Yulong Deposit, Eastern Tibet: A High-Sulfidation Cu-Au Porphyry Copper Deposit in the Eastern Indo-Asian Collision Zone

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Abstract

The Yulong body is the largest Cu deposit (6.22 million metric tons [Mt] at 0.99% Cu) in the 300 km long Himalayan porphyry copper belt, and is controlled by major Cenozoic strike-slip faults in the eastern Indo-Asian collision zone. It is associated with a steeply dipping, pipe-like multiphase (42–35 Ma) monzogranitic stock. The host rocks are potassic calc-alkaline or shoshonitic, and show geochemical affinities with adakites. They appear to have been derived from a thickened lower crustal source in East Tibet.

The Yulong deposit consists of a ring-shaped, high-grade Cu-Au zone overlying and/or surrounding a porphyry-type Cu-Mo ore body. Cu-Mo mineralization produced a steeply dipping, pipe-like, veinlet-disseminated ore body within the stock. A associated hydrothermal alteration produced K-silicate and quartz-sericite assemblages within the stock, and contemporaneous propylitic alteration in the Upper Triassic sandy-slate wall rock. Fluid inclusion and δ18O-δD data indicate that the ore-forming fluid was supercritical, and exsolved from a high-level magma chamber at >620°C; it then separated into a hypersaline aqueous liquid and a coexisting low-salinity vapor at 340°–600°C.

The high-grade Cu-Au zone (3 Mt at 4.74% Cu, and 4.5 g/t Au) is dominated by a supergene chalcocite-malachite blanket resting on an underlying supergene/hypogene sulfide transition unit and a hypogene pyrite-chalcopyrite sulfide unit. The Cu-Au zone was controlled by a subhorizontal or gently outward dipping breccia horizon developed along the marginal fracture zone near the roof of the stock, produced by hydrothermal brecciation due to regional uplift and/or fluid boiling. Alteration associated with the hypogene Cu-Au mineralization was texture-destructive advanced argillic alteration, characterized by associations of quartz, kaolinite, dickite endellite, montmorillonite, hydromica, and minor alunite. It mainly developed within the breccia horizons, and partially overprinted the early-formed K-silicate zone and the quartz-sericite zone. Associated mineralization was of the high-sulfidation epithermal-type, characterized by chalcocite, tennantite, covellite, bornite,
and minor pyrite, which formed the main ore body in the high-grade Cu-Au zone. Epithermal fluids also caused the dissolution of early-formed sulfides and remobilization of Cu-Mo, the latter transported into the intense advanced argillic alteration halo within the mineralized stock. This late-stage alteration and mineralization is attributed to a CO₂-rich, low-temperature (<350°C), low-salinity (<12 wt% NaCl equiv.) meteoric fluid, involving input of magmatic fluid.

Based on alteration, mineralization, fluid inclusion and stable isotopic data, a two-stage genetic history has been reconstructed for the Yulong deposit. It spans (1) a magmatic hydrothermal environment reflecting the emplacement of the monzogranite stock and Cu-Mo introduction through (2) hydrothermal fluid infiltration of breccia zones to epithermal overprinting.

Introduction

The Himalayan Yulong porphyry copper belt in eastern Tibet forms part of a significant metallogenic province in the eastern Indo-Asian collision zone (Hou et al., 2003a). This porphyry copper belt is localized along a major Cenozoic strike-slip fault system (Hou et al., 2003a; Fig. 1A). The porphyry copper deposits in the belt were produced during episodic stress relaxation accompanying transition from a transpressional to a transtensional regime (Hou et al., 2003a, 2006). Although the Yulong porphyry Cu belt deposits lie in a continental collision zone and are similar in many aspects to those in continental-margin and arc settings (Hou et al., 2003a), significant differences exist. For example, supergene enrichment, epithermal overprinting, and telescoping of alteration systems, commonly occurring in porphyry Cu deposits in arc settings (Sillitoe, 1989; Ojeda, 1990; Perello et al., 2001), do not occur in most deposits in this belt (Rui et al., 1984; Tang and Luo, 1995). The sole exception is the giant Yulong deposit (6.22 Mt at 0.99% Cu), the largest in the belt, in which high-sulfidation epithermal mineralization associated with advanced argillic alteration recently has been recognized (Fig. 1).

Therefore, the Yulong deposit is a key to unraveling spatial-temporal relations of this high-sulfidation style of mineralization as well as the porphyry mineralization, and to understand why high-sulfidation mineralization did not develop in other deposits in the belt.

This paper describes the alteration zonation and mineral parageneses of the Yulong deposit. It also discusses the genesis of this significant deposit on the basis of our new data on fluid inclusions and stable isotopes combined with previously published information.

Geology

The geology of the Yulong district was described in detail by Ma (1990) and Tang and Luo (1995). Three main lithological units are recognized (Fig. 1B): (1) a 1500 m thick, weakly metamorphosed crystalline basement unit, cropping out in the eastern parts of the district; (2) a 470 m thick sequence of Upper Triassic slate and limestone, thermally metamorphosed to hornfels and marble near an Eocene stock; (3) the Yulong Eocene felsic porphyry and breccia, a complex multiphase intrusion ranging in age from 55 Ma to 33 Ma, which hosts the porphyry-type Cu-Mo ore bodies (Hou et al., 2003a). Pre-mineralized porphyries are dominated by quartz monzonite with ages ranging from 55 to 41 Ma, whereas the post-mineralized stocks are mainly granite, quartz syenite, and quartz-albite dikes formed at ~33 Ma (Ma, 1983, 1990; Tang and Luo, 1995). The intra-mineralized porphyry body forms a steeply dipping multiphase stock with ages ranging from 42 to 35 Ma (Tang and Luo, 1995). Liang (2002) recently reported a high-precision zircon SHRIMP age of 40.9 ± 0.1 Ma for the host monzonite, which coincided with a Re-Os isochron age of 40.1 ± 1.8 Ma for four molybdenite samples from the quartz-sericite alteration zone (Hou et al., 2006).

