Spatial-Temporal Distribution, Geological Characteristics and Ore-Formation Controlling Factors of Major Types of Rare Metal Mineral Deposits in China

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Abstract: Rare metals including Lithium (Li), Beryllium (Be), Rubidium (Rb), Cesium (Cs), Zirconium (Zr), Hafnium (Hf), Niobium (Nb), Tantalum (Ta), Tungsten (W) and Tin (Sn) are important critical mineral resources. In China, rare metal mineral deposits are spatially distributed mainly in the Altay and Southern Great Xinggan Range regions in the Central Asian orogenic belt; in the Middle Qilian, South Qinling and East Qinling mountains regions in the Qilian–Qinling–Dabie orogenic belt; in the Western Sichuan and Bailongshan–Dahongliutan regions in the Kunlun–Songpan–Garze orogenic belt, and in the Northeastern Jiangxi, Northwestern Jiangxi, and Southern Hunan regions in South China. Major ore-forming epochs include Indosinian (mostly 200–240 Ma, in particular in western China) and the Yanshanian (mostly 120–160 Ma, in particular in South China). In addition, Bayan Obo, Inner Mongolia, northeastern China, with a complex formation history, hosts the largest REE and Nb deposits in China. There are six major rare metal mineral deposit types in China: Highly fractionated granite; Pegmatite; Alkaline granite; Carbonatite and alkaline rock; Volcanic; and Hydrothermal types. Two further types, namely the Leptyntype and Breccia pipe type, have recently been discovered in China, and are represented by the Yushishan Nb–Ta–(Zr–Hf–REE) and the Weilasituo Li–Rb–Sn–W–Zn–Pb deposits. Several most important controlling factors for rare metal mineral deposits are discussed, including geochemical behaviors and sources of the rare metals, highly evolved magmatic fractionation, and structural controls such as the metamorphic core complex setting, with a revised conceptual model for the latter.

Key words: critical metals, geochemistry, rare metals, distribution, metal ores, formation control factors, China

1 Introduction

‘Critical Metals’ or ‘Critical Mineral Resources’ have been proposed in recent years as general names for a group of special metals and/or their ore deposits by the international community (USDI-USGS, 2017). These metals not only have important economic value and special characteristics that other elements cannot replace, but they also exhibit a high supply risk. The supply of these critical metals is driving some of the biggest advancement in cutting-edge modern technology fields such as new materials, new energy, information technology, aeronautics and astronautics, and high-tech industry (Jowitt et al., 2018). As demand for these metals has exploded rapidly in recent decades, it is urgent to carry out in-depth studies on the formation and enrichment mechanisms, distribution regularity and mineral exploration technology for the critical metal mineral deposits and the ‘green’ sustainable usage of these metals. In general, the critical metals include/comprise four groups of special metals, namely, the rare metals (Li, Be, Rb, Cs, Nb, Ta, Zr, Hf, W, Sn); rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc, Y); rare dispersed elements (Ga, Ge, Se, Cd, In, Te, Re, Tl); and rare noble metals such as PGE (Ru, Pd, Os, Ir, Pt), Cr and Co (Jiang et al., 2019; Zhai et al., 2019). In this paper, we will focus on the rare metals only. We summarize the main geological characteristics and ore genesis of the typical rare metal deposits in China, and introduce several of the most important types of rare metal deposits.

Since Tungsten (W) and Tin (Sn) are the dominant mineral resources in China, most Chinese researchers do not attribute these two elements to the rare metal elements group (e.g., Wang et al., 2013, 2016). However, many other scholars worldwide consider that both W and Sn belong in this category. Since we have recently made an overview on the W and Sn deposits in China (Jiang et al., 2020), we will not focus on them here, but the relationship of W–Sn deposits with other rare metal deposits is discussed.
2 Spatial-Temporal Distribution of Rare Metal Mineral Deposits in China

The rare metal mineral deposits in China are spatially distributed mainly in the following belts: 1) the Central Asian orogenic belt (CAOB); 2) the Qilian–Qinling–Dabie orogenic belt (QQDOB); 3) the Kunlun–Songpan–Garze orogenic belt (KSGOB); and 4) South China Block (SCB) (Fig. 1). A summary of the mineralization ages for these rare metal deposits indicates a major ore-forming epoch in the Yanshanian in particular for those deposits in South China, as well as in the Indosinian period, such as many deposits in the QQDOB and the KSGOB (Fig. 2). The Caledonian period is important for the QQDOB rare metal deposits in the QQDOB and the KSGOB (Fig. 2). The rare metal deposits in China are spatially distributed mainly in the following belts: 1) the Central Asian orogenic belt (CAOB); 2) the Qilian–Qinling–Dabie orogenic belt (QQDOB); 3) the Kunlun–Songpan–Garze orogenic belt (KSGOB); and 4) South China Block (SCB) (Fig. 1). A summary of the mineralization ages for these rare metal deposits indicates a major ore-forming epoch in the Yanshanian in particular for those deposits in South China, as well as in the Indosinian period, such as many deposits in the QQDOB and the KSGOB (Fig. 2). The Caledonian period is important for the QQDOB rare metal deposits (Fig. 2).

In the northwestern part of the CAOB occurs one of most concentrated metallicogenetic region for rare metals in China, namely the Xinjiang Altay region, which extends more than 500 km in length and is 40–80 km wide along a NW–SE trending direction (Wang et al., 1981; Zou and Li, 2006; Li et al., 2014). The Xinjiang Altay region contains more than 35 pegmatite ore fields, including the Koktokay, Kelumute, Kukalagai, Kalu‘an–Azubai, and Askäert pegmatite deposits, with a wide range of formation ages from the Caledonian, Hercynian, Indosinian, to Yanshanian, of which the Indosinian is the most important (Fig. 2) (Li et al., 2014). The most well-known and large-scale rare metal deposits include the pegmatite-type Keketuohai Li–Be–Nb–Ta–Cs deposit (no. 28 in Fig. 1) and the Kelumute Li–Ta–Nb deposit (no. 27 in Fig. 1) (Zhang H. et al., 2019). In the northeastern CAOB, a recently recognized rare metal concentrated region is the Southern Great Xing’an Range, where a number of large Sn–W polymetallic and rare metal deposits occur, including the super-large alkaline granite-type Baerzhe REE–Nb–Be–Zr deposit (no. 6 in Fig. 1) (Wang and Zhao, 1997), the large highly fractionated granite and breccia-type Weilasituo Sn–Pb–Zn–Rb–Li deposit (no. 4 in Fig. 1) (Li et al., 2018; Zhang T. et al., 2019), and the large highly fractionated granite and

Fig. 1. Distribution of major rare metal mineral deposits in China.

pegmatite-type Shihuiyao Nb–Ta–Rb deposit (no. 3 in Fig. 1) (Zhu et al., 2013).

