

Ridge subduction and porphyry copper-gold mineralization: An overview

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Many large porphyry Cu-Au deposits are connected to adakitic rocks known to be closely associated with ridge subduction. For example, there are several subducting ridges along the east Pacific margin, e.g., in Chile, Peru, and South America, most of which are associated with large porphyry Cu-Au deposits. In contrast, there are much fewer ridge subductions on the west Pacific margin and porphyry Cu-Au deposits are much less there, both in terms of tonnage and the number of deposits. Given that Cu and Au are moderately incompatible elements, oceanic crust has much higher Cu-Au concentrations than the mantle and the continental crust, and thus slab melts with their diagnostic adakitic chemistry have systematically higher Cu and Au, which is favorable for mineralization. Considering the geotherm of subducting slabs in the Phanerozoic, ridge subduction is the most favorable tectonic setting for this. Therefore, slab melting is the likely link in the spatial association between ridge subduction and Cu-Au deposits. Geochemical signatures of slab melting and hence maybe ridge subduction in less eroded regions in eastern China, the central Asian orogenic belt etc. may indicate important exploration targets for large porphyry Cu-Au deposits.

ridge subduction, porphyry Cu-Au deposits, adakite, slab melting

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Porphyry Cu is an important type of deposit, comprising >60% of the world's Cu reserves. The circum-Pacific region is the largest porphyry Cu mineralization province [1, 2]. For example, Chile on the east Pacific margin hosts more than 10 world class porphyry Cu deposits, with a total reserve of more than 0.35 billion tones of Cu metal, which accounts for >30% of the world's Cu reserves. These deposits are El Teniente, Chuquicamata, Río Blanco-Los

Bronces, La Escondida, Los Pelambres, El Pachón, Rosario, Radomiro Tomic, El Salvador and Toki, of which, El Teniente is the world's largest porphyry Cu deposit, with a reserve of 90 million tones of Cu metal [2–6]. There are also many porphyry Cu-Au deposits in the Philippines, southwest Pacific [2, 7]. Most of these deposits are associated with adakites—the products of slab melting [4–6, 8], and are spatially related to the subduction of ocean ridges or island chains [2].

In contrast to many other places along the circum-Pacific,

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eastern China is poor in Cu, with a total reserve of ca. 10 million tones. Plate reconstruction shows that eastern China became an active continental margin from the Jurassic [9, 10]. Similar to the South and North Americas, there are also abundant adakite and/or adakitic rocks in eastern China, many of which show Cu-Au mineralization, but large deposits with more than 10 million tones of Cu metal are not yet known. However, Dexing and the Lower Yangtze River belt have smaller-scale porphyry and/or skarn Cu (Au) deposits [11–17].

What are the main controls on the distribution of porphyry Cu-Au deposits in the circum-Pacific region and elsewhere? What is the connection between ridge subduction and porphyry Cu deposits? Are there any porphyry Cu deposits derived from Pacific subduction in eastern China? To answer these questions, we review previous studies on circum-Pacific large porphyry Cu-Au deposits, discuss the genesis and distribution of these deposits, as well as the connection between ridge subduction and porphyry Cu-Au deposits from a geochemical perspective.

1 Ridge subduction and porphyry Cu-Au deposits along the circum-Pacific region

An ocean ridge can be subducted into the mantle when it

intersects a trench [18], as was first discovered 4 decades ago during studies on orogenic processes in the western America [19]. It is now known that ridge subduction is a common phenomenon along the circum-Pacific subduction zones [20–24], and may have occurred several times since the late Mesozoic [25–29]. Because of the unique physical and thermal structures of ocean ridges, ridge subduction has major influence on the subduction angle, the thermal structure of the subduction zone, as well as the nature of magmatism and associated mineralization. Therefore, these processes have been the focus of wide interest [2, 22, 30–34] (Figure 1).

Many large porphyry Cu-Au deposits are closely associated with ridge subduction. For example, three of the world's largest porphyry Cu deposits, El Teniente (94 Mt Cu), Río Blanco-Los Bronces (57 Mt Cu), Los Pelambres-El Pachón (27 Mt Cu), ranking 1, 3, 10 respectively, are located close to each other in central Chile, along the east Pacific margin. All these deposits are spatially associated with the subduction of the Juan Fernández ridge [2, 36]. Similarly, the Cerro Colorado large porphyry Cu-Au deposit (21 Mt Cu) corresponds to subduction of the Cocos ridge (Figure 2) [3].