The main host phases at Yulong are porphyritic monzogranite and quartz monzogranite, characterized by high K₂O contents (4.15–8.06 wt %), high K₂O/Na₂O ratios (>1.0), and alkali enrichment (K₂O+Na₂O > 8 wt%), thus indicating shoshonitic and high-K calc-alkaline signatures (Zhang et al., 1998a). These rocks display high Sr/Y and La/Y, coupled with low Y and low HREE, suggesting geochemical affinity with adakite (Defant and Drummond, 1990; Hou et al., 2003b, 2004a). They yielded a limited range of ðNd(t) (~2.2 to ~4.2) and relatively high ðSr/88Sr, of 0.7058 to 0.7068 (Zhang and Xie, 1997; Zhang et al., 1998b), suggesting a basaltic lower-crustal source thickened by
the Indo-Asian collision at 65–50 Ma (Hou et al., 2004b).

**Cu-Mo-Au Mineralization**

The Yulong deposit consists of a Cu-Mo pipe-like ore body hosted in a porphyry stock surrounded by a high-grade Cu-Au zone (Fig. 2). The pipe-like ore body is steeply dipping, 1000 m long and 600 m wide, with a down-dip extension of 500 m and an average grade of 0.65% Cu (Fig. 3; Hou et al., 2003a). The high-grade Cu-Au zone (~3 Mt at 4.74% Cu; Tang and Luo, 1995) is gently dipping, about 200–300 m wide and 20–100 m thick, thinning outward from the stock, and comprises a supergene chalcocite-malachite blanket overlying
Almost the entire porphyry has been mineralized to form a pipe-like, steeply dipping ore body, dominated by veinlets and disseminated sulfides (Fig. 4) that have been oxidized to various degrees. A 2–10 m thick leached cap, consisting of a malachite and goethitic limonite assemblage, grades downward into a 28–35 m thick oxidized oxide-sulfide transition zone with copper grades ranging from 0.5 to 0.8% Cu (Tang and Luo, 1995). This transition is dominated by malachite, tenorite, native copper, cuprite, and minor chalcocite, but some relict crystals of hypogene chalcocite are present in partly oxidized ores. The underlying main Cu-Mo ore body is a ~450 m thick, steeply-dipping hypogene sulfide zone, in which the upper part of hypogene mineralization is characterized by chalcocite-tennantite-covellite-bornite assemblages, which overprinted earlier hypogene chalcopyrite-pyrite-molybdenite assemblages.
Hypogene copper-molybdenum mineralization is characterized by chalcopyrite, chalcocite, molybdenite, with minor tennantite, chessylite, and bornite, and appears to have been deposited in two episodes (Fig. 5). The first episode is poor in magnetite and bornite, and formed several generations of veins and disseminations. This episode consists of pyrite, chalcopyrite, and molybdenite in the stock, associated with K-silicate and quartz-sericite alteration. In general, molybdenite is concentrated in the upper part of the stock and is exclusively associated with K-silicate alteration, whereas chalcopyrite formed A- and B-type veinlets during the K-silicate alteration, and D-type veins and disseminations.
during quartz-sericite alteration (cf. Gustafson and Hunt, 1975). In hornfels surrounding the stock, pyrite-chalcopyrite stockwork has a ratio ~1/10 of chalcopyrite/pyrite. Late-stage mineralization is associated with structurally controlled advanced argillic alteration and consists of chalcocite, tennantite, covellite, bornite, chesylite, and minor pyrite and molybdenite (Fig. 5). Hypogene molybdenite is fine-grained, either intergrown with bladed hypogene kaolinite and alunite, or in sparse quartz veins within the advanced argillic alteration halo. Hypogene copper was deposited mainly as chalcocite, tennantite, and covellite, which commonly replace early-formed disseminated chalcopyrite-pyrite assemblages. These chalcocite-tennantite-covellite assemblages are more abundant in sparse quartz veins in an advanced argillic halo, but rarely occur as fine-grained crystals, typically intergrown with kaolinite and quartz in a dickite-enriched advanced argillic halo. Hypogene Cu-Mo introduction produced a series of veinlets, including chalcocite-dickite-quartz, chalcocite-chesylite-kaolinite-alunite, tennantite-bornite-covellite, pyrite-bornite-quartz, molybdenite-kaolinite, and molybdenite-quartz in the porphyry stock. The overprinting by late-stage Cu-Mo mineralization over early-formed porphyry Cu-Mo ore bodies produced local, high-grade, fine-veined, and disseminated ores and resulted in a rough chemical zonation of the pipe-like ore body (Fig. 3). The Mo-rich ore bodies mainly occur in middle parts of the porphyry Cu-Mo deposit due to overprinting.

**Lenticular high-grade Cu-Au ore body**

The high-grade Cu-Au mineralization forms a ring-shaped ore body surrounding the Cu-Mo pipe-like ore body. This ore body is controlled by the front fracture zone (breccia zone) on the roof of the stock, and laterally extends along gently dipping contacts between overlying limestone and hornfelsed sandy-slate (Fig. 2). Due to the supergene overprinting, the high-grade zone is dominated by a supergene chalcocite-malachite blanket, in which a leached cap grades downwards into a malachite-rich supergene enrichment unit, which is in turn underlain by a transition zone where mixed hypogene and
supergene sulfides overlie hypogene pyrite-chalcopyrite sulfides.

Leached cap. The leached cap has a thickness of 3–5 m and is dominated by jarostic, hematitic, and goethitic limonite and associated clay minerals (Fig. 4). It is overlain by crystalline limestone and grades downward into a malachite-rich zone.

Malachite unit. The unit has a thickness of 2–12 m and is dominated by malachite, covellite, digenite, and minor limonite clasts, yielding 6–10% Cu grades. The malachite-digenite assemblage in the unit yields the highest Cu grades, reaching 23% Cu (Tang and Luo, 1995). Disseminated malachite occurs in various hydrothermal breccias and advanced argillic altered rocks, whereas veined malachite mainly fills in the opened fissures of porous advanced argillic alteration halos. The clasts in the hydrothermal breccias are dominated by lime-
stone with minor skarn, hornfels, and porphyry clasts, which underwent texture-destructive advanced argillic alteration.

Limonite unit. The red-brown unit has a thickness ranging from 2 to 63 m, with variable Cu contents (0.5–2.0 %), averaging ~1.5% Cu (Fig. 4). It is composed of powder-like limonite interbedded with massive limonite layers. The formers consist of limonite, jarosite, and clay minerals; the latter is dominated by limonite with minor jarosite, hematite, and magnetite. Delafossite, malachite, cuprite, and minor chalcocite occur as fine-grained disseminations in the powder-like and massive limonite.