In the QQDOB, a new large-scale Nb–Ta–Zr–REE deposit was recently discovered at Yushishan (no. 32 in Fig. 1) in the Middle Qilian orogen, which is hosted in metamorphosed volcanic-sedimentary rocks (named as leptynite) (Yu et al., 2012). A number of large-scale granite- and pegmatite-related Rb deposits also occur in the QQDOB, such as the Tuanaobo (no. 36 in Fig. 1), Liuzhangshan (no. 7 in Fig. 1), Ziyigou (no. 9 in Fig. 1) and Shimen (no. 11 in Fig. 1) (Zhou et al., 2015). In the South Qinling occurs some of the largest carbonatite REE–Nb deposits in China, the Miaoya (no. 8 in Fig. 1) and Shaxiongdong (Xu et al., 2015; Ying et al., 2017). A number of carbonatite veins such as Huanglongpu, Huangshufan and Huayangchuan occur in the Xiaoqinling area, which are unique because of the special metal association of Mo–Pb with U and REE (in particular HREE) and Nb in these deposits (Xu et al., 2007, 2010; Xue et al., 2020). In the East Qinling orogen also occurs one of the largest rare metal pegmatite-concentrated regions, with more than 6900 granitic pegmatite dykes, which are mainly distributed in the metamorphic basement of the Precambrian Qinling Group, with one of the largest one being the Guanpo Nb-Ta-Li deposit (no. 10 in Fig. 1) (Qin et al., 2019).

In the KSGOB, two new pegmatite-type Li-concentrated regions, in the Western Sichuan and the Bailongshan-Dahongliutan, have recently been discovered. The Western Sichuan Li belt hosts 11 pegmatite-type Li deposits, including the three largest spodumene pegmatite deposits in Asia, namely the super-large Jiajika Li–Be–Nb–Ta–Rb deposit (no. 37 in Fig. 1) with lithium resources of 0.92 Mt in the Jiajika orefield and the super-large Dangba deposit (no. 39 in Fig. 1), 0.66 Mt in the Lijiaogou deposit (no. 38 in Fig. 1), and 0.51 Mt in the Keeryin ore field (Wang et al., 2005, 2016; Li et al., 2014; Fu et al., 2017; Li et al., 2019; Fei et al., 2020). Another significant discovery in the KSGOB is the Bailongshan-Dahongliutan pegmatite-type rare metal deposits in the West Kunlun orogenic belt, Xinjiang (Yan et al., 2018; Wang et al., 2020), where 14 rare metal deposits along the 600-km-long belt have been discovered, including the Huoshikashi, Kalawala, Xiaoberulong, Dabudaer, Sansu, Tatulugou, Kangxiwa, Zhongfulugou, No. 496, Akeshaiy, Dahongliutan, Bailongshan, Xufengling, and Bingzhou deposits (Yan et al., 2018; Wang et al., 2020). Of these the Bailongshan (no. 40 in Fig. 1) is the largest Li–Rb–Be–Ta–Nb deposit, with occurrence of 52 rare metal orebodies and estimated ore reserves of more than 5.06 Mt Li₂O, 160,020 t BeO, 316,200 t Rb₂O, 40,060 t Nb₂O₅, and 10,750 t Ta₂O₅ (Wang et al., 2020).

South China hosts concentrated W–Sn ore occurrence, and most major W–Sn deposits show a metal association with or without Ta–Nb and other rare metal mineralization (Mao et al., 2019; Jiang et al., 2020). Both large and super-large rare metal deposits are distributed in Jiangxi (Yashan, FE Huangshan, Songshugang), Hunan (Xianghuangling, Jianfengling, Zhengchong, Renli) and Guangxi provinces (Shuiximiao, Jinzhuyuan); the majority of these were formed during the Yanshanian (mostly during 160–120 Ma), with a few in the Indosinian (mostly during 240–200 Ma) (Fig. 2). In northwestern Jiangxi province, the most well-known and largest deposit is the Yashan granite-type Nb–Ta–Li deposit (no. 22 in Fig. 1) (Yin et al., 1995; Wu et al., 2018). In this deposit, Rb is also abundant and currently accounts for one third of Rb products in China (Sun et al., 2019). Beside the Yashan deposit, a number of rare metal deposits were recently explored in the Jiujiang rare metal-concentrated region, such as the Shiziling deposit, where montebrasite (Li₂O around 10%) in a topaz–Li mica–alkali feldspar granite is super-enriched with a mineral percentage of 4–5%, together with other rare metal minerals such as Ta-rich cassiterite and columbite-group minerals (Wang et al., 2019). In northeastern Jiangxi, around the Late Yanshanian (Early Cretaceous, ca. 130 Ma), in the Lingshan granite complex occurs the super-large Geyuan rare metal deposit, including the Huangshan Nb–(Ta) and Songshugang Ta–(Nb–W–Sn) deposits (no. 23 in Fig. 1)
pyrochlore, baotite, fergusonite, columbite, and fersmite, mainly aeschynite, with various amounts of ilmenorutile, mineral compositions. The Nb isminable because of the extremely fine grains and complex al., 2016; He et al., 2018), although it is currently not of China’s Nb resources (2.2 Mt@0.13% Nb2O5, average grade at 0.036 wt% and 14057 t of Nb2O5, average grade at 0.047 wt% (Zhou et al., 2019). There are more than 926 pegmatite dykes in the Renli mining district, occurring from within the composite-granite to the host Lengjiaxi Group metamorphic rocks. The main ore minerals include columbite-group minerals, with minor beryl and lepidolite. The mineralization has been suggested to be genetically related to the Early Cretaceous muscovite monzogranite (Xiong et al., 2020).

In the Linu district of Guangxi province, granite type Ta–Nb mineralization from the Shuiximiao and Jinzhuyuan deposits (no. 13 in Fig. 1) mainly occurs in a muscovite granite body that formed during the crystallization differentiation of magma, whereas W–Sn mineralization occurs mainly in the magmatic-hydrothermal stage as quartz vein-type orebodies (Li S H et al., 2015).

Except for abovementioned rare metal mineralization belts, there are also several large or super-large rare metal deposits that are not located in those metallicogenic belts, and one of the most celebrated is the Bayan Obo REE–Nb–Fe deposit (no. 1 in Fig. 1), which hosts more than 70% of China’s Nb resources (2.2 Mt@0.13% Nb2O5; Fan et al., 2016; He et al., 2018), although it is currently not minable because of the extremely fine grains and complex mineral compositions. The Nb-bearing minerals are mainly aeschynite, with various amounts of ilmenorutile, pyrochlore, baotite, fergusonite, columbite, and fersmite (Zhang et al., 2000; Yang et al., 2001; Zhang and Mu, 2006; Fan et al., 2016).