Several large porphyry Cu-Au deposits in the southwest of the United States, e.g., Bingham (28 Mt Cu, 1603 t Au), Butte (35 Mt Cu), are located close to ongoing ridge sub-

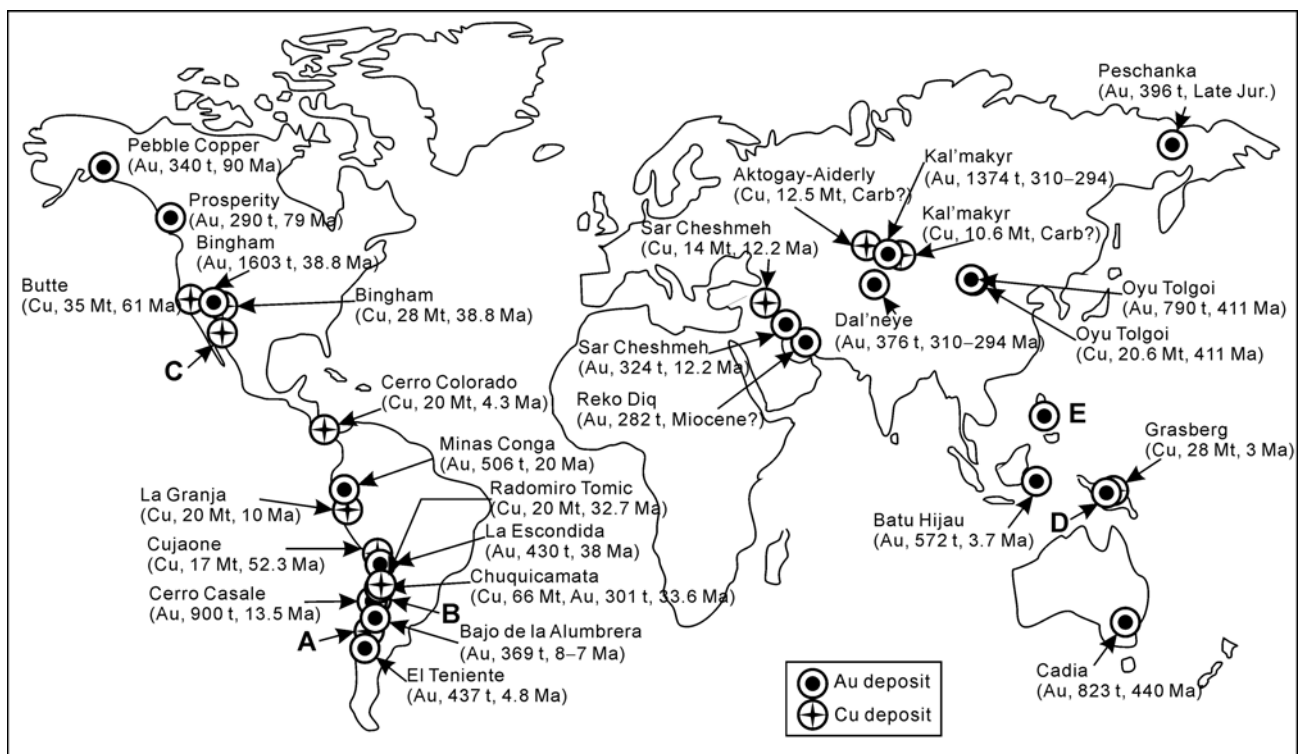


Figure 1 Global distribution of large porphyry Cu-Au deposits. Data from refs. [2, 3, 35]. A, B, C are regions dominated by Cu deposits; D, E are regions dominated by Au deposits. A, central Chile province (El Teniente, Río Blanco-Los Bronces, Los Pelambres); B, northern Chile province (Chuquicamata, La Escondida, Radomiro Tomic, Rosario, El Salvador, El Abra); C, southwest Arizona-Sonora province (Cananea, Lone Star, Morenci-Metcalf, Pima, Ray); D, Papua New Guinea-Irian Jaya province (Grasberg, Ok Tedi, Panguna, Frieda River); E, Philippines province (Far South East-Lepanto, Tampakan, Atlas, Sipalay).

