Syn-mineralization Uplifting and Exhumation of Porphyry Systems in China: Evidence from Fluid Inclusion Data

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Abstract: In order to understand how the metallogenic process of porphyry deposit specifically and directly respond to regional uplifting and exhumation, we compiled previous fluid inclusion data of 32 porphyry deposits in China by recalculating the fluid trapping depths and trapping depth reduction magnitude from early to late mineralization stage veins. The data reveal that the average trapping pressure ratio (Ave TP/E TP) between early- and late-stage veins of the these deposits are 1.2–18.4, mainly in the range of 1.35–5.83, with average trapping pressure reduction (1–Ave TP/E TP) from early- to late- stage veins are 17%–95%, and mainly in the range of 25%–83%. The fluid trapping pressure based mineralization depths most of the porphyry deposits in China had decreased from early to late vein stages by at least 450 m (900–5800 m predominant), or greater than 950 m when took the average depth reduction value, which is greater than the current gap between early- and late-stage veins of each deposit. We propose that the apparently greater mineralization depth reduction magnitude than the current elevation gaps between early and late veins are likely a consequence of syn-mineralization uplifting and exhumation process that often occurs in porphyry systems.

Key words: fluid inclusion, syn-mineralization uplifting, exhumation, porphyry deposit

1 Introduction

Porphyry deposits presently supply nearly three-quarters of the world’s Cu, half the Mo, perhaps one-fifth of the Au (Sillitoe, 2010). The magmatism that drives porphyry mineralization is always associated with compressional tectonics and is, thus, typically synchronous with rock uplift and exhumation, leading to poor preservation potential of deposits in the geological record (Cooke, 2017). Syn- and post-mineralization exhumation have made the ages for the world-wide porphyry deposits mostly clustered in the Cenozoic with three major stages of the Paleocene to Eocene, Eocene to Oligocene, and the Middle Miocene to Pliocene (Cooke et al., 2005; Kesler and Wilkinson, 2006; Yanites and Kesler, 2015). Hence, obtaining the exact syn- and post-mineralization exhumation history of the porphyry deposit could not only provide better understanding the role of exhumation in the temporal-spatial distribution of ore deposits, but also provide a potentially valuable contribution to prediction of the presence and character of porphyry-style mineral endowment. Post-mineralization exhumation history of porphyry system has been widely evaluated by previous works worldwide (Kesler and Wilkinson, 2006; Liu et al., 2014; Sun et al., 2021; Wainwright et al., 2017).

The effect of uplifting-exhumation events during metallogenic process, however, remains unclear. Some researchers have indirectly inferred that the porphyry metallogenic processes are spatially and temporally accompanies regional uplifting-exhumation events. For instance, based on zircon U/Pb dating and geochemical-isotopic studies on pre-ore monzogranite-granodiorite and syn-ore intrusions, Yang Z et al. (2009) conclude that the Miocene magmatism in Qulong porphyry Cu-Mo deposit lasted about 5 Ma between 19.5–16 Ma, which is consistent with the 20–15 Ma rapid uplifting-exhumation stage of the Gangdese porphyry copper belt (Copeland et al., 1987; Carrapa et al., 2014; Tremblay et al., 2015; Li et al., 2016; Zhou et al., 2019). Also, Sillitoe (2010) show that porphyry mineralization is significantly correlated with regional uplifting-exhumation events in the Laramide porphyry copper province of southwestern North America (Late Cretaceous–Paleocene), the Central-Andean metallogenic belt of South America (Middle Eocene–Early Oligocene, Late Miocene–Pliocene), the Iran metallogenic belt (Middle Miocene) and the Pliocene Papua New Guinea and Philippine porphyry copper belt. Whereas little attention has been paid on the response of ore body itself to uplifting-exhumation during porphyry mineralization. It is unclear what specific and direct effect the uplifting-exhumation has on the porphyry mineralization.

China, lies in the junction and superimposition of three world-class metallogenic domains, namely the Central Asian, Tethyan and Circum-Pacific metallogenic domains, is the region with the most extensive distribution of metallogenic ages (Early Paleozoic–Miocene) and mineral
assemblages (W, Sn, Mo, Cu, Pb, Zn, Au and Ag) of porphyry deposits in the world, where porphyry mineralization occurs in the continental arc, the island arc and the intra-continental setting. All these features make China as the most ideal place to study the response of metallogenic progress of porphyry deposits to uplifting-exhumation.