Chalcocite unit. This blue-grey unit has a thickness of 6–13 m and is composed of mixed hypogene and supergene sulfides associated with endellite-rich advanced argillic assemblages (Figs. 4 and 5). The chalcocite unit shows brecciated, massive, banded, and disseminated structures. The upper part of the unit is characterized by disseminated and fracture-controlled cuprite, covellite, digenite, delafossite, and minor chalcocite as coatings on pyrite and trace chalcopyrite. This supergene enrichment assemblage yields an average Cu grade of 5.4%. The middle part of the unit is a transition zone between oxide and sulfide facies. The oxide facies is characterized by disseminated and powder-like chalcocite, with minor digenite filling pores in clay assemblages or rimming pyrite and chalcopyrite. The sulfide facies is characterized by hypogene chalcocite, tennantite, covellite, bornite, and minor pyrite. Hypogene chalcocite is commonly intergrown with bladed, hypogene endellite and minor hypogene covellite, and also occurs along hairline pyrite-veinlets with kaolinite and covellite in the matrix of hydrothermal breccias, and in massive veins in association with tennantite, bornite, and minor pyrite. The Au- and Ag-rich ores developed near the redox boundary between oxide- and sulfide facies. Au and Ag are concentrated in the hypogene sulfide facies, yielding 4–6 ppm Au and 810–2070 ppm Ag (Tang and Luo, 1995).

Pyrite-chalcopyrite unit. The unit is composed of a 7–10 m thick pyrite-chalcopyrite lens (1.4–2.7% Cu) overlying a 3.5 m thick skarn Cu lens (Fig. 4). The pyrite-chalcopyrite lens grades upward into a thin (<1 m) advanced argillic layer, dominated by an endellite-hydromica-alunite assemblage, and was replaced by hypogene chalcocite. The skarn Cu mineralization developed along gently dipping contacts between hornfels and limestone (Fig. 3B). The skarn is fine-grained, composed of massive grossular cut by vein-like and disseminated pyrite-chalcopyrite. It underwent advanced argillic alteration, forming yellow-green clay assemblages with residual grossularite.

Hydrothermal Alteration

The Yulong deposit is characterized by concentric alteration zones with an inner K-silicate zone surrounded by quartz-sericite and argillic alteration zones and an outer propylitic zone (Zhou, 1980; Rui et al., 1984; Ma, 1990; Tang and Luo, 1995), similar to that found in porphyry Cu deposits worldwide (Meyer and Hemley, 1967; Lowell and Guibert, 1970; Sillitoe, 1972). Recent investigation recognized a structurally controlled advanced argillic alteration, overprinted on an early-formed alteration halo related to the porphyry stock at Yulong.

K-silicate alteration

The potassic alteration developed pervasively in the deep and central parts of the mineralized stock (Fig. 2). The K-silicate alteration is laterally enveloped by a quartz-sericite alteration zone, and grades downward into the least altered host monzogranite at ~4300 m elevation (Fig. 2B). It is characterized by K-feldspar, Mg-rich biotite, and fine-grained quartz. In intensely altered rocks, the original textures are partially to completely destroyed, and pre-existing amphibole, K-feldspar, and plagioclase phenocrysts and groundmass are selectively replaced by potassic mineral assemblages. The hydrothermal biotite is generally interstitial to K-feldspar and quartz, and locally replaces hornblende and biotite phenocrysts. Relict crystals of hydrothermal biotite are widely developed in all altered rocks, suggesting that K-silicate alteration was initially extensive, but has been overprinted by retrograde alteration. Albite (An1–25) forms rims around K-feldspar and plagioclase in the alteration zone, but its overall occurrence and distribution are poorly constrained.

The K-silicate alteration displays close spatial association with Cu-Mo mineralization (Fig. 3). Associated sulfides occur as disseminated, quartz-sulfide vein swarms, biotite-quartz-sulfide and quartz-K-feldspar–sulfide stockworks. Magnetite-rich stockworks, commonly found in the K-silicate zone for some porphyry Cu-Au deposits (Ford, 1978; Eastoe, 1978, 1982; Perello et al., 2001; Ulrich and Heinrich, 2001; Ulrich et al., 2001) have been not observed.
Quartz-sericite alteration

The quartz-sericite alteration is characterized by replacement of most silicate minerals by sericite and quartz, overprinting the earlier K-silicate alteration. It forms a ring-shaped zone around the K-silicate alteration, and is in turn surrounded by a zone of advanced argillic alteration (Fig. 2). Original rock textures are partially destroyed, with original plagioclase, biotite, and K-feldspar replaced by sericite typically associated with hematite, apatite, rutile, and carbonate. Quartz veins are commonly surrounded by sericite halos.

Copper mineralization in this alteration stage occurs in quartz-sericite-pyrite-chalcopyrite, sericite-chalcopyrite, quartz-chalcopyrite-pyrite, and quartz-carbonate-sericite-chalcopyrite-pyrite veins and disseminations. Disseminated pyrite-chalcopyrite assemblages occur in intensely sericitized rocks. Total sulfide content in the alteration episode varies in this zone, ranging from 5 to 10 vol%, and is highest where quartz-sericite zones coalesce (Perello et al., 2001).

Advanced argillic alteration

Two types of structurally controlled advanced argillic alteration are characterized by kaolinite-endellite-montmorillonite-hydromica and kaolinite-dickite-alunite, and overprint early-formed quartz-sericite and K-silicate alteration zones (Fig. 2). The first type mainly occurs in a high-grade Cu-Au zone surrounding the stock, and also developed pervasively in the upper part of the stock. In the high-grade Cu-Au zones (Fig. 3), hydrothermal breccias along gently dipping contacts between overlying limestone and hornfels (Fig. 2B) were intensely replaced by endellite with minor illite, alunite, allophane, gibbsite, chalcedony, and opal (Fig. 5). This complex assemblage probably formed during the advanced argillic alteration and the post-mineral supergene alteration. Within the stock, this alteration locally overprinted the early-formed alteration zones to form small patches, in which some plagioclase phenocrysts were replaced by montmorillonite and hydromica, and original rock textures underwent partial destruction. The second type is characterized by kaolinite-dickite-alunite along steeply dipping contacts between the stock and hornfels (Fig. 2B), which form a ring-shaped alteration zone surrounding the early-formed quartz-sericite zone in the interior of the stock (Figs. 2A and 2B). In this alteration zone, igneous plagioclase is replaced by kaolinite and minor hydromica, whereas orthoclase is replaced by either kaolinite or a fine-grained assemblage of kaolinite, dickite, and quartz. The groundmass is replaced by kaolinite-alunite associated sulfide-quartz veins and open-space silica (quartz, chalcedony). Pyrophyllite, a typical advanced argillic alteration mineral in porphyry Cu-(Au) deposits (Hedenquist et al., 1998; Perello et al., 2001), is lacking, suggesting a low temperature (<350°C) for this stage of alteration (Montoya and Hemley, 1975).