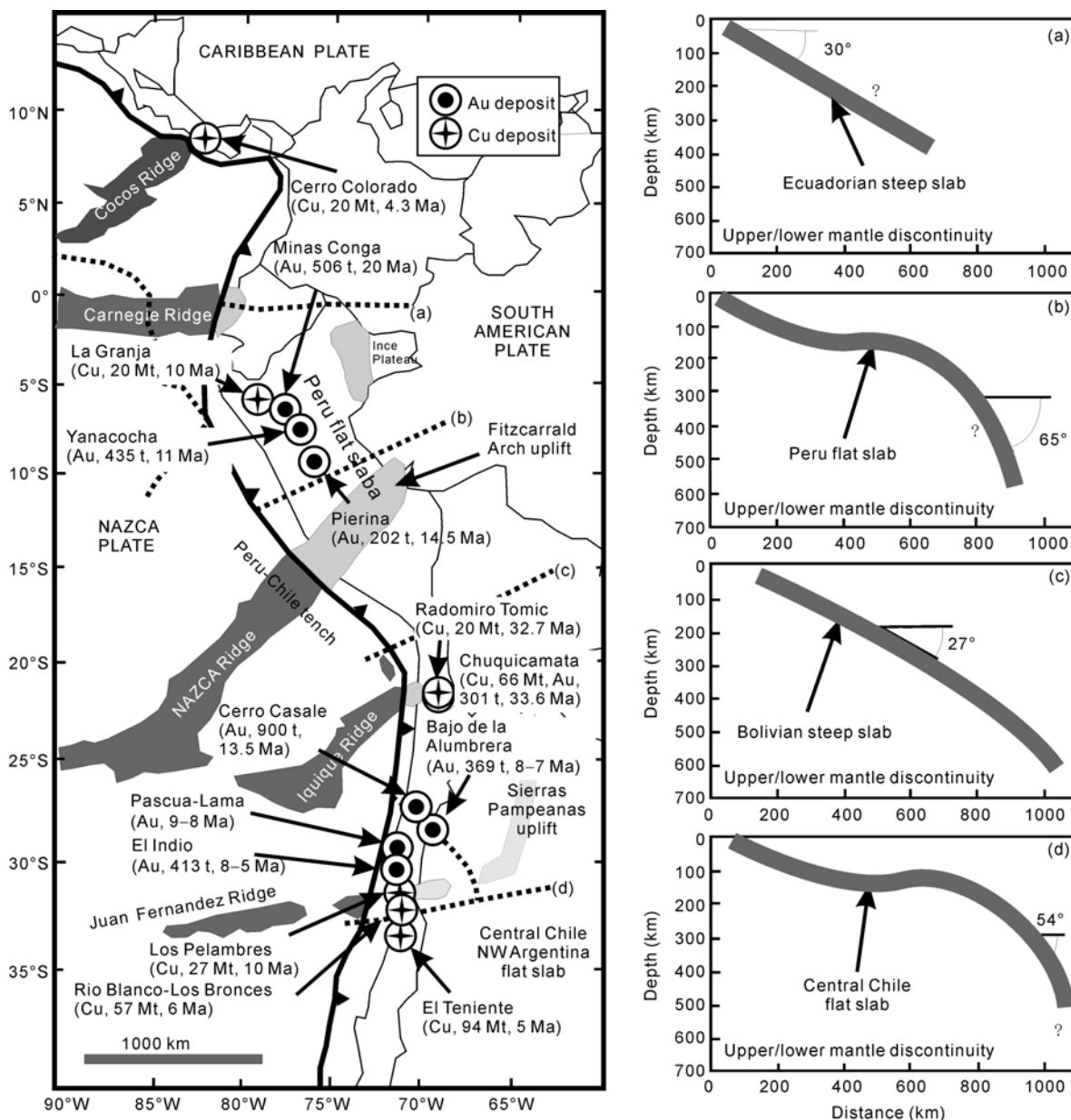


Figure 2 Ridge subduction in the eastern Pacific and large porphyry Cu-Au deposits in South America. The tectonic setting is adapted from ref. [20], and the distribution of ore deposits from refs. [2, 3].

duction in the Baja California [33]. It is however, not clear how closely these deposits are related to the ridge subduction, because they formed at 38–60 Ma. Chuquicamata in central Chile is the second largest porphyry Cu-Au deposit in the world with a total of 66 Mt Cu metal and 300 t Au. About 5 km to the north Chuquicamata, there is another large porphyry deposit, Radomiro Tomic (20 Mt Cu) [2]. Both deposits are located above the ongoing subduction of the Iquique ridge, and formed at 33.6 Ma [2] and 32.7 Ma [37], respectively. In general, ridge subduction is slower than normal plate subduction. Assuming an average rate of 10 cm/yr, about 3000 km may be subducted within 30 Ma. Therefore, more work is needed to test whether there is any

genetic connection between these particular deposits and the Iquique ridge subduction, even though most ocean ridges are much longer than 3000 km.