3 Major Types of Rare Metal Deposits in China

The major rare metal ore deposit types include the highly fractionated granite, pegmatite, alkaline granite, carbonatite and alkaline rock, volcanic rock and hydrothermal types. Here, we propose the leptynite type and the breccia pipe type as two new potentially important economic assets in China.

3.1 Highly fractionated granite type

Most rare metal deposits are associated with highly fractionated granitic rocks, with the ore-formation processes suggested to be mostly related to a highly evolved, fractionated granitic magmatism (Mao and Wang, 1997; Wu et al., 2017). Two-mica, muscovite, albite and lepidolite granites are the most common rock types. Commonly, the ore metals are concentrated in the last magmatic stage and transition to early hydrothermal stages (Zhao et al., 1992; Zhang, 2001; Ballouard et al., 2016), although hydrothermal mineralization or remobilization have recently been recognized as important processes in some areas (e.g., Li J et al., 2015; Wu et al., 2018).

A typical example is the super-large Yashan Ta–Nb–Li deposit at Yichun, Jiangxi Province. This deposit is located within the Wugongshan metamorphic core complex (Shu et al., 1998), and four granite phases were emplaced from early to late Late Jurassic during an extensional environment (Luo et al., 2005; Yang Z et al., 2014). The process included two-mica (protolithionite–muscovite), muscovite, albite and lepidolite–albite granites with a highly fractional crystallization trend (Fig. 3).

In all these granites, the feldspar is albite with An<5, and so the rocks can be classified as alkali-feldspar granite type. Ore minerals include columbite-group minerals (columbite–tantalite), lepidolite, and Nb–Ta-rich cassiterite, mostly of magmatic origin. The REE distribution patterns of the granites show a clearly evolved fractionation trend with the highest REE concentrations and less negative Eu anomaly in the early two-mica granite, decreasing to the lowest REE contents and more pronounced negative Eu anomaly, together with a remarkable lanthanide tetrad effect, in the late albite and lepidolite–albite granites (Fig. 4a). A number of other elements, such as Li, Rb, Cs, Ta, F, P, and ratios such as Nb/Ta and Zr/Hf, for these granites all show consistent magmatic evolution and fractionation trends, namely with increasing concentrations of these elements but decreasing ratios from early- to late-stage granites (Li and Huang, 2013; Li J et al., 2015).

Many other rare metal granites in South China also show similar geochemical characteristics and the highly fractionated trend with those of the Yashan granites. For example, the multiple-phase Dengfuxian complex granites and associated W–Sn–Nb–Ta deposits in Hunan province (Cai 2013; Xiong et al., 2020), where three stages of granite occurrence from Triassic to Cretaceous, showing a decreasing REE concentration and more pronounced...
negative Eu anomaly trend not only for different stages but also for different phases within the same stage (Fig. 4b). Both the Jurassic and Cretaceous two-mica and muscovite granites are highly evolved and have a genetic relationship with W–Sn–Nb–Ta mineralization (Xiong et al., 2020).

In recent years, except for the well-known rare metal-concentrated regions in southern China, a number of new rare metal metallogenic belts have also being found in association with highly evolved, differentiated granites elsewhere, such as those reported in southern Tibet (Li G M et al., 2017; Wu et al., 2017). Wang R C et al. (2017) studied 15 leucogranites from this belt, and 12 of them have a number of different rare metal minerals such as beryl, topaz, columbite-group minerals, indicating a potential for new rare metal deposits, but more in-depth studies and exploration are in need in order to find economical mineralization.

3.2 Pegmatite type

Two types of rare metal pegmatites, namely, the LCT (Li–Cs–Ta) type and the NYF (Nb–Y–F) type, are enriched either with rare metals Li, Be, Rb, Cs, Ta and Sn or the rare metals and other critical metals Nb, Sc, Y, REE, Ti, Zr, Th and U, respectively (Černý, 1991a, b, 1992; Černý and Ercit, 2005). The major global characteristics of these two types are compared with typical ore deposit examples in China in Table 1. The LCT-type pegmatite has long been considered as the highly evolved product of S-type granitic magmatic differentiation where the magma might have originated from marine sedimentary materials (Černý, 1991a, b; Černý et al., 2012). However, the parent rocks of many such pegmatites worldwide have not been confirmed, including the world-class Tanco rare metal pegmatite in Canada, the Greenbush rare metal pegmatite in Australia (London, 2018) and the Koktokai No 3 pegmatite in
Xinjiang, western China (Zhang et al., 2019). Therefore, some researchers also proposed a direct anatexis origin for some of the LCT-type pegmatites (Simmons et al., 2016).

The Chinese Altay area hosts one of the largest pegmatite provinces in the world, with more than 100,000 dykes with an area of 20,000 km² (Zou and Li, 2006), among which the Keketuohai No.3 pegmatite is the most well-known and economic one with large-scale Be–Li–Ta–Nb–Cs–Rb–HF mineralization (Zhang, 2001; Zou and Li, 2006). The Keketuohai No.3 pegmatite body intruded into Lower Devonian amphibolite strata, being bell shaped in the upper part and plate shaped in the lower part. Zonation is well developed in this pegmatite body with ten different subdivided zones. In contrast, many other pegmatites in the region occur as small dykes/veins also intruded into the metasedimentary rocks or Paleozoic granites. The ore minerals comprise: spodumene for Li, followed by lepidolite, elbaite, and minor eucryptite and lithium-manganese phosphates; mainly beryl for Be, with trace amounts of chrysoelite and phenakite; columbite-group minerals for Na and Ta, including manganocolumbite, tantalite, manganotantalite, and tapiolite, with minor microlite and pyrochlore; mainly pollucite for Cs, with some Cs-rich beryl and Cs-rich mica. In different pegmatites, the rare metal association can be different, such as Be only, Be–Na–Ta, Li–Be–Nb–Ta, and Be–Li–Nb–Ta–Cs–Rb.

Previous results indicate four stages of pegmatitic magmatism in Altay, including Devonian to Early Carboniferous (403–333 Ma), Permian (275–250 Ma), Triassic (248–200 Ma), and Jurassic (199–157 Ma) (Zhang et al., 2019), with the Keketuohai No.3 pegmatite of Triassic age (220–198 Ma). Because the emplacement depth of the Triassic pegmatites is obviously shallower than the other pegmatites, which is conducive to the enrichment of volatiles as well as the rare metals and reduces the liquid-phase temperature to promote a highly differential evolution of the magma, it has been suggested that this is the key for the enrichment and mineralization of rare metals in residual melts (Huang et al., 2016; Zhang et al., 2019).