Advanced argillic alteration is associated with hypogene copper-molybdenum mineralization, consisting of chalcocite-tennantite-covellite-bornite, and molybdenite-quartz-dickite assemblages (Fig. 5). Fine-grained molybdenite is mainly developed within the altered stock. Hypogene chalcocite-rich assemblages usually replace early-formed chalcopyrite and pyrite in the altered stock, but dominate the main ore body in the high-grade Cu-Au zone. Attending the last supergene overprinting, hypogene chalcocite changed into powder- or ash-like material, adhering to surface or filling holes left by leached sulfide minerals.

Fluid Inclusion Data

A reconnaissance survey of fluid inclusions of the Yulong deposit was conducted by Li et al. (1981). In order to assess the variation of fluid inclusion characteristics in various alteration zones and mineralization stages, the locations and types of samples analyzed by Li et al. (1981) were re-examined, and fluid inclusion data were recompiled according to the recognized alteration zones (see Table 1). On the basis of this examination, 16 representative samples from various alteration zones and associated ore bodies were collected in this study; their fluid inclusions were studied for further understanding of the evolution of the Yulong hydrothermal system.

Petrography of fluid inclusions

Fluid inclusions are abundant in either gangue quartz of all hydrothermal stages or phenocryst quartz in host porphyries, and range in diameter from 2 to 20 µm. The majority of inclusions in gangue quartz are primary according to Roedder (1984), but minor secondary inclusions also occur. Primary fluid inclusions typically have regular negative forms, including smooth grain, pillar, and polygon, and in some cases are aligned along the growth zones of gangue quartz. They are commonly larger
### Table 1. Microthermometric Data for Type-I, -II, and -III Fluid Inclusions in the Yulong Deposit

<table>
<thead>
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<th>Sample no.</th>
<th>Alter. zone</th>
<th>Type</th>
<th>V/L</th>
<th>Tm(_{ICE}) (°C) range</th>
<th>Avg. (°C)</th>
<th>Tm(_{ICE}) range</th>
<th>Avg. (°C)</th>
<th>Tm(_{V}) (°C) range</th>
<th>Avg. (°C)</th>
<th>Tm(_{H}) (°C) range</th>
<th>Avg. (°C)</th>
<th>Th (°C) range</th>
<th>Avg. (°C)</th>
<th>Salinity</th>
<th>Wt % NaCl equi. range</th>
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<td>545</td>
<td>540 to 550 (2)</td>
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<td>480 to 590 (2)</td>
<td>535</td>
<td>11.4 to 23.3 (2)</td>
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<td>490 to 530 (3)</td>
<td>513</td>
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<td>513</td>
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YULONG DEPOSIT, EASTERN TIBET

(3–10 µm), with the largest diameter of 20 µm, and mainly occur as scattered and isolated inclusions in host minerals. Secondary fluid inclusions are small (<3 µm) and commonly contain one-phase liquid with low salinity (3–5 wt% NaCl equiv.). They occur along planes crosscutting several mineral grain boundaries (Roedder (1984). Fluid inclusions in phenocryst quartz are dominated by secondary inclusions, which also occur along fissures.

Type of fluid inclusions

The fluid inclusions can be divided into three types, based on textural, paragenetic, and phase proportion relationships at room temperature. Type I inclusions consist of volumetrically dominant liquid (H₂O and/or CO₂) with minor vapor. They usually have negative crystal shapes (Fig. 6B), and all homogenize to liquid. Based on their CO₂ contents, two inclusion groups can be identified—type II-1 without a solid CO₂ phase, and type II-2 CO₂-rich inclusions. The former is dominated by H₂O, with no CO₂ spikes shown in the laser Raman spectra. The latter consists of vapor-phase CO₂ and liquid H₂O (Fig. 6C) and a wide vapor CO₂/liquid CO₂ ratio varying from 10 to 45% at room temperature.

Type II inclusions consist of liquid + vapor + halite ± other solids (daughter crystals). Type III inclusions are the most abundant type in mineralized stock and veinlet-disseminated ore bodies. At least five types of daughter crystals are recognized. Halite and halite-disseminated inclusions are forming dominantly at growth temperatures of 48–112°C and occupy 3–12 percent of the inclusion volume. Sylvite dissolves at temperatures of 45–49°C and occupies 0.5–7 percent of the inclusion volume. Chalcopyrite is the most abundant type in mineralized stock and veinlet-disseminated ore bodies. It is primarily accompanied by multiple-phase inclusions (Fig. 6A). These inclusions usually have negative crystal shapes and homogenize to vapor or liquid (<240°C). Type I1 inclusions are usually accompanied by secondary mineralization along planes crosscutting several mineral grain boundaries (Roedder (1984). Fluid inclusions in phenocryst quartz are also dominated by secondary inclusions, which also occur along fissures.