There are several porphyry Cu-Au deposits closely associated with subduction of the Scarborough ridge in the Philippines, southwest Pacific [2]. These are: Lepanto-Far South East (5.48 Mt Cu, 970 t Au) [38], Santo Tomas II (1.2 Mt Cu, 233 t Au) [1], Guinaoang (2 Mt Cu, 200 t Au) [3]. In addition to porphyry Cu-Au deposits, Scarborough ridge subduction is also associated with Baguio large low sulfur epithermal deposit. All these deposits are younger than 3 Ma (Figure 3) [39]. In contrast to ridge subductions along South America, the Scarborough ridge formed by slab tear-

ing [40]. In Japan, Kyushu-Palau ridge subduction [23] spatially corresponds to the Hishikari lower sulfur epithermal deposit and the Nansatsu high sulfur deposits (Figure 4). Both the above mentioned ridge subductions are associated with epithermal deposits. There are however, no world class porphyry deposits as found in South America. Probably this is because deposits connected to ridge subduction in the Philippines and Japan are very young, and much less exposed due to limited erosion. If this is correct, there could be porphyry deposits at depth (Figures 3, 4). Because there are considerably fewer ridge subductions in the west Pacific than in the east, this provides a feasible interpretation for much more abundant porphyry Cu-Au deposits along the east Pacific margin.

Eastern China is located on the west Pacific margin, but is now far away from Pacific subduction zones. The Lower Yangtze River belt is the most important Cu, poly-metal mineralization belt in eastern China, which was formed at

138 ± 5 Ma [13, 14, 17]. These Cu-Au deposits are mainly related to adakite or adakitic rocks, distributed linearly with a roughly east-west trend. More normal calc-alkaline rocks flank both sides of the adakite belt. There are also A-type granites whose distribution roughly overlaps with the adakites, but they are ca. 10 million years younger, having formed mainly at 125 Ma [41–44].

Many workers have proposed that the Mesozoic adakites in eastern China, including the Lower Yangtze River belt, were formed by partial melting of thickened or delaminated lower continental crust, based mainly on the enriched isotopic characteristics [13, 45–51]. If so, the porphyry Cu deposits associated with adakites would have no connection with plate subduction. In contrast, other workers have proposed that the Cu mainly came from the mantle [11, 52].

Copper is a moderately incompatible element [53, 54], therefore its abundance in the depleted mantle is lower than that of the primitive mantle (30 ppm) [55]. Interestingly, Cu