In recent years, China has made major breakthroughs in pegmatite-type rare metal prospecting, and a number of large and super-large rare metal deposits have been successfully discovered, for example, the Jiajika pegmatite Li-ore deposit in Sichuan Province (Li et al., 2014; Fu et al., 2017), the Bailongshan pegmatite Li–Rb–Be–Na–Ta ore deposit in Xinjiang (Wang et al., 2020), and the Renli pegmatite Ta–Nb deposit in Hunan Province (Li et al., 2020; Xiong et al., 2020).

The Jiajika deposit occurs around an Indosinian two-mica granite pluton that intruded along the short axis of the Jiajika metamorphic core complex dome (or called the gneiss dome, Xu et al., 2018). A series of more than 110 rare metal granitic pegmatite dykes are derived around the internal and external contact zones of the granite, forming a super-large Li- and large-scale Be-deposits, as well as significant amounts of Nb, Ta and Rb (Li et al., 2014; Fu et al., 2017). In the Lijiagou deposit, the pegmatite dykes also surround a granite pluton, and with increasing distance include microcline (0–800 m), microcline–albite (800–1500 m), albite–(1500–2300 m), albite–spodumene (2300–5000 m), and lepidolite pegmatites (Fei et al., 2020).

The Bailongshan pegmatite deposit is a super-large Li deposit with estimated ore reserves of 3.45 Mt of Li₂O and 176,000 tons of Rb₂O (Wang et al., 2020), which shows typical LCT-type zonation around a granodiorite pluton, from nearby barren pegmatite to outer pegmatite orebodies rich in Be, Nb, Ta, Rb, and Li, including quartz–albite–tourmaline, quartz–muscovite, quartz–albite–spodumene, and quartz–spodumene pegmatite belts, with Li-rich pegmatites being in the farthest belt away from the mother granite (Wang et al., 2020). Within a single pegmatite dyke, internal zonation is also well developed, including elbaite–albite–muscovite, blocky albite–quartz, quartz–muscovite, quartz–albite–spodumene, and quartz–spodumene zones (Wang et al., 2020). The Dahongliutan rare metal pegmatite hosts a medium-size Li–Be–Ta–Nb resource (Yan et al., 2018). The Dahongliutan monzogranite pluton is the major intrusion in the mining area, and more than 7000 pegmatite dikes are present within or near the pluton, among which 24 dykes are economic with Li–Be–Ta–Nb mineralized. The pegmatites show LCT-type zonation from inside the pluton to outside the metamorphic rocks, including, ore-barren muscovite–microcline, Be-mineralized muscovite–microcline–albite and Li–Be–Ta–Nb-mineralized quartz–albite–spodumene pegmatites (Yan et al., 2018).

NYF-type pegmatites are characterized by

| Table 1 Comparison of the Li–Cs–Ta (LCT)-type and Nb–Y–F (NYF)-type rare metal pegmatites |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Type               | Tectonic setting | Metal association | Chemical composition and ore minerals | Parent granites | Magma source regions | Ore deposit examples |
| LCT                | Late orogenic and post orogenic | Nbr–Ta, Ti, Y, REE, Zr, U, Th, F; normally no metal zoning | Subaluminous or metaluminous, to weakly peraluminous; Li-silicates, phoscolphate, columbite-titanate, pollucite | A-type granites dominate, I-type granites in some cases | Middle and lower crust with depleted incompatible elements, primary graniteoids, and crust replaced by mantle-derived alkaline fluids | Keketuohai No 3 (Xinjiang), Bai tongshan (Xinjiang), Renli (Hunan) |
| NYF                | Anorogenic, extensional | Nb–Ta, Cs, Be, Sn, Ta–Nb (B, P, F); metal zoning is very common around the parent granite | Aluminum to peraluminous; Li-silicates, phoscolphate, columbite-titanate, pollucite | S-type granites | Middle and upper crust with enrichment of incompatible elements, low-degree partial melting of basement metamorphic rocks | Shishiri (Zhejiang), Huayangchuan (Shanxi), Shanghu (Xinjiang) |

subaluminous or metaluminous to weakly peralkaline, usually with a genetic linkage with A-type granites, but in some cases also I-type granites (Černý and Erict, 2005). Rare metal deposits associated with NYF-type pegmatite in China are relatively rare when compared to the widespread LCT-type. Wangwu et al. (2019) reported the Shishishi pegmatites in Lin’an, northwest Zhejiang Province, which show Nb–Y–F enrichment and thus belong to the NYF type. These pegmatites formed at 133 Ma, according to coltan U–Pb dating, and have a genetic relationship with the A-type granite at Heqiao (Wangwu et al., 2019). The main ore minerals include Nb–Ta oxide minerals (columbite, tapiolite, microbite), Y-bearing minerals (fergusonite, polycrase), W-bearing minerals (wolframate, scheelite, Nb–W-bearing minerals), Ce-bearing minerals (monazite, fluorocite, bastnaesite) and Th-bearing minerals (Wangwu et al., 2019).

3.3 Alkaline granite type

Alkaline granite is commonly in genetic association with REE and rare metal mineralization, with ore minerals either precipitated directly from highly fractionated and volatile-rich residual magmas or in post-magmatic hydrothermal stages (Salvi and Williams-Jones, 1990). The most representative example of the alkaline granite type in China is the super-large Baerze Zr–REE–Nb deposit in Inner Mongolia, which holds an estimated resource of about 100 Mt at 1.84 wt% ZrO2, 0.30 wt% CeO2, 0.30 wt% Y2O3, 0.26 wt% Nb2O5, and 0.03 wt% BeO (Wang and Zhao, 1997; Yang W. et al., 2014). In this deposit, the ore-related granites include albite and arvedsonite-aegirine granites and a pegmatite-aplite dyke, and the parental magma is highly enriched in alkali and F with abundant aegirine and fluorite. The ore minerals consist of zircon, yttroceberysite, synchysite, pyrochlore, ferrocolumbite, monazite and fergusonite. LA-ICP-MS dating of the zircon yields a date of ~123 Ma for the Baerze pluton (Qiu et al., 2014). The lanthanide tetrad effect of both whole rock and zircon indicates a strong melt-fluid interaction during the ore-forming processes (Zhao et al., 2002; Yang W. et al., 2014). Various types of zircon from the ore-bearing pluton indicate mineralization from magmatic, magmatic-hydrothermal transition to hydrothermal remobilization (Yang Z. et al., 2018). It has been suggested that the Nb-bearing minerals such as pyrochlore, fersmite and columbite in the ore-hosting dolomite and calcioarbonatite dykes from Bayan Obo might have had an igneous origin (Le Bas et al., 1992), but the aeschynite, fergusonite and baotite are now thought to be hydrothermal products accompanied by fluoritization and fenitization (Liu et al., 2018a, b), or in the barite-sulfide hydrothermal veins (Liu et al., 2004).