| Y55* | K-silicate | III-2 | 10 | 262 to 429 (4) | 329 | 236 to 317 (4) | 273 | 290 to 429 (4) | 343 | 33.8 to 39.1 (4) | 36.2 |
| Y11-29* | K-silicate | III-2 | 15 | 340 to 340 (2) | 340 | 180 to 230 (2) | 205 | 240 to 340 (2) | 340 | 31.0 to 34.0 (2) | 32.5 |
| Y62* | Q+Se | III-2 | 10 | 251 to 301 (15) | 265 | 286 to 405 (15) | 361 | 286 to 405 (15) | 361 | 38.3 to 46.5 (15) | 42.9 |
| Y110-67-B | Q+Se | III-2 | 23 | 257 to 364 (8) | 296 | 225 to 378 (8) | 330 | 225 to 378 (8) | 330 | 36.5 to 44.0 (8) | 40.0 |
| Y111-181A | Q+Se | III-2 | 28 | 305 to 326 (2) | 316 | 302 to 310 (2) | 306 | 305 to 326 (2) | 316 | 38.1 to 38.5 (2) | 38.3 |
| Y111-181B | Q+Se | III-2 | 25 | 240 to 336 (5) | 269 | 285 to 328 (5) | 315 | 285 to 328 (5) | 315 | 36.5 to 39.2 (5) | 38.5 |
| Y139-250B | Q+Se | III-2 | 24 | 200 to 306 (3) | 243 | 260 to 377 (3) | 314 | 260 to 377 (3) | 314 | 35.0 to 44.0 (3) | 38.9 |
| Y99-11 | Q+Se | III-2 | 10 | 234 to 272 (9) | 258 | 178 to 340 (9) | 258 | 258 to 340 (9) | 282 | 30.0 to 40.8 (9) | 35.4 |
| Y307-130 | K-Sili | III-3 | 27 | 330 to 472 (2) | 401 | 370 to 400 (2) | 365 | 75 to 132 (2) | 935 | 370 to 472 (2) | 421 |
| Y111-281 | K-Sili | III-3 | 22 | 320 to 430 (8) | 336 | 320 to 400 (8) | 340 | 60 to 100 (8) | 78.9 | 320 to 410 (8) | 344 |
| Y111-67 | K-Sili | III-3 | 28 | 285 to 349 (4) | 318 | 273 to 333 (4) | 311 | 48 to 78 (4) | 67.5 | 293 to 349 (4) | 329 |
| Y139-250 | K-Sili | III-3 | 31 | 335 to 475 (6) | 401 | 195 to 395 (6) | 314 | 69 to 98 (6) | 84.3 | 348 to 475 (6) | 404 |
| Y109-25 | K-Sili | III-3 | 20 | 400 (1) | 400 | 400 (1) | 400 | 80 (1) | 80 | 400 (1) | 400 |
| Y110-71 | Q+Se | III-3 | 15 | 290 (1) | 290 | 340 (1) | 340 | 100 (1) | 100 | 340 (1) | 340 |

This table is compiled using inclusion data from this study (*) and previously published data (Li et al., 1981; Tang and Luo, 1995). Number of inclusions measured is given in parentheses; Tmice = ice-melting temperature; Th = homogenization temperature; Tm_v = temperature of vapor bubble disappearance; Thalite = halite-melting temperature; Tsylvite = sylvite-melting temperature. Avg. = average. Argillic = advanced argillic alteration zone; K-sili = K-silicate alteration zone; Q + Se = quartz-sericite alteration zone; K-sili = K-silicate alteration zone.
Hematite was identified by its red color, hexagonal shape, and high refraction. It comprises <5% of inclusion volumes (Li et al., 1981).

Three subtypes of fluid inclusions may be divided based on daughter mineral, composition, and V/L ratio: (1) III-1 inclusions with V/L ratios >30; (2) III-2 inclusions with V/L ratios <30; and (3) III-3 inclusions containing a sylvite daughter-mineral. Both III-1 and -2 inclusions are characterized by the presence of daughter minerals including halite, chalcopyrite, and anhydrite, whereas type III-3 inclusions are characterized by the presence of daughter minerals including sylvite, halite, and anhydrite.

Microthermometry results
The microthermometry was conducted using a Chaixmeca and Linkam freezing-heating stage, with
a measured temperature range from -200°C to 600°C. Accuracy of the measurements was ensured by calibrating with the triple point of CO₂ (-56.6°C) and the freezing point (0.0°C) of pure water. The precision of the temperature measurement is reproducible within 0.2°C for freezing and 2°C for heating.

Only three type-I inclusions were measured, due to high vapor/liquid ratios. They yielded an initial temperature ($T_e$), ranging from -75 to -85°C, which is lower than the triple point temperature of pure CO₂ (-56.6°C), suggesting vapor-phase compositions dominant by CO₂ with minor CH₄. LRM analysis also determines the CO₂ peak (1383–1388) for a large gas bubble in the type I inclusion (Fig. 7A).

Most of the type I inclusions homogenize to vapor or critical state between 420° and 600°C, some to liquid between 340° and 420°C (Fig. 8). The appearance of inclusions homogenized to the critical state while heating, the existence of many metallic

![Fig. 7. Laser Raman spectra of fluid inclusions (type I, II-2, III) in quartz from various alteration and associated ore zones in the Yulong deposit. Sample number is the same as in Figure 6. Laser power is 40 mW with 3 cm⁻¹ band pass. Spectra were averages from 10 accumulations at 10 s counting times.](image-url)
daughter minerals, and the absence of a correct relationship of vapor/liquid ratios with homogenization temperature for these inclusions suggests that this fluid was entrapped under near-critical or super-critical conditions (Roedder, 1984). For these inclusions, their salinities are estimated to be 5 to 23 wt% NaCl equiv. (Table 1), based on the relationship of homogenization temperature with the salinity of the NaCl-H2O system (Li et al., 1981).

The temperatures of initial (T_e) and final melting (T_m_{ice}) of ice were measured on liquid-rich Type II-1 inclusions. T_e ranges from -21° to -25°C, close to the eutectic temperature of the NaCl-H2O system (-20.8°C), suggesting that NaCl ± KCl are the principal salts in solutions, whereas T_m_{ice} varies from -9.4° to -1.5°C (Table 1), corresponding to salinities of 12.3 to 2.6 wt% NaCl equiv. (Sterner et al., 1988; Bodnar, 1993). These inclusions homogenize to liquid at temperatures (T_h) between 115° and 345°C, with a mode at T_h = -241°C for quartz in the advanced argillic alteration halo (Fig. 8).

The type II-2 inclusions have a partial homogenization temperature (27.2°-27.5°C) for vapor CO2, which is close to the critical temperature of pure CO2 (31°C). Laser Raman spectroscopic (LRS) analysis also identified both vapor-liquid CO2 phases (Fig. 7D). Although vapor CO2 in some type II-2 inclusions with small size has been not observed under the microscope, LRS analysis indicates that the gas components are predominated by CO2.