In this paper, previous fluid inclusions data of porphyry deposits in China are compiled by summarizing the fluid trapping pressures, and calculating the fluid trapping depths and depth reductions from (magmatic stage or) early vein stage to late vein stage. Then, combining with the geological and mineralogical evidences, this paper discusses the syn-mineralization uplifting-exhumation progress of porphyry system. The result not only provide constraints on the study of the genetic relationship between porphyry mineralization and regional uplifting-exhumation events, but also have important indications for regional tectonic evolution and orogenic uplifting mechanisms.

2 Tectonic Framework

The China continental crust consists mainly of the North China, Tarim, Yangtze cratons and the Tianshan–Xingmeng, Qinling–Qilian–Kunlun, Wuyi–Yunkai–Taiwan, Tibet–Sanjiang orogenic systems. All of three cratons had undergone ancient continental nucleus, oceanic-continental transition, accretion, collisional aggregation and solidification stages to form a stable crystalline basement, and then became stable crustal tectonic units after post-collisional rifting and the development of thick carbonate platforms. Orogenic system is a composite arc-basin tectonic unit integrated with a series of large-scale ophiolitic melange belts, different types of arcs, different eras of drift blocks, which is the products of ocean-continent convergence, subduction and demise process (Pan et al., 2009) (Fig. 1).

The Tianshan–Xingmeng orogenic system (or Central Asian Orogenic Belt) is the product of evolution of the Paleozoic–Triassic Paleo-Asian Ocean and the Triassic–Jurassic Mongolian Okhotsk Ocean (Xiao et al., 2019). The Qinling–Qilian–Kunlun orogenic system (or China Central Orogenic System) records the northward subduction of Late Cambrian–Ordovician Proto-Tethys Ocean, the southward subduction of Late Cambrian–Ordovician Proto-Tethys Ocean, and multi-stage subduction process of Paleo-Asian Ocean, and multi-stage subduction process of Late Ordovician–

Fig. 1. Tectonic framework of China and its adjacent areas. The regional faults and tectonic boundaries are after Pan et al. (2009). Notes: 1–Yuchiling (Li et al., 2012); 2–Yaocchong (Wang et al., 2014); 3–Donggou (Yang et al., 2015); 4–Nannihu (Yang et al., 2012); 5–Xiaofan (Tang X W et al., 2017); 6–Jinduicheng (Yang Y F, 2009); 7–Qianchong (Yang et al., 2013); 8–Reshiu (Guo et al., 2019); 9–Yandong (Wang et al., 2017, 2018); 10–Donggebi (Wu et al., 2014); 11–Shishu (Li et al., 2017); 12–Gaogangshan (Zhao, 2019); 13–Huazhagaitu (Liu et al., 2019); 14–Dabaoshan (Wei et al., 2011); 16–Baituyingzi (Sun et al., 2017); 17–Daheishan (Zhou et al., 2015); 18–Yaqijigou (He et al., 2017); 19–Laojigou (Liu et al., 2012); 20–Changfagou (Peng et al., 2018); 21–Hamaling (Bian, 2018); 22–Wuziqilong (Chen et al., 2011); 23–Luozi (Zhong et al., 2012); 24–Dabaozhu (Mao et al., 2017); 25–Tongchang (Liu et al., 2016); 26–Fujianwu (Li L et al., 2015); 27–Zhushahong (Zhang et al., 2012); 28–Dabuza (Li et al., 2007); 29–Jiama (Zhou et al., 2011); 30–Zhenwu (Li M et al., 2015); 31–Banggu (Luo et al., 2012, 2015); 32–Jiudingshan (Li et al., 2016).
Triassic Oceanic basin, as well as collision between the North China and Yangtze blocks (Pan et al., 2009). The Tibetan–Sanjiang orogenic system records the formation and expansion of the Carboniferous–Middle Permian Paleo–Tethys Ocean, and multi-stage subduction–reduction–accretion processes (Middle Late Permian, Middle Triassic, Cretaceous) of Paleo- and Neo Tethys Ocean, and Indo-Eurasian collision orogeny events (Pan et al., 2009). The Wuyi–Yunkai–Taiwan Orogenic System records the demise of the South China Ocean (Middle–Neoproterozoic to Early Paleozoic) between the Yangtze and Cathaysia block, and the subduction history of the ancient Western Pacific plate (Pan et al., 2009). In addition, the ancient Western Pacific plate subduction related magmatism is also superimposed over a wide area in eastern China (Tianshan–Xingmeng and eastern part of Qinling–Qilian–Kunlun Orogenic System).