3.4 Carbonatite and alkaline rock type

Globally, many super-large REE–Nb deposits are associated with a carbonatite-alkaline rock complex, such as the Morro dos Seis Lagos deposit, Nigeria (Nb2O5: 2897.9 Mt@2.81%) and the Araxá deposit (Nb2O5: 2608 Mt@1.75%) in Brazil (Mitchell, 2015; Giovannini et al., 2017). In China, this type of Nb deposit is concentrated in only a few localities. The world's largest is the Bayan Obo REE–Nb–Fe deposit (Fan et al., 2016; Yang X. et al., 2017); the Mianning–Dechang carbonatites in western Sichuan produce the second largest REE–Nb deposit in China, followed by the Zhushan carbonatites in the South Qinling Orogeny that produce the third largest carbonatite-type REE–Nb deposit (Miaoya) in China (Xu et al., 2015; Ying et al., 2017).

The origin of the Baiyun Obo REE–Nb–Fe deposit is highly debatable, and many different models have been proposed for the formation of the REE, Fe, and Nb (cf. Fan et al., 2016; Yang X. et al., 2017), and we do not intend to make a comprehensive summary here. Many Nb-bearing minerals have been reported and some of them were first discovered in this deposit, such as fergusonite–Ce and baotite, but the major Nb-bearing minerals are aeschynite, fergusonite and pyrochlore (Zhang et al., 2000; Hou et al., 2018). It has been suggested that the Nb-bearing minerals such as pyrochlore, fersmite and columbite in the ore-hosting dolomite and calcioarbonatite dykes from Bayan Obo might have had an igneous origin (Le Bas et al., 1992), but the aeschynite, fergusonite and baotite are now thought to be hydrothermal products accompanied by fluoritization and fenitization (Liu et al., 2018a, b), or in the barite-sulfide hydrothermal veins (Liu et al., 2004).

3.5 Volcanic rock type

Volcanic rock-type rare metal deposits are very important in the world in particular for Be and Nb mineralization, such as the noted F-rich Be–U deposit of Spor Mountain, United States (Lindsey, 1977) and the Brockman niobium tuff in Australia (Ramsden et al., 1993). However, in China only a few deposits of this kind have been reported, such as the Baiyanghe U–Be deposit in Inner Mongolia, one of the largest Be deposits in Asia (Wang and Zhao, 1997; Yang W. et al., 2014; Hou et al., 2018). It has been suggested that the Nb-bearing minerals such as pyrochlore, fersmite and columbite in the ore-hosting dolomite and calcioarbonatite dykes from Bayan Obo might have had an igneous origin (Le Bas et al., 1992), but the aeschynite, fergusonite and baotite are now thought to be hydrothermal products accompanied by fluoritization and fenitization (Liu et al., 2018a, b), or in the barite-sulfide hydrothermal veins (Liu et al., 2004).
precipitation into the deposit (Li X F et al., 2015).

In the south Qinling orogen, a number of alkaline volcanic rock-related Nb deposits have been recently discovered, such as the Guanyazi, Jiangjiayan, Tianbao, and Tudiling (Liu et al., 2015; Yang C et al., 2017). In the large Tianbao Nb deposit, the major rock types include trachyte, trachytic tuff and ignimbrite. The Nb orebodies are located within the lower to middle part of the volcanic sedimentary rock sequence. The ore-bearing trachytes are alkali-rich, with high abundances of REE, Nb, Ta, Zr, Hf; their geochemical and isotopic characteristics indicate an origin in mantle-derived basaltic magma forming in an intraplate extensional environment (Yang C et al., 2017). The Nb ore minerals are mainly aeschynite and Nb-aeschynite. The Nb resource is estimated as 0.21 Mt Nb₂O₅ @0.06–0.092% in the Tianbao deposit (Liu et al., 2015). In the Tudiling Nb–Ta deposit (Xiong et al., 2018), the ore-bearing rocks are trachyte, trachytic tuff lava, trachytic clastic tuff, potassium-bearing feldspathic tuffaceous sericite phyllite, and the ore minerals are mainly columbite-group, together with some Nb-rich titanite, Nb-ilmenite, and allanite. The Nb and Ta resources are estimated to be 68,856 t Nb₂O₅ @0.08–0.376% and 4616 t Ta₂O₅@0.010–0.021% in the Tudiling deposit (Xiong et al., 2018).

3.6 Hydrothermal type

We consider the skarn-type deposits as typical hydrothermal deposits for rare metal mineralization, with the hydrothermal fluids predominantly derived from magmatic fluids but can mix with meteoric water during the mineralization evolution. The major rare metals are also sourced from magma, although a contribution from country rocks is also highly likely.

One typical example is the Be-bearing ribbon rocks in the Xianghualing area of Hunan province. The Be mineralization occurs in the contact zones between Yanshanian (155–154 Ma) F-rich granites and the Middle to Upper Devonian country rock of limestone and dolomite limestone (Zhang et al., 2012). Five types of ribbon rocks are distinguished according to their mineral paragenesis, namely, zinnwaldite, fluoroborate, chrysoberyl, chondrodite–magnetite, and phlogopite-chlorite ribbon rocks. The main minerals include fluoroborate, taaffeite, emerald, xianghualite, casserite and magnetite, together with tourmaline, fluorite, phlogopite, and calcite. A typical zonation can be distinguished from within the granite and away to the country rocks, including the fresh granite, vesuvianite–garnet skarn, F- and B-metasomatic rock, B-metasomatic rock, phlogopite-fluoroborate marble, and dolomite marble. These rocks are thought to have been formed via strong metasomatism by F-, B-, Be-rich hydrothermal fluids of probable magmatic origin (Zhao et al., 2017).