Almost all type III-1 inclusions homogenize by the disappearance of vapor bubbles. The liquid and vapor phases homogenize to liquid at temperatures between 294° and 600°C with a mode at T_h = 436°C. Inclusions in gangue quartz from the K-silicate alteration zone yielded a T_h range from 301° to 600°C with a mode at 451°C, whereas inclusions in sulfide-quartz veins within quartz-sericite zone yielded a T_h range from 294° to 408°C, with a mode at 353°C (Table 1). Type III-2 inclusions in K-silicate alteration zone homogenize by disappearance of vapor bubble at temperatures of 290° to 442°C (av. 364°C), whereas most fluid inclusions in quartz-sericite zones homogenize by dissolution of halite. Parts of the alteration zone homogenize by bubble disappearance at T_h ranging from 225° to 405°C with a mode at 320°C (Table 1; Fig. 8). The liquid/vapor homogenization temperatures for type III-3 inclusions vary from 293° to 472°C with a mode at T_h = 361°C (Table 1).

The halite in both type III-1 and III-2 inclusions dissolves between 147° and 450°C and 170° and 442°C, respectively. Corresponding salinities vary from 29 to 51 wt% NaCl equiv for type III-1 and 31 to 51 wt% NaCl equiv for type III-2 inclusions, based on the halite dissolution temperatures (Sterner et al., 1988; Fig. 9). For type III-3 inclusions, the first mineral to dissolve is sylvite, at temperatures between 48° and 112°C, and then halite, dissolved between 195° and 400°C (Table 1), which
correspond to salinities of 40 to 55 wt% NaCl equiv (av. 48 wt %) (Table 1; Fig. 9; Roedder, 1984).

Interpretation of fluid inclusions

All fluid inclusions were trapped in various hydrothermal stages, characterized by different mineralization events and associated alteration zones at Yulong. Almost all type-I and some type III-1 fluid inclusions with high \( T_h \) (Fig. 8) are commonly isolated or clustered in gangue quartz from the quartz-sulfide veins and associated K-silicate alteration halo. These inclusions are usually characterized by dominant vapor in volumes (V/L >30) and homogenize to vapor, rarely to liquid at \( T_h \) up to 600°C. They are usually interpreted as the earliest episode of fluid entrapment during porphyry-type mineralization (Hezarkhani and Williams-Jones, 1998). Both type III-1 and III-3 fluid inclusions mainly occur in clusters in gangue quartz from the K-silicate alteration zone, whereas type III-2 inclusions mainly occur in the quartz-sericite alteration zone, but parts of them were probably inherited from the K-silicate stage due to multiphase overprinting, based on the criteria of Bodnar et al. (1985). All these inclusions are characterized by the coexistence of vapor-rich, liquid-rich, and multiphase inclusions. Based on the relationships among the multiphase veinlets, these inclusions probably represent fluids entrapped during the K-silicate stage (\( T_h = 293°–600°C \)). Only parts of type III-2 inclusions in the molybdenite-quartz veins are most likely to record the fluid entrapped in quartz-sericite stage (\( T_h = 225°–405°C \)).

Type II inclusions mainly occur in quartz from the advanced argillic alteration halo and associated hypogene sulfide assemblages at Yulong. These intermediate-T (115°–345°C), low-salinity (2.6–12.3 wt% NaCl equiv.) inclusions may be interpreted to represent the hydrothermal fluid entrapment during high-sulfidation mineralization.

**Oxygen and Hydrogen Isotopic Data**

Oxygen and hydrogen isotopic studies were conducted on the Yulong porphyry Cu deposit. \( \delta^{18}O \) values were determined using the method of Clayton and Mayeda (1963), whereas \( \delta^D \) values of inclusion fluids were measured using the method described by Ding et al (1992). Analysis of O and D isotopic compositions were done in the Laboratory of Isotopic Geology, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing; precision is at the level of 0.1‰ for \( \delta^{18}O \) and 1‰ for \( \delta^D \). Analytical results are listed in Table 2.

\( \delta^{18}O-\delta^D \) composition of the K-silicate alteration

Rui et al. (1984) reported a \( \delta^{18}O \) value range of 9.5–10.4‰ for two quartz separates from fine-grained quartz veinlets in the K-silicate alteration zone. Our analysis yielded a similar but lighter \( \delta^{18}O \) value of 8.8‰ and a \( \delta^D \) value range of -60 to -65‰ (Table 2). Based on the homogenization temperatures of fluid inclusions in quartz separates, using the equation of Matsuhisa et al. (1979), a wide range of \( ^{18}OH_2O \) (2.0–7.4‰) was obtained for fluids in equilibrium with hydrothermal quartz (Table 2). The composition is close to that of the hydrothermal
fluids that produced the K-silicate alteration halo associated with porphyry-type deposits (Bodnar, 1995; Hedenquist et al., 1998; Hedenquist and Richards, 1998), indicating that fluids are dominated by magmatic water during the hydrothermal activity (Fig. 10; Sheppard et al., 1969; 1971; Reyes and Giggenbach, 1992). Because almost all inclusions in the quartz separates are primary, as a first order of approximation the δD value of extracted water from these fluid inclusions might represent that of hydrothermal fluids to precipitate quartz. Assuming that paleometeoric water has about -17‰ δ¹⁸O and -125‰ δD (cf. Rui et al., 1984), and magmatic fluid has a δ¹⁸O value of 8‰ and δD value of -50‰ (Taylor, 1992), about 3–24 % of meteoric water is estimated to have been input into the hydrothermal system at the K-silicate alteration stage.

Table 2. δ¹⁸O Values of Quartz and δD Values of Fluid Inclusions in Gangue Quartz from the Yulong Deposit

