolution. Episodes 2006;29:26–33.

[80] Chen L, Zhao ZF. Origin of continental arc andesites: the composition of source rocks is the key. J Asian Earth Sci 2017;145:217–32.

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