Tianshan–Xingmeng (or Central Asian), Tibet–Sanjiang and Wuyi–Yunkai–Taiwan orogenic systems respectively corresponds to Paleo-Asian Ocean, Tethyan and Circum-Pacific meteorologic domains. The porphyry mineralization in Qinling–Qilian–Kunlun (or Central) orogenic system shows close relationship with Paleo-Asian Ocean and Tethyan Ocean evolution. Besides, Circum-Pacific meteorologic domain is widely superimposed on the eastern part of Tianshan–Xingmeng and Qinling–Qilian–Kunlun orogenic systems (Pan et al., 2009).

**3 Evaluation Method, Data Sources and Result**

The magmatic-hydrothermal stage of metallogenic porphyry system is generally short-lived (Fu et al., 2010) and mineralization mainly occurs in the hydrothermal stage. The vein-type and mineralization characteristic of porphyry deposits in China are generally consistent with the global porphyry deposits, and the hydrothermal stage can be roughly divided into 4 stages. I stage: early quartz (± potassium feldspar ± magnetite) vein (EQ); II stage: quartz + molybdenum vein (QM); III stage: quartz + polymetallic sulfide vein (QP); IV stage: quartz ± calcite/ calcite ± quartz ± pyrite veins ± fluorite (QC). EQ, QM+QP, PC veins are equal to A, B and D veins of Sillitoe (2010), and respectively correspond to the potassic, quartz-sericitic and propylitic alterations. Cu mineralization of porphyry deposits mainly associates with potassic alteration as well as quartz-sericitic alteration, while Mo mineralization usually develops in quartz-sericitic alteration stage (Sillitoe, 2010; Li et al., 2012; Yang et al., 2015).

Fluid inclusion is formed when rock- and ore-forming fluids are trapped in crystal defects or cavities during mineral growth. Fluid inclusion (primary and pseudo-secondary) is considered to be volume-invariant since formation and no material exchange with the primary mineral (Roedder and Bodnar, 1980), as a closed and independent physical-chemical system with isovolume characteristic. The fluid homogenization pressure is obtained by measuring the homogenization temperature ($T_h$), ice point temperature ($T_{sp}$) of fluid inclusion, calculating fluid salinity (%) and simulating pressure-volume-temperature-composition (PVTx). The homogenization pressure is equal to trapping pressure when boiling/immiscible fluid inclusion is measured. Hence, the study of fluid inclusions can constrain the evolution of temperature and pressure conditions of ore-forming fluids by measuring and calculating homogenization temperatures and pressures of boiling/immiscible fluid inclusions from different metallogenic stages. Further, fluid trapping depths of the early and late veins indicative of mineralization depths can be calculated by conversion of pressure to depth basing on Geostress gradient.

This paper collected the results of fluid inclusion studies for 32 porphyry deposits (all the results available until now) from Paleo-Asian Ocean, Tethyan and Circum-Pacific metallogenic domains in China that were carried out the fluid inclusion homogenization temperature and pressure conditions of veins at different hydrothermal stages as well as some quartz phenocrysts from magmatic stage. Statistically, depressurization is prevalent in porphyry system from magmatic stage or early vein stage to late vein stage (Figs. 2a, b). Specially, due to fluids in the quartz-calcite vein (latest) stage generally lack of boiling phenomenon, the calculated fluid homogenization pressure might be lower than the actual fluid trapping pressure. Therefore, this paper only takes the homogenization temperature and pressure data of boiling or immiscible fluid inclusions that directly reflect the fluid trapping pressure, ensuring the reliability of the data. On the whole, the average trapping pressure ratio (Ave $T_P$/ $T_P$) from magmatic stage or early vein stage to late vein stage of the studied porphyry systems are 1.2–18.4, mainly in the range of 1.35–5.83; the average trapping pressure reduction (1−Ave $T_P$/ $T_P$) are 17%–95%, mainly in the range of 25%–83% (Fig. 2b).