Another example is the recently discovered Cuonadong super-large Be–Rb–W–Sn deposit (BeO reserve 115300 t, Rb₂O 38200 t,WO₃ 271000 t, Sn 11500 t, Xia et al., 2019), where the main orebodies occur as skarn in between leucogranite and marble within the Cuonadong gneiss dome structure. The main Be-ore minerals include phenakite and bertrandite, which are in close association with the skarn minerals (diopside, epidote, garnet and tremolite). The W–Sn ore minerals include cassiterite and scheelite and the mineralization shows a close association with the highly evolved composite leucogranite, including early-stage coarse-grained (18–21 Ma) and late-stage fine-grained (15–17 Ma) tourmaline–garnet-bearing two-mica granite (Li G M et al., 2017). The ore-bearing rocks occur either as fine-grained lamination or as a coarse-grained layer-like body. The fine-laminated rock shows interbanded green skarn mineral beds and white-grayish marble beds of 10–100 cm thick; very fine quartz veinslets with scheelite also occur within the skarn. The coarse-grained layers are 1–10 m thick, with small pegmatite pockets and lenses (generally < 50 cm wide and < 2 m long). Beryl occurs within these layers (Xia et al., 2019).

Many rare metal-bearing quartz veins mostly associated with W–Sn deposits are also formed during a hydrothermal stage and thus belong to the hydrothermal type, for example, the Malipo emerald deposit in Yunnan Province, occurring as quartz–beryl–scheelite–tourmaline pegmatitic veins in metamorphic rocks of the Nanwenhe metamorphic core complex (Zhang et al., 1999), and the Hetaoping W–Be deposit in Zhen’an, southern Qinling, which occurs as layer-like skarn or beryl and scheelite-bearing quartz–carbonate veins within metamorphic rocks of schist and marble (Dai et al., 2019). In the above two examples, although granite rocks are not found in the mining district, the deposits are thought to relate to magmatic hydrothermal fluids derived from blind and deep-seated granites. In South China, many granite-related greisen-type and quartz vein-type W–Sn deposits may also accompany Be mineralization with occurrence of beryl and topaz in alteration rocks and veins (Li J K et al., 2017).

3.7 Leptynite type

The lephtinite-type deposit was first proposed by Yuan et al. (2012) for rare earth element deposits that occur within metamorphic rocks. It is worth noting that the term ‘leptynite’, or ‘leptite’ when dark silicate minerals such as biotite and hornblende are less than 10%, originated from a study on metamorphic basement rocks of the Variscan orogenic belt in Europe in the last century, describing a set of metamorphic rocks with felsic minerals (quartz, feldspar and muscovite) as the main component, up to low amphibolite facies and granulite facies metamorphism. Although in modern petrological research, some scholars would like to discard the terms leptynite and leptite, and instead suggest the use of ‘leucogneiss’, considering the wide usage of the original terms by Chinese scholars, we propose to keep them.

One of the typical leptynite-type rare metal deposits is the large-scale Yushishan Nb-Ta-(Zr–Hf–REE) deposit, recently found in Gansu Province, northwestern China (Figs. 5, 6), which occurs in the metamorphosed and deformed volcanic-sedimentary rock strata of the Neoproterozoic Ao'yougou Formation, with stratabound orebodies extending at least 11 km long and 3 km wide (Yu et al., 2012, 2015).

The protoliths of the lephtinite–leptite rocks are alkaline felsic volcanic rocks with eruption ages of ca. 830 Ma that have undergone later strong metamorphism and
deformation along a shear zone (Jia, 2016; Jia et al., 2016). The main ore types include disseminated-, banded- and veinlet-type ores. The ore minerals include columbite-group, aescynite, polycrase, bastnäsite, monazite, zircon and thorite. The monzonite occurs as a pluton in the north part of the mining district and both gneissic granite and aegirine syenite occur as dykes and veins within the ore-bearing metamorphic strata. LA-ICP-MS dating of zircon and apatite from these magmatic rocks shows similar dates of ~500 Ma, indicating their emplacement age (Jiang et al., 2018). However, the titanite in these rocks and the ore-bearing strata show two-stage formation ages of ~500 Ma and ~460 Ma, and their trace element signatures indicate either magmatic or metamorphic origin (Jiang et al., 2018). Hence we suggest the formation of this deposit is likely in multiple stages, with the first stage in the Neoproterozoic (at ca. 830 Ma) when the alkaline volcanic rocks erupted with a Nb–Ta pre-enrichment in these rocks, later on during the Caledonian tectonic-magmatic stage, the emplacement of syn-tectonic alkaline magmatic rocks (ca. 500 Ma) exsolved magmatic hydrothermal fluids that brought rare metals for the formation of the deposit, and the syn-tectonism also produced shear zone-related metamorphic fluids, which contributed remobilization and final enrichment of the rare metals in the host volcanic-sedimentary rock strata at ~460 Ma to form the large-scale Yushishan Nb–Ta–Zr–Hf–REE deposit.

3.8 Breccia pipe type

Breccia pipe-type mineralization has been reported in W–Sn deposits worldwide, such as the Erzgebirge–Slavkovsky les ore field in Europe and the Dahutang ore field in northern Jiangxi (Seltmann and Schilka, 1994; Breiter et al., 1999; Jiang, et al., 2015). In the Erzgebirge, the ore-forming processes are connected with the crystallization and high fractionation of the Sn–W–Li–Rb–Cs–F–specialized granoids, such as the biotite monzogranites, topaz-bearing Li-biotite syenogranites, albite–zinnwaldite alkali-feldspar leucogranites, and the extreme enrichment in rare metals (Li, Rb, Nb, Ta, Sn, and W) is thought to be controlled not only by the strong magmatic differentiation but also the ore metal supply by post-magmatic fluids penetrating the granites (Seltmann and Schilka, 1994). In the Dahutang deposit, the breccia pipe-type mineralization formed mainly W–Cu orebodies without any other rare metals (Jiang et al., 2015).

Recently, a large-scale breccia pipe-type Li deposit has been discovered in the Weilasituo ore field, Inner Mongolia, which is closely associated with alkali-feldspar
granite-type Rb and quartz vein-type Sn–W–Zn mineralization (Fig. 7a, b), with estimated resources of 688,300 t Li$_2$O @ avg. 1.27% (0.8–3.6%), 87,000 t Sn @ avg. 0.89%, 14,700 t WO$_3$ @ avg. 0.13%, 80,200 t Zn @0.74%, with the grade of Rb$_2$O between 0.1% to 0.58% with avg. 0.35% (Li et al., 2018; Zhang T. et al., 2019).