<table>
<thead>
<tr>
<th>Samples</th>
<th>Location</th>
<th>Mineral</th>
<th>Temperature (°C)</th>
<th>δ¹⁸Oq (‰)</th>
<th>δDf (‰)</th>
<th>δ¹⁸OH₂O (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y111-71a</td>
<td>Quartz vein; K-silicate zone</td>
<td>Quartz</td>
<td>420–520c</td>
<td>10.4</td>
<td>-</td>
<td>5.7–7.4</td>
</tr>
<tr>
<td>Y110-19ab</td>
<td>Quartz vein; K-silicate zone</td>
<td>Quartz</td>
<td>380–540c</td>
<td>9.5</td>
<td>-60</td>
<td>3.8–6.8</td>
</tr>
<tr>
<td>Y55-1b</td>
<td>Quartz vein; K-silicate zone</td>
<td>Quartz</td>
<td>340–550c</td>
<td>8.8</td>
<td>-65</td>
<td>2.0–6.2</td>
</tr>
<tr>
<td>Y59-2b</td>
<td>Quartz vein; Quartz-sericite zone</td>
<td>Quartz</td>
<td>280–400c</td>
<td>9.5</td>
<td>-85</td>
<td>0.5–4.4</td>
</tr>
<tr>
<td>Y59-1b</td>
<td>Quartz vein; Quartz-sericite zone</td>
<td>Quartz</td>
<td>251–340c</td>
<td>10.3</td>
<td>-98</td>
<td>0.0–3.5</td>
</tr>
<tr>
<td>Y29-2ab</td>
<td>Hydrothermal quartz Quartz-sericite zone</td>
<td>Quartz</td>
<td>280–360c</td>
<td>8.8</td>
<td>-101</td>
<td>-0.2 to 2.6</td>
</tr>
<tr>
<td>Y29-3ab</td>
<td>Hydrothermal quartz Quartz-sericite zone</td>
<td>Quartz</td>
<td>260–340c</td>
<td>8.2</td>
<td>-103</td>
<td>-1.6 to 1.4</td>
</tr>
<tr>
<td>Y105b</td>
<td>Hydrothermal quartz Advanced argillic zone</td>
<td>Quartz</td>
<td>200–290c</td>
<td>8.7</td>
<td>-110</td>
<td>-4.5 to -0.2</td>
</tr>
<tr>
<td>Y32-1b</td>
<td>Hydrothermal quartz Advanced argillic zone</td>
<td>Quartz</td>
<td>201–250c</td>
<td>7.5</td>
<td>-115</td>
<td>-5.6 to -2.8</td>
</tr>
<tr>
<td>Y106-70a</td>
<td>Hydrothermal quartz Advanced argillic zone</td>
<td>Quartz</td>
<td>200–250c</td>
<td>7.6</td>
<td>-5.5 to -2.8</td>
<td></td>
</tr>
</tbody>
</table>

¹The δ¹⁸O of quartz and δD of fluid inclusions were determined at the Laboratory of Isotope Geology, Institute of Mineral Resources, Chinese Academy of Geological Sciences (Beijing). The precision is at a level of 0.1‰ for δ¹⁸O. Sources: a = Rui et al. (1984); b = this study; a,b = δ¹⁸O from Rui et al. (1984), and δD from this study; c = homogenization temperatures of fluid inclusions in quartzes from various alteration zones.
inclusions in these four quartz separates range from -103 to -85‰ (Table 2). These δD-δ18O data plot on or near the simple mixing line between the extrapolated magmatic water (-50‰ δD, 8‰ δ18O) and paleometeoric water at Yulong (Fig. 10), which might be interpreted to be a mixing fluid involving the introduction of meteoric water. It is estimated that the input amount of the paleometeoric water was in the range of 25–75 % during the quartz-sericite alteration stage.

**δ18O-δD composition of the advanced argillic alteration**

Two hydrothermal quartz samples from the advanced argillic alteration zone were analyzed, and their δ18O values range from 7.5 to 8.7‰ and δD values range between -110‰ and -115‰ (Table 2). Using Tp data of type-II inclusions in gangue quartz from the advanced argillic zone, the δ18O compositions of the water that formed hydrothermal quartz were calculated at 200°–290°C for sample Y 105 and 201°–250°C for sample Y 32-1 (Table 2), which yielded a wide range of δ18O values between -5.6 and -0.2 ‰, and also fall on a simple mixing line on Figure 10. The two samples indicate that about 68% magmatic water was diluted to up 10% by progressive meteoric water during the advanced argillic alteration. This dilution trend is consistent with the temperature-salinity relations for the fluid inclusions in the advanced argillic alteration zone (Table 1).

**Discussion and Conclusions**

High-sulfidation epithermal mineralization

The Yulong Cu-Mo deposit is characterized by advanced argillic alteration and a high-grade Cu-Au zone surrounding the porphyry-type Cu-Mo ore bodies. The high-grade Cu-Au ore body occurs as outward gently dipping lenses along the contact zone, which led Hou et al. (2003a) to interpret it as a replacement product related to a porphyry system. New observations indicate that the replacement is characterized by high-sulfidation epithermal mineralization accompanied by late-stage advanced argillic alteration.

Brecciation is a significant event in the porphyry magmatic-hydrothermal system at Yulong. The absence of K-silicate and quartz-sericite alterations and associated porphyry-type Cu-Mo mineralization of the hydrothermal breccias suggest that this event occurred during the last stage of the porphyry Cu
system. These breccias are mainly clast supported, with ~70 vol% clasts, ~25 vol% matrix, and ~5 vol% open spaces. The matrix consists of variable amounts of silt- to sand-sized clastic material and hydrothermal mineral assemblages, mainly consisting of endellite, hydromica, and hypogene chalcocite-rich sulfides. Clasts are dominated by angular or subrounded limestone, with minor skarn and hornfels. Both clasts and matrix underwent advanced argillic alteration, characterized by kaolinite-endellite-montmorillonite-hydromica assemblages. These facts indicate that this brecciation was followed by advanced argillic alteration and chalcocite-rich mineralization.

The location of the high-grade Cu-Au zone is controlled by a subhorizontal or outward gently dipping hydrothermal breccia horizon, mainly developed along the front fracture zone near the roof of the mineralized stock, and laterally extended outward along a gently dipping contact between overlying limestone and hornfelsed sandy slate (see Fig. 2B). This breccia horizon was partly eroded due to post-mineralization regional uplift, thus presently appearing as a ring-shaped zone surrounding the stock. Mineralization associated with advanced argillic alteration extends along the strike of the breccia horizon, and forms a lenticular, brecciated, mineralized zone, which comprises major parts of the high-grade Cu-Au zone. Chalcocite-rich sulfide assemblages occur as strata-bound lenses within the breccia horizon, but also occur as matrix or fragments in breccias and as replacement minerals. These observations indicate that the high-grade Cu-Au zone prior to supergene enrichment was formed during last-stage advanced argillic alteration, and overprinted a porphyry-type Cu-Mo ore body at Yulong. This characteristic is comparable with the Lepanto epithermal Au-Cu ore body in Philippines (Hedenquist et al., 1998).