**4 Discussion**

**4.1 Fluid trapping (mineralization) depth decrease from early to late vein stages**

The decrease of the mineralization depth of porphyry deposits from early to late vein stages have been proposed by researchers. Yang et al. (2012) got an early vein (EQ) mineralization depth of ~7 km and late vein mineralization depth of ~3 km from the Early Cretaceous Nannihu porphyry Mo-W deposit in the East Qinling Mo belt on the basis of the minimum trapping pressure of boiling fluid inclusions; Guo et al. (2019) acquired mineralization depths of 8.8–13 km, 6.4–10.4 km and 5.8–6.9 km (under hydrostatic pressure) for EQ, QM and QP veins, respectively, in Triassic Reshui porphyry Mo deposits in the East Kunlun orogenic belt; Wu et al. (2014) obtained mineralization depths of 8.4 km, 7.9 km and 5.6 km for the first, second and third-stage veins (under lithostatic pressure) at Triassic Donggebi porphyry Mo deposit in eastern Tianshan metallogenic belt through measuring boiling fluid inclusions; Zhou et al. (2011) acquired magmatic-hydrothermal transition depth of 2.2 km and early hydrothermal quartz vein (EQ) mineralization depth of 1.2 km at Miocene Jiama porphyry-skarn type Cu-Au deposit in the Gangdese metallogenic belt by studying
Fig. 2. Pressure-Temperature Path from early to late stage veins of porphyry deposits in China. The fluids temperature-pressure curve of the mineralization processes are acquired by minimum and maximum fluids trapping temperature (X)–pressure (Y) coordinate plotting (some deposits only have mean value) and regression analysis (index) of each stage, then the upper and lower limits of the trapping temperature-pressure of each stage are projected onto the evolution curve to obtain the fluid temperature-pressure evolution map. Since the purpose of this paper is to discuss the metallogenic pressure, the vertical X-axis projection is generally used for the projection, the range of fluids trapping temperature on the temperature-pressure path is different from the actual measured ones. Notes: 1–Yuchiling; 2–Yaochong; 3–Donggou; 4–Nannihu; 5–Xiaofan; 6–Jinduicheng; 7–Qian’e’echong; 8–Reshu; 9–Yandong; 10–Donggebi; 11–Baogutu; 12–Shiwa; 13–Gaogangshan; 14–Huzhagaitu; 15–Duobaoshan; 16–Baituyingzi; 17–Duobaoshan; 18–Yaojiagou; 19–Laogangzhou; 20–Changfagou; 21–Hamaling; 22–Wuziqilong; 23–Luoboling; 24–Dabaoshan; 25–Tongchang; 26–Zhushahong; 28–Duobuza; 29–Jiamu; 30–Zhungou; 31–Bangpu; 32–Jinduicheng. Plots (b) of fluids pressure reduction rate (%) vs. pressure reduction rate (%) between from early and latest magmatic veins of porphyry deposits in China. Notes: TP–fluid trapping pressure; MinTP–minimum fluid trapping pressure; MaxTP–maximum fluid trapping pressure; AveTP–average fluid trapping pressure. fluid trapping pressure of melt inclusions in quartz phenocryst and boiling fluid inclusions in hydrothermal vein respectively. In addition, the mineralization depth reduction from early to late vein stages are also found in porphyry deposits such as Yaochong, Baogutu, Duobaoshan, Changfagou, Luoboling, Dabaoshan, Duobuza, Bangpu and Zhunuo (see references in Appendix 1).

The above results indicate that the mineralization depth of porphyry deposits varies considerably from early to late vein stages, generally greater than 1 km and even up to 6 km. However, the current elevation/depth gaps between the different stage veins are less than 1000 m (the samples used for fluid inclusion studies are taken from surface, drill-core or tunnel of vertical elevation gaps less than 1000 m and mainly <500 m). The early and late veins are basically superimposed spatially, with widespread interpenetrating relationship and symbiosis of different veins. The predecessors have failed to give a reasonable explanation to this.