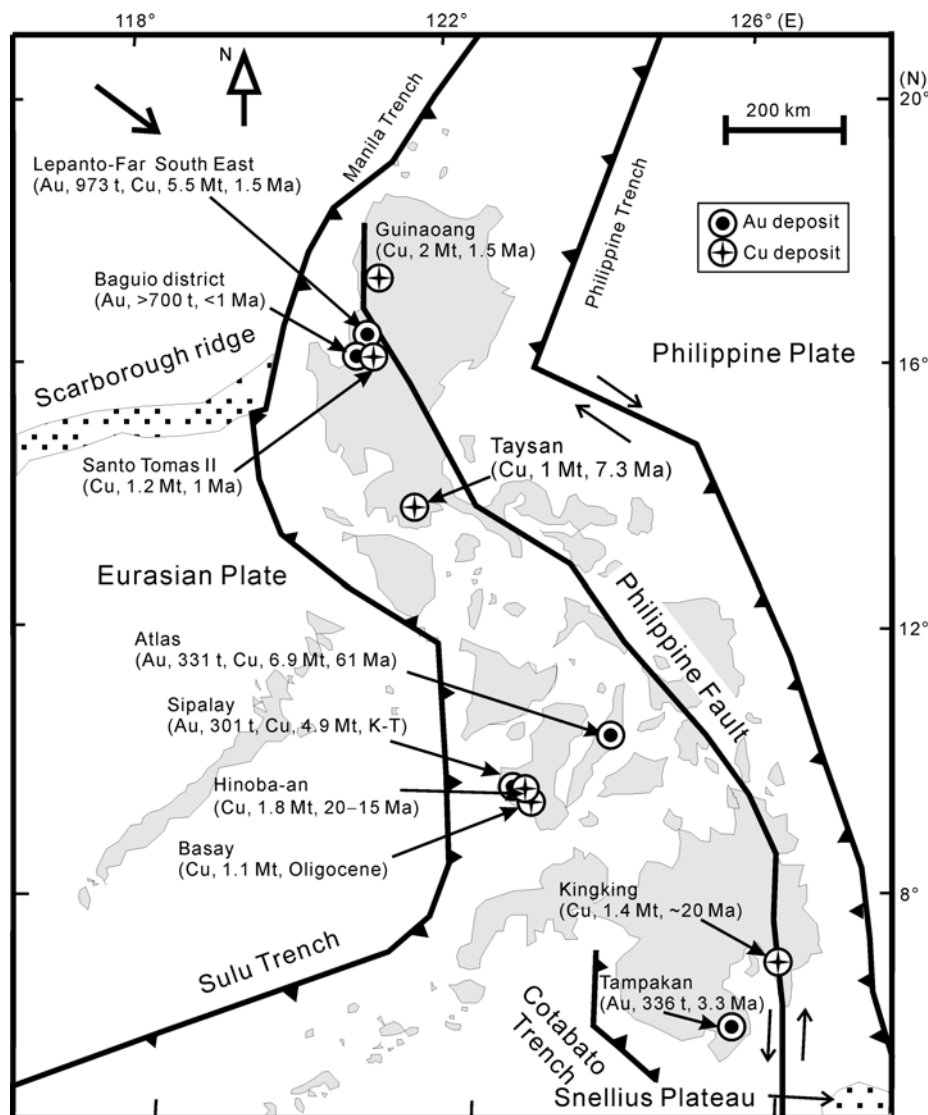


Figure 3 Ridge subduction and Cu-Au deposits in the Philippines (modified after ref. [2]).