The breccia pipe-type orebody (approx. 247 × 480 × 640 m) is located just above the porphyric alkaline feldspar granite body (Fig. 7b). The breccia is composed of mainly gneiss and also minor quartz diorite with different sizes, angular shape and strong greisenization. The cement is greisen, and the main minerals are quartz, topaz, fluorite, lepidolite and Li-rich muscovite. Cassiterite, beryl and a small amount of sulfides can be locally seen. Previous studies show emplacement ages of 139.5 ± 1.2 Ma and 138 ± 2 Ma (zircon U–Pb, Liu et al., 2016; Zhu et al., 2016), whereas the cassiterite from various ore veins yielded LA-ICP-MS U-Pb dates of 138 ± 6 Ma, 136 ± 6.1 Ma and 135 ± 6 Ma (Wang F X et al., 2017; Liu et al., 2018), suggesting a coeval age for the magmatism and mineralization. Geochemical studies indicate that the alkali-feldspar granite is of highly fractionated I type with positive $\varepsilon$Nd(t) values of +1.1 to +3.8 and positive zircon $\varepsilon$Hf(t) values of +4.2 to +8.7 (Zhang T et al., 2019). The alkali-feldspar granites show vertical zoning and only the roof zone shows enrichment of Rb with an abundant amount of amazonite (Zhu et al., 2016; Li et al., 2018). Along with the magmatic evolution, a large amount of exsolved fluid converged to the roof zone of the pluton, and the upper surrounding rock was hydraulically fractured, with formation of a cryptoexplosive breccia pipe and a large number of tensile fractures with Sn–Zn–Pb-bearing quartz veins.

4 Controlling Factors for Rare Metal Deposit Formation

4.1 Geochemical behavior of rare metal elements

The geochemical properties and the behavior of the rare metal elements under various geological processes and physicochemical conditions determine the characteristics of their mineralization. At present, the research on the geochemical properties and behavior of the rare metal elements is still in its infancy, and many issues regarding rare metal mineralization mechanism are still controversial.

The elements Li, Be, Rb and Cs are called as alkaline earth elements, and the elements Zr, Hf, Nb and Ta are called as high field strength elements. The latter form smaller cations with a valence of +4 or +5, and $\text{Zr}^{4+}$ and $\text{Hf}^{4+}$, $\text{Nb}^{5+}$ and $\text{Ta}^{5+}$ have nearly the same ionic radius and very similar chemistry. The studies of Nb and Ta show that they have the same valence state, similar ionic radius, and almost identical chemical properties, which are called ‘twin pairs’. The Nb/Ta ratio of most mantle-derived rocks is close to the Bulk Earth value, suggesting that partial melting of the mantle can only cause very limited fractionation, but in the continental crust, the ratio varies greatly and exhibits a characteristic Nb loss (Rudnick et al., 2000). In theory, pairs of twin elements like Nb and Ta should be consistent with the mantle and the continental crust, so the low Nb/Ta ratio has become the proxy for the continental crust and is currently a frontier of academic research (Tang et al., 2019). In the mineralized granite and pegmatite, Nb and Zr tend to be enriched in the less fractionated rocks, whereas the Ta and Hf are more enriched in the highly fractionated rocks (Černý et al., 1985). The Nb and Ta mineralization is controlled by fractional crystallization, solubility decrease of niobium–tantalum oxides accompanied with decreasing temperature and alkalinity and increasing phosphorus content in the melt (Tang et al., 2016). It has also been proposed that the fractional crystallization of muscovite and biotite in the melt can affect the fractionation and mineralization of Nb and Ta in the granites (Stepanov et al., 2014). Crystallization of biotite and muscovite increases the Ta/Nb ratio of the melt. Although crystallization of rutile and titanite that are enriched in Ta can deplete Ta at the early
stages of magma fractionation, mica crystallization can suppress their saturation and allow Ta to increase in the melt, and columbite can originate from recrystallization of mica (Stepanov et al., 2014).

The enrichment of Li and Be in the granitic melt and their mineralization is controlled by their solubilities. The Li and Be concentrations in the melt affect the precipitation of beryl and spodumene, which are controlled by temperature and the aluminum saturation index (ASI) of the magma. As a result, the low solubility of beryl in highly under-cooled melts can well explain the crystallization of beryl in the early marginal zone and wall zone of a pegmatite (London, 2018). Other factors such as P-rich, F-rich, and liquid immiscibility of the silicate phase may also place varied control on Be mineralization (Zhang H et al., 2019).

Cesium is a strongly incompatible element that only exists in a highly differentiated magma system. Unlike Be, Cs is highly soluble in silicate melts. The content of Cs in the melt saturated with Cs-zeolite can reach up to percentage level. Therefore, in most cases, Cs is dispersed into alkali feldspar, muscovite and beryl minerals without independent Cs minerals, and only in rare cases can pollucite crystallize in the magma system (Wang et al., 2006; London, 2018).

4.2 Source of rare metal elements

An important prerequisite for mineralization is the source supply of the ore metals. The abundance of the rare metal elements in the earth's rocks is very low, and their contents in the mantle and crust are very different. The rare metal mineralization is closely related to major geological events and the cycling of the elements in the Earth's crust and mantle. For example, numerous studies have shown that the Nb and rare earth elements are enriched in carbonatite and alkaline rock complexes originated from the mantle, while highly differentiated granites in the crust and the LCT-type pegmatite are enriched in rare metals like Li, Be, Rb, Cs, Nb and Ta, and crust-mantle mixed-source alkaline granite and the NYF-type pegmatite have high abundances of Nb, Ta, Zr, Hf and Y. The possible formation of alkaline granite includes the differentiation of basaltic magma, partial melting of deep crustal materials, or the mixing of crust-derived magma and mantle-derived mafic magma (Dostal and Shellnutt, 2015; Siegel et al., 2018). The genetic mechanism of the NYF-type pegmatite includes low-degree partial melting of the lower crustal material, such as granulite, granite, quartz diorite, the extreme fractionation of mantle-sourced magma, such as basaltic, tonalitic magma, the magma generated in the lower crust and upper mantle transition zone, and the anatasis of the depleted granulate source zone (McCauley and Bradley, 2014; London, 2018; Siegel et al., 2018).

Although it is generally thought that the LCT-type pegmatite has a genetic link to the parent rock of highly fractionated S-type granite, but this link is uncertain in most cases. For example, recent geochronology and isotope studies of pegmatite and the nearby granite in Altay show that the granites and pegmatites that were previously thought to have genetic relationships might have had significant time and source decoupling; for example, both the ages and $\varepsilon_{Hf}(t)$ values of the Azuba Be mineralized pegmatite (215–192 Ma, $\varepsilon_{Hf}(t) = -0.6$ to $+6.3$), the Jiamukai Be–Nb–Ta mineralized pegmatite (212–192 Ma, $\varepsilon_{Hf}(t) = +0.4$ to $+3.3$) and the Karuan Li mineralized pegmatite (228–211 Ma, $\varepsilon_{Hf}(t) = +0.65$ to $\varepsilon_{Hf}(t) = +2.50$) differ from the nearby Halon granites (401–403 Ma, $\varepsilon_{Hf}(t) = +7.85$ to $+14.95$) (Zhang et al., 2016). Therefore, these rare metal pegmatites cannot originate from the Halon granites.