4.2 Syn-mineralization uplift and exhumation
Syn-mineralization uplift and exhumation (Sillitoe, 1999; Simpson et al., 2004; Tang J X., 2017) could well explain the phenomenon large mineralization depths discrepancy but spatially superimпозing between early and late veins of porphyry deposits. In order to verify whether the syn-mineralization uplift and exhumation process generally occurs in porphyry system, the differences of mineralization depth between the early and late veins of porphyry deposits in China are recalculated basing on previous fluid trapping pressure data. The fluid pressure state during porphyry mineralization is considered to change between lithostatic and hydrostatic pressure (Roedder and Bodnar, 1980). Theoretically, the maximum/minimum value of fluid trapping pressure of co-genetic veins from a single sample comes approximately to 2.85 (density ratio of country rock to water). The maximum trapping pressure of fluid inclusions tends to correspond to lithostatic pressure, while the minimum trapping pressure corresponds to hydrostatic pressure. In this paper, depth reductions from early to late vein stages in China porphyry deposits are acquired by calculating the maximum (ΔMaxTP) and minimum (ΔMinTP) trapping pressure reductions, using a lithostatic pressure gradient of 28.5 MPa/km and hydrostatic pressure gradient of 10 MPa/km, respectively (Fig. 3). The results show that the amount of depth reduction at hydrostatic pressure condition for most of the deposits are greater than the value at lithostatic pressure condition, with some deposits reaching up to three times the latter, indicating that even if the fluid is boiling or immiscible, the minimum fluid trapping pressure reflects a greater pressure state than hydrostatic, and that the results obtained from the minimum trapping pressure may overestimate the mineralization depth and depth reduction values. There are also some deposits where the hydrostatic pressure calculations are less than the lithostatic pressure calculations, which might be the result of sampling height differences or extreme (ultra-high or ultra-low) pressure conditions (Roedder and Bodnar, 1980). In order to improve the reliability of the
conclude that rapid crustal uplift during the hydrothermal valley ore district in New Zealand. Sillitoe (1999) upper part of porphyry mineralization in the Maratoto to superimposition of epithermal mineralization on the exhumation process during mineralization might have led process:

- fluids trapping pressure was calculated in the Huzhagaitu Mo deposits, have mineralization depth Mo, Fujiawu Cu deposits (6/32), such as the Laojiagou Mo, Jiudingshan deposit, the Zijinshan high South China, including the Luoboling porphyry Cu deposit, the Zijinshan porphyry metallogenic belt or smaller ore district, for example, the Yueyang low.

- discrepancy could only be achieved by syn-mineralization trapping depth reduction value than current elevation 950 m (Fig. 3). This apparently greater mineralization/exhumation events pre- or syn-mineralization; Sun et al. (2018) pointed out that pre-mineralization monzogranite and ore-forming porphyry have similar diagenetic ages (~14.7 Ma) in Zhunuo porphyry Cu-Mo deposit from Southern Tibet, and pre-mineralization monzogranite is megaporphyritic with a matrix of medium-grain granitoid texture that shows obvious deep intrusive features, while ore-forming porphyry has typical porphyry texture indicative of shallow emplacement. Li M et al. (2015) had acquired mineralization depths of 2.9 km, 2.7 km and 2.3 km, respectively for the A, B and D veins from Zhunuo deposit through fluid inclusion study. All of these evidences in line with the Zhunuo deposit had been suffered syn-mineralization uplifting and exhumation process.

The results show that most of the porphyry deposits (28/32) in China have minimum depth reduction from early to late veins greater than 450 m (900–5800 m predominant), with average depth reduction greater than 950 m (Fig. 3). This apparently greater mineralization/trapping depth reduction value than current elevation discrepancy could only be achieved by syn-mineralization uplifting and exhumation process. A small number of deposits (6/32), such as the Laojiagou Mo, Jiudingshan Mo, Fujiawu Cu-Mo, Changfagou Cu, Shiwu Cu-Au and Huzhagaitu Mo deposits, have mineralization depth reduction values from early to late veins less than 500 m, which is likely due to underestimation of trapping pressure as well as sampling strategy. For example, the ore forming fluids of Laojiagou, Changfagou and Huzhagaitu deposits belong to H2O-NaCl-CO2 system indicative of deep trapping depth and high trapping pressure, however, the fluids trapping pressure was calculated in the H2O-NaCl system (Peng et al., 2018).

Additionally, the geological and mineralogical features of a mass of metallicgenic porphyry systems worldwide support the syn-mineralization uplifting and exhumation process:

1. Superimposition of porphyry- and epithermal-type deposits: Simpson et al. (2004) argue that the uplifting-exhumation process during mineralization might have led to superimposition of epithermal mineralization on the upper part of porphyry mineralization in the Maratoto valley ore district in New Zealand. Sillitoe (1999) conclude that rapid crustal uplift during the hydrothermal stage led to a decrease of groundwater table and a downward shift in the extent of high sulphide alteration, allowing high sulfidation epithermal mineralization to superimpose on porphyry mineralization, on a summary of several typical deposit features (high sulfidation copper-gold mineralization superimposed on porphyry mineralization).