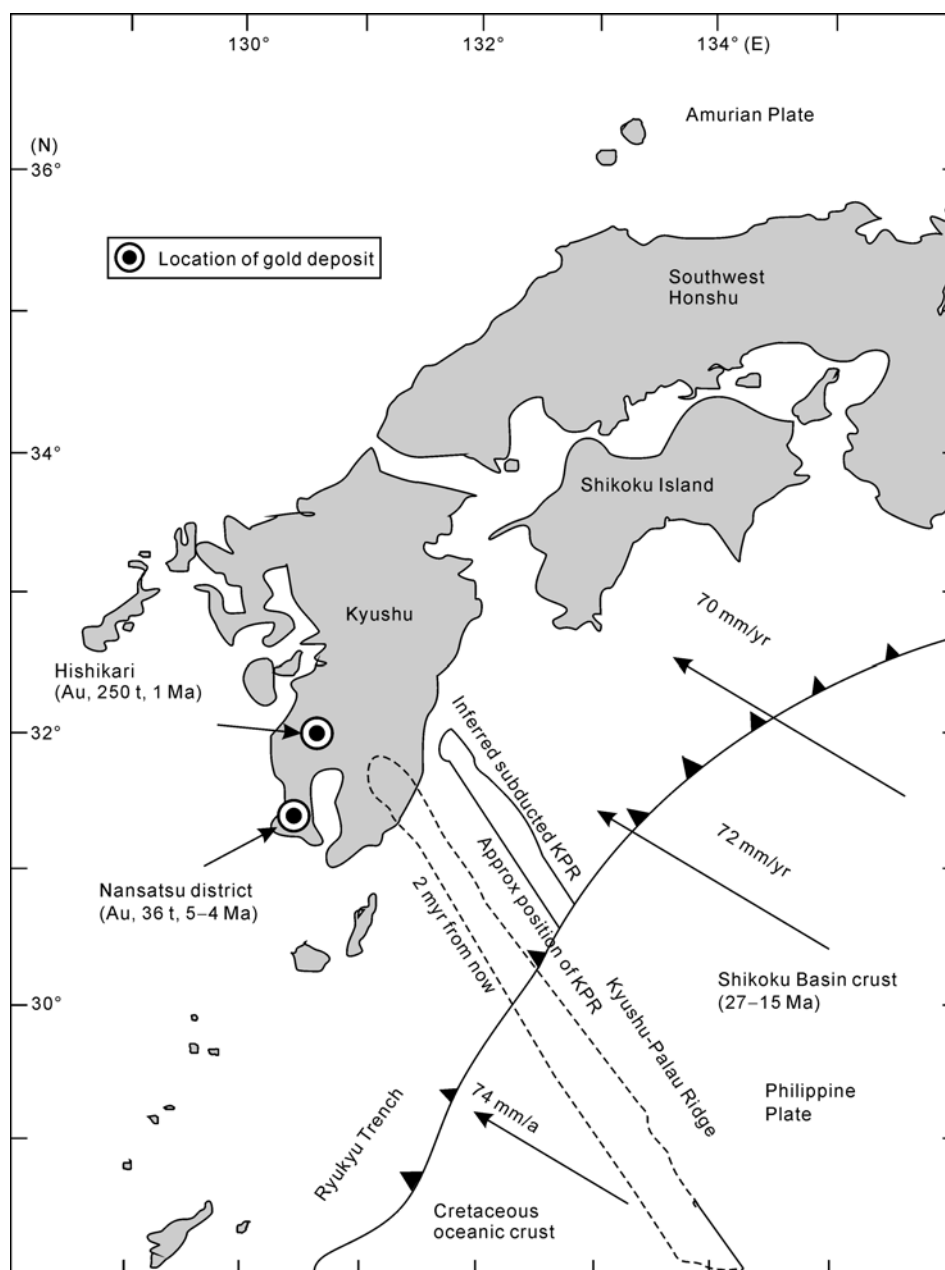


Figure 4 Ridge subduction and Cu-Au deposits in south Japan. The tectonic settings after ref. [23] and the mineral deposit distribution follows ref. [2].

abundance in the continental crust is also low (27 ppm) [56]. This is mainly because Cu and Au are scavenged into fluids at the late stage of magma evolution [53, 54]. Because of the characteristics of Cu, solely intracontinental processes or direct addition of mantle components do not necessarily result in Cu enrichment.

Alternatively, it has been proposed that the Lower Yangtze River mineralization belt can be better explained by ridge subduction, whereby associated adakites formed through slab melting have been contaminated by the continental crust and enriched mantle [27]. Between ~125–140 Ma, the Pacific plate drifted southwestward, whereas the Izanagi plate drifted north-northwestward [57], and the

ocean ridge between these two plates was subducted in what is now the Lower Yangtze River region. The ridge subduction model can well explain the association and distribution of adakite, calc-alkaline rocks, Nb enrichment, A-type granites and associated mineral deposits [27]. Because oceanic crust near a ridge is hotter, it is prone to be partially melted during ridge subduction, to form adakites. On the other hand, when older, colder and wetter oceanic crust distal from the ridge is subducted, it undergoes dehydration, which triggers flux-melting in the overlying mantle, to produce more typical calc-alkaline arc magmas. As subduction continues, the opening of a slab window along the ridge can be filled by upwelling asthenosphere, giving rise to high

temperature, anhydrous, A-type granites [33]. A geochemical character of ridge subduction is the production of Nb-enriched igneous rocks [33]. The Nb-enriched nature of the Lower Yangtze River belt volcanic rocks thus also supports the ridge subduction model [27].

It is worth mentioning that Cretaceous adakites in the Dabie Mountains formed at roughly the same time as those in the Lower Yangtze River belt, with high-Mg adakite in the southeast margin. These adakites, however, are not mineralized. Geochemical characteristics suggest the Cretaceous adakite from the Dabie Mountains formed through melting of the lower continental crust [49], likely triggered by ridge subduction [27].

2 Adakites and porphyry Cu deposits

Adakite was originally proposed to describe a special type of rocks found in Adak Island, Aleutian Islands, which has components from slab melting [58–60]. The close genetic association between porphyry Cu deposits and adakites has been proposed for more than a decade [8]. Among all the 43 deposits or mineralization districts, 38 are connected to adakites, and often directly occur in adakites. In places where adakites coexist with non-adakitic igneous rocks, mineralization is usually associated with the adakites [8]. This model has gained wide support, because most of the porphyry Cu and epithermal Au deposits are closely related to adakites both in terms of age and space [7]. Thus in Mongolia, the Erdenet porphyry Cu deposit is associated with adakite [61]; whereas many porphyry Cu deposits in Chile, e.g., Los Pelambres, Chuquicamata, etc., are also connected to adakites [4–6, 62, 63]. In China, the Tongling, Shaxi, Dexing porphyry or skarn Cu deposits are all associated with adakite or adakitic rocks [12, 46, 47, 64–66]. It has even been proposed that adakite should be taken as an exploration target for Cu deposits [67].