To summarize, the mobilization, transportation, enrichment and mineralization of the rare metal elements are controlled by various magmatic and hydrothermal processes within the crust, the mantle and/or interaction between the mantle and crust.

4.3 Magmatic fractionation and its role for rare metal enrichment

Highly differentiated or highly evolved granites refer to those that have undergone a high degree of fractional crystallization, which are often closely related with rare metal mineralization. However, there exist various viewpoints regarding the petrogenesis and ore genesis of the high differentiation of granitic magma and associated mineralization, such as magma crystallization differentiation, the specific mechanism of separation of minerals and magma, i.e., gravity sorting, flow differentiation, convection, etc., the crystal cumulation, and the exsolution of the hydrothermal solution (Wu et al., 2017). Because granitic magma tends to have high viscosity and is even a crystal 'porridge', it will make the magma crystallization differentiation difficult, and the increase of the content of F, B and Li in the melt can reduce the melt viscosity. These magmatic processes still need further investigation.

In general, in the process of rare metal element mobilization, transportation and enrichment during magmatism and crust-mantle interaction, the following factors place major constraints on the formation of large-scale rare metal deposits (Jiang et al., 2019). First, the abundance of rare metal elements in the magma source regions, second, whether these elements can be efficiently mobilized from the source rock into the magma, and the third is the rare metal element behavior that is controlled by the magma differentiation crystallization and fluid exsolation process (López-Moro et al., 2017; Siegel et al., 2018).

A number of geochemical indices have been successfully used to evaluate the magmatic fractionation. For example, the Nb/Ta and Zr/Hf ratios have been widely applied to trace magmatic fractionation and compositional changes (Stepanov et al., 2014; López-Moro et al., 2017).

The study of various minerals, including rock-forming minerals, such as mica, feldspar and quartz, accessory minerals, such as zircon, titanite, apatite, as well as ore minerals, such as the columbite-group minerals, cassiterite, beryl, topaz, lepidolite, in granites and pegmatites, has been used to indicate the evolved magmatic systems and ore-forming processes. Among which, the Nb–Ta-bearing oxides, e.g., columbite-group minerals, have long been considered as the main phases...
controlling Nb–Ta concentrations and their fractionation in the residual melt (Linnen et al., 2014). However, Stepanov et al. (2014) considered that the fractional crystallization of muscovite, biotite, and amphibole in the magma system also creates a significant role to fractionate Ta from Nb in granitic melts. Therefore, the chemical compositional variations and zonation of these minerals have been extensively analyzed to reveal the magmatic fractionation and rare metal enrichment processes.

4.4 Metamorphic core complex and its role for rare metal granite and pegmatite formation

Recent studies have shown that granite and/or pegmatite in metamorphic core complexes are closely related to the genesis of rare metal mineralization. Typical examples in the world are the rare metal pegmatite deposits in the Lewisian metamorphic core complex in Scotland (Shaw et al., 2016), the rare metal pegmatites in the Bohemian metamorphic core complex in the Czech Republic (Melleton et al., 2012), and the granitic pegmatite in the Congo Manono–Kitotolo metamorphic complex, which hosts the world’s largest Sn–Nb–Ta–Li deposits (Dewaele et al., 2016).

Most of the rare metal deposits with economic significance in China are also related to a granite and/or pegmatite accompanying the development of a metamorphic dome structure or core complex that formed by regional extension, such as the Wugongshan metamorphic core complex with association of the Yashan Ta–Nb–Li deposit (Shu et al., 1998; Luo et al., 2005), the Yajiang–Malon gneiss dome complex with association of the Jiajika–Keertying Li deposits (Xu et al., 2018), and the Cuonadong gneiss dome complex in the North Himalaya (Xia et al., 2019).

In the Wugongshan metamorphic core complex, various stages of granites occur including Caledonian, Indosinian and Yanshanian (Fig. 8). Firstly, the development of an extensional structure and detachment was initiated in the
Late Triassic, and then a dome structure finally formed during the Late Jurassic to Early Cretaceous (Luo et al., 2005; Yang Z et al., 2014). The Yashan rare metal granites at Yichun occur at the outer zone of the Wugongsan dome structure (Fig. 8). In the North Himalaya, a number of metamorphic core complexes have been reported over a long time (Li et al., 2003), and in one of them, namely, the Cuonadong gneiss dome, a super-large Be–Rb–W–Sn deposit has recently been discovered (Zhang et al. 2017; Xia et al., 2019). The Cuonadong gneiss dome is composed of three parts, the core of Cambrian granitic gneiss, the mantle sourced Early Paleozoic mica schist and marble, and the outer part of metamorphic sedimentary rocks, together with a number of syn-tectonic leucogranites and pegmatite dikes, mostly intruded into the inner parts. The orebodies occur at the skarn zone, with beryllium and rubidium ore resources estimated to be of up to super large and paragenetic W–Sn ore resources of large scale. In addition, pegmatite-type rare metal mineralization and cassiterite–sulfide polymetallic ore veins were also found (Xia et al., 2019). The pegmatites emplaced mostly along the foliation, schistosities and deformation structures, partly cross-cutting and belonging to the syn-tectonic stage, occurring as lenticular, ‘stone sausage’, and ‘eyeball-like’ (augen) structures.

A conceptual model for the formation of rare metal mineralization in granite and pegmatite of the syn-tectonic stage accompanying a metamorphic core complex is shown in Fig. 9.

5 Conclusions

Rare metal mineral deposits are widespread throughout China, with particularly concentrated regions in the Altay and southern Great Xing’an Range regions (CAOB), the Qilian, South Qinling and East Qinling regions (QQDOB), the Western Sichuan and Bailongshan–Dahonglutan regions (KSGOB) and the Northeastern Jiangxi, Northwestern Jiangxi, Southern Hunan regions (S. China). The most important mineralization periods are the Yanshanian and Indosinan.

Six major rare metal mineral deposit types are identified in China, namely the Granite, Pegmatite, Alkaline granite, Carbonatite and alkaline rock, Volcanic, and Hydrothermal types. In addition, two new types, recently discovered in China, are coined as the Leptynite-type Nb–Ta–(Zr–Hf–REE) deposit at Yushishan in western China and the Breccia pipe-type Li–(Rb–Sn–W–Zn–Pb) deposit at Weilasiitu in northeastern China.

The ore-forming controls of the rare metal mineral deposits are closely related to various geological processes, such as magma-source region characteristics, highly fractional crystallization, the physical and chemical conditions of the ore-forming system. The metamorphic core complex is particularly mentioned as an important control for many granites and pegmatites with associated rare metal mineralization.

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References


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