2. Ore-forming porphyry often intrudes into contemporaneous (or slightly earlier) plutons: Zhao et al. (2016) got an age of 17.6–17.2 Ma for the pre-mineralization plutons and age of ~16 Ma for the ore-forming porphyry from the Miocene Qulong porphyry Cu-Mo deposit, Southern Tibet, with emplacement depth of 3–4.5 km (Zhao et al., 2016) and 1.3–2.8 km (Zhou et al., 2019), which indicate that the Qulong deposit had experienced rapid uplifting-exhumation events pre- or syn-mineralization; Sun et al. (2018) pointed out that pre-mineralization monzogranite and ore-forming porphyry have similar diagenetic ages (~14.7 Ma) in Zhunuo porphyry Cu-Mo deposit from Southern Tibet, and pre-mineralization monzogranite is megaporphyritic with a matrix of medium-grain granitoid texture that shows obvious deep intrusive features, while ore-forming porphyry has typical porphyry texture indicative of shallow emplacement. Li M et al. (2015) had acquired mineralization depths of 2.9 km, 2.7 km and 2.3 km, respectively for the A, B and D veins from Zhunuo deposit through fluid inclusion study. All of these evidences in line with the Zhunuo deposit had been suffered syn-mineralization uplifting and exhumation process.

3. Syn-mineralization conglomerates develop in porphyry deposits: Wainwright et al. (2017) found that the Oyu Tolgoi porphyry Cu-Au deposit in Mongolia develop conglomerates contemporaneous with ore-forming porphyry through geological-mineralogical observations and geochronological studies, indicating that the deposit had been exhumed during mineralization. Sillitoe et al. (2019) pointed out that the Late Oligocene (25–24.5 Ma) Josemaría porphyry Cu-Au deposit in Argentina is overlain by volcanic-sedimentary rocks composed of red conglomerates and sandstones at the lower part and volcanic rocks with an age of 22.5 Ma at the upper part, which suggests that the deposit had experienced erosion and later burial events after mineralization. Moreover, the conglomerates and sandstones below the volcanic rocks should be older than 22.5 Ma, which suggests that the erosion might had originated at an earlier stage, for example mineralization stage, which corresponds to the rapid uplifting-exhumation process of convergent plate setting in Central Andes.

In addition, the syn-mineralization uplifting and exhumation model is also a good explanation for the fact that the deeper porphyry deposits and the shallower epithermal deposits tend to coexist in the same metallicgenic belt or smaller ore district, for example, the Zijinshan porphyry-epithermal mineralization system in South China, including the Luoboling porphyry Cu-Mo deposit, the Zijinshan high-sulfidation Cu-Au deposit and the Yueyang low-sulfidation epithermal Ag polymetallic deposit (Zhong et al., 2014); The Mankayan ore concentrating area of Luzon island in Philippines, including the Far Southeast porphyry Cu-Au deposit, the
Lepanto high-sulfidation epithermal Cu-Au deposit, the Victoria intermediate-sulfidation epithermal Au-Ag deposit and the Teresa low-sulfidation epithermal Au-Ag deposit (Chang et al., 2011); The Tujuh Bukit ore concentrating area of Indonesia, including the Tumpangpitu porphyry-epithermal (high-intermediate sulfidation) Cu-Au deposit (Harrison et al., 2018); The Maricunga ore concentrating area in Chile, including the Refugio, Aldebarán, La Pepa, Marte, Lobo porphyry Au-Cu deposits and the La Coipa high sulfidation epithermal Au-Ag deposit (Muntean and Einaudi, 2001); The Canaan Creek ore concentrating area in Canada, including the Cyprus porphyry Cu-Au deposit and the Klaaza intermediate sulfidation epithermal Au-Ag-Zn-Pb deposit (Chapman et al., 2018).

5 Conclusion

Compiling result of the previous fluid inclusion studies by recalculating the fluid trapping depths and depth reductions from (magmatic stage or) early vein stage to late vein stage of metasomatic porphyry systems reveals that most of the porphyry deposits in China have minimum mineralization depth reduction from early to late vein stages greater than 450 m (900–5800 m predominant) and average depth reduction greater than 950 m. It also indicates that syn-mineralization exhumation often occurs in metasomatic porphyry systems worldwide. Besides, our findings highlight the usefulness of fluid inclusion studies to quantify uplifting and exhumation progress in active orogens.

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References


Yang, Y.F., Li, N., and Ni, Z.Y., 2009. Fluid inclusion study of


Zhao, W., 2019. Cathodoluminescence, composition and fluid inclusions of quartz in Gaogangshan Mo deposit, Heilongjiang Province. China University of Geosciences (Beijing).


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