The genetic connection between adakite and porphyry deposits has been attributed to the high oxygen fugacity of adakitic magmas [68]; with oxygen fugacity taken as a more important controlling factor than actual adakites for porphyry Cu mineralization [69]. The geochemical behavior of Cu is indeed highly influenced by oxygen fugacity [1, 54, 70], with mineralized porphyry usually having higher oxygen fugacity [71]. Most arc rocks, however, have high oxygen fugacity, amongst which adakite is not the most oxidized variety [72–74]. Therefore, the high oxygen fugacity of arc rocks is not controlled mainly by slab melting, but more by slab dehydration [75]. Consequently, the close genetic connection between adakites and porphyry deposits does not totally depend on high oxygen fugacity.

Copper is a moderately incompatible element during MORB production and flux melting arc magmatism, with a partition coefficient similar to the heavy rare earth elements [53, 54]. Copper concentrations in oceanic crust range from

60–125 ppm [76], with an estimated average of 74 ppm [77], much higher than the average abundance of primitive mantle (30 ppm) [55] and the continental crust (27 ppm) [56]. Therefore, partial melts of oceanic slab should have much higher initial Cu concentrations than melts derived directly from the mantle or from within the continental crust [78, 79]. Thus the genetic connection between porphyry Cu deposits and adakites links to slab melting, with its elevated Cu abundance [79].

The geochemical behaviors of Cu and Au during magmatism are very similar to each other [53, 54]. Therefore, fundamentally Au mineralization may be connected to ridge subduction in a way similar to that of Cu. But in contrast, Cu and Au behave quite differently in fluids, resulting in diverse types of deposits and spatial distribution for these metals.

3 Discussion

3.1 Adakite and ridge subduction

Slab melting is believed to be a major process in the early history of the Earth, which in those times was responsible for the formation of the continental crust [80–83]. In contrast, the thermal structure of modern subducting slab suggests very limited slab melting [60, 84], with it occurring mainly during subduction of young, hot oceanic crust [60, 85].

Because of the unique thermal structure of ocean ridges, it is then safe to say that ridge subduction is the most favorable geological process for slab melting in the Phanerozoic. This gives the essential link between the coincidence of ridge subduction and world class porphyry Cu deposits.

3.2 Slab melts and porphyry Cu deposits

Although the genetic connection between adakite and porphyry Cu-Au deposits has been supported by increasing number of studies [4–6, 62, 63], there are still a group of scholars who argue strongly against the adakite mineralization model [86–88]. The argument is that the geochemical characteristics of adakite do not necessarily need slab melting, but can be produced through fractional crystallization of normal arc magmas [88–91]. Therefore, magma evolution at crustal levels was taken as a more important factor that controls Cu mineralization [88]. This actually argues against the genetic relation between slab melting and porphyry Cu deposits. According to such model, all types of arc rocks are potential candidates to host porphyry Cu deposits. In our opinion, this contradicts with observations so far available. As pointed out in section 2, the Cu concentration in oceanic crust is 2–4 times as high as the Cu abundances in the mantle and the continental crust. Therefore, slab melts are more favorable for spawning mineralization [78, 79].

It is true that not all the adakites are associated with porphyry Cu deposits [49, 92]. For example, there are abundant Mesozoic adakites in eastern China, but large porphyry Cu deposits are only found in Dexing and the Lower Yangtze River belt. However, many of the non-mineralized adakites are considered to have formed by partial melting of continental crust [49]. In this context, it is important to note that porphyry Cu deposits are formed at shallow depths (usually <3 km). Therefore, less eroded places in supra paleo-subduction zone settings, dominated by volcanic/hypabyssal suites rather than deep-seated plutonic complexes are the more promising sites for porphyry Cu exploration. However, although adakite is the most favorable host for porphyry Cu-Au mineralization, normal calc-alkaline arc andesites may also be the setting for deposits [69]. Adding further to the complexity of using adakite as an exploration tool, these magmas may lose their adakitic trace element signatures (e.g. high Sr/Y) during assimilation and, particularly plagioclase crystallization. In the case of plagioclase crystallization, Sr in evolving melt is lowered quickly, coupled with moderate increase in Y, resulting in dramatic decreases in Sr/Y. In this case, fractionated adakite can easily lose its distinctive geochemical character. Therefore, it is important to identify and characterize the composition of primitive magmas devoid of intra-crustal fractionation and assimilation. Despite these complications, ridge subduction sites have the best exploration potential for large porphyry Cu deposits.

3.3 Ridge subduction and porphyry Cu deposits

Although ridge subduction is favorable for slab melting, there are many other processes that can result in slab melting; flat subduction, subduction of newly formed oceanic crust, subduction of torn slab as well as the edge of subducting slabs. Consequently these settings are favorable Cu enrichment in primitive magmas and thereby for porphyry Cu deposits. For example, the porphyry Cu deposit Minas Conga, and the porphyry Cu, Mo deposit La Granja in Peru are several hundred kilometers away from the Nazca ridge subduction (Figure 2). These deposits are attributed to the subduction of the Inca plateau together with the Nazca ridge [2].

On the other hand, not all ridge subduction forms porphyry Cu-Au deposits. For example, no large porphyry deposits are associated with the Carnegie ridge subduction in Ecuador. One likely reason is that the Carnegie ridge subduction has just started, such that there is no major slab melting yet. This is supported by the steep subduction angle and limited deformation of the overriding continental crust (Figure 2(a)). By contrast, the Juan Fernández ridge subduction has a very small subduction angle with major crustal deformation, and is the largest porphyry Cu-Au mineralization region (Figure 2(d)).

For ancient ridge subduction, where the ridge itself has

disappeared, traces of ridge subduction can only be found in the magmatic products preserved in the supra-subduction zone environment. Important for identifying ancient ridge subduction are the combination of adakite, high-Mg andesite and Nb-enriched basalts [93–95]. For locations with thick overlying continental crust, there might be Nb-enriched andesitic rocks. Also, whereas typical arc-type calc-alkalic rocks are rare due to limited dehydration near the ridge, instead A-type granites and alkalic rocks are more prevalent as a result of slab window opening [27, 33]. In terms of tectonic evolution, ridge subduction is usually accompanied by shearing, faulting, uplifting and extension [18, 23]. Furthermore, when the subducting ocean ridge is not perpendicular to the subduction zone, magmatic zone moves laterally with time [96, 97].

There are several orogenic belts of different ages in China, e.g., the Central Asian orogenic belt, Qinling-Dabie orogenic belt, etc. Traces of ridge subduction in these orogenic belts are useful clues for the exploration of porphyry Cu and other related deposits. In eastern China, the Lower Yangtze River belt aside, Shandong and the north margin of the North China craton may also have experienced ridge subduction, and thus potentially are favorable places for Cu and Au mineralization. In the Central Asian orogenic belt, exploration should focus on locations with rock assemblages of adakite, Nb-enriched basalt, high-Mg andesite and A-type granites, e.g., Fuyun county in north Xinjiang [98, 99]. The Cu-Au mineralization in Baogutu, west Junggar has been attributed to Carboniferous ridge subduction [100], which needs further attention. In fact, the rock assemblage of adakite, Nb-enriched basalt and high-Mg andesite is found close to many Cu-Au deposits, e.g., Lamasu, Axi, Tuwu-Yandong, Chihu etc. [101], implying ridge subduction in these locations, and thus are worthy of intense exploration.

4 Conclusions

Ridge subduction is favorable for slab melting and thus is promising for Cu-Au mineralization. Many large porphyry Cu-Au deposits along the circum-Pacific region are spatially associated with ridge subduction. Slab melting is the link between ridge subduction and porphyry Cu mineralization. Ridge subduction is much more common in the East Pacific margin than in the West Pacific margin, resulting in an uneven distribution of large porphyry Cu deposits along the Pacific rim. In the Mesozoic, the ocean ridge between the Pacific and Izanagi plates was subducted underneath eastern Asian continent, which may have controlled the Lower Yangtze River Cu, poly-metal belt. Traces of ridge subduction in less eroded regions in eastern China, the Central Asia orogenic belt, the Qinling-Dabie orogenic belt, etc. are useful clues for future exploration of porphyry Cu and other related deposits.

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