Hypogene copper mineralization in the high-grade Cu-Au zone consists of chalcocite, tennantite, covellite, bornite, and minor pyrite. Hypogene chalcocite is more abundant in the lower part of the zone, where it occurs as millimetric crystals intergrown with minor hypogene covellite and endellite, whereas hypogene covellite occurs along hairline fractures with kaolinitic clays in the matrices of hydrothermal breccias. Associated advanced alteration is characterized by quartz-dickite-kaolinite, kaolinite-dickite-alunite, endellite-montmorillonite-hydromica, and kaolinite-dickite-hydromica-quartz associations. This sulfide assemblage and advanced argillic alteration are typical of high-sulfidation epithermal environments (White, 1991; Arribas, 1995; Perello et al., 2001), but are more indicative of deep (>1 km) epithermal conditions (Sillitoe, 1999).

There are, at least, two styles of high-sulfidation mineralization in the epithermal and porphyry systems of island-arc settings. The first is the epithermal Au-Cu mineralization, genetically related to porphyry Cu deposits. The Lepanto deposit in the Philippines is a typical example, in which the epithermal Au ore body with an average grade 3.5 g/t Au, associated with the advanced argillic alteration, is located above and adjacent to the Far Southeast porphyry Cu deposit (Hedenquist et al., 1998). The classic high-sulfide assemblage is enargite-luzonite and minor tennantite, associated with an advanced argillic assemblage consisting of kaolinite, alunite and pyrophyllite (Hedenquist et al., 1998). Arribas et al. (1995) demonstrated that both the ore bodies are contemporaneous (1.4 to 1.3 Ma).

The second style is epithermal Cu mineralization, directly overprinting the porphyry Cu ore body. A representative deposit is Oyu Tolgoi, Mongolia, in which the high-sulfidation Cu ore body occurs in upper parts of the porphyry system overlain by a Cretaceous chalcocite blanket (Perello et al., 2001). The high-sulfidation ore body contains tennantite, chalcocite, covellite, bornite, and minor sulfanite, instead of enargite-luzonite. Associated alteration assemblages include quartz-sericite-illite, quartz-dickite-pyrophyllite and quartz-alunite associations, reflecting deep (>1 km) epithermal condition (Sillitoe, 1999). The gold (0.3-0.4 g/t) is mainly concentrated in an early-formed magnetite-rich, K-silicate-stable, chalcopyrite-bornite mineralization zone rather than in the advanced argillic alteration halo at Oyu Tolgoi.

Comparing both styles in arc settings, the Yulong high-sulfidation epithermal mineralization shows transitional characteristics in high-sulfur mineral assemblages and advanced argillic assemblages. Moreover, gold is mainly concentrated in the hypogene chalcocite-rich layer, with an average grade of 4.5 g/t Au (Tang and Luo, 1995). Other metals associated with gold include Ag (810-2070 ppm), W (0.15% WO$_3$), and Bi (0.074%), which together occur in the chalcocite-rich unit at Yulong.

Detailed studies have established that shallow high-sulfidation epithermal mineralization formed at temperatures between 90° and 480°C, with a typical temperature range of 230° to 260°C, and
estimated depths of 300–500 m below the paleo-water table, whereas a deeper high-sulfidation system formed at temperatures of 260° to >300°C and estimated depths of about 1000 m (Arribas, 1995; Sillitoe, 1999; Hedenquist et al., 1998). The thickness of the Triassic strata column in the Yulong
FIG. 12. Schematic longitudinal cross-sections showing the two-stage evolution of the Yulong magmatic-hydrothermal system. A. High-level emplacement of the monzogranitic intrusion and associated alterations are shown. Mineralization, accompanied with centric K silicate, marginal quartz-sericite, and peripheral propylitic alterations of the stock, produced a steeply dipping pipe-like Cu-Mo ore body and associated small skarn-type ore lens. B. In the late stage of the life of the porphyry systems, hydrothermal brecciation mainly occurred near the roof of the mineralized stock, due to...

Caption continued on next page
district is about 470 m, which corresponds to a hydrostatic pressure of about 50 bars. Fluid inclusion results show that fluid entrapped during the advanced argillic alteration yielded a $T_h$ range of 115°–345°C, with most of the data indicating 210°–340°C (Table 1), similar to temperature condition for deeper high-sulfidation mineralization. Independent estimates of pressure (50–100 bars) by these inclusion data (Fig. 11) also suggest a deeper (0.5–1 km) epithermal condition (Sillitoe, 1999).

Fluid evolution of porphyry to epithermal systems

Calculated $\delta^{18}O$ and measured $\delta^D$ of hydrothermal fluids for K-silicate and quartz-sericite alteration zones (Fig. 10), and high temperature (300°–600°C) and high salinities (30–52 wt% NaCl equiv.) of type-III fluid inclusions in gangue quartz suggest an orthomagmatic origin of fluids for the Yulong porphyry-type Cu-Mo mineralization. These orthomagmatic fluids are also confirmed by vapor-rich fluid inclusions and vapor bubble-bearing melt inclusions with $T_h$ of 700°–850°C in quartz phenocrysts of the porphyry stock (Li et al., 1981). The exsolution of fluid probably occurs at $>620°C$ as a one-phase supercritical fluid, because vapor bubbles in the melt inclusions generally disappear at 620°C, whereas large amounts of type-I vapor-rich fluid inclusions began to appear at 600°C (Li et al., 1981). The vapor phase in type-I inclusions exhibit no changes during heating (420° to 600°C), but suddenly expands to fill the inclusions at 420°C, suggesting a near-critical or supercritical characteristic. The $<600°C$ supercritical fluid with a salinity range of 3–23 wt% NaCl equiv. (Table 1) would have intersected its solvs at about 900 bars (see Fig. 11A), which implies that the magma chamber exsolving the supercritical fluid was located 3–4 km beneath the paleosurface at Yulong.

The separation of fluid beginning at $<600°C$ would have produced two fluid phases, consisting of a hypersaline liquid and coexisting low-salinity vapor (see Fig. 11). As we have shown, the former probably is recorded by some type III-1 inclusions with high $T_h$ (500°–600°C) and high salinity (up to 41 wt% NaCl equiv.), whereas the latter may be presented by some type I inclusions with high $T_h$ (>500°C) (Fig. 11). After the initial two-phase separation, the two fluid phases probably followed different evolution trends with decreasing temperature. The low-salinity vapor phase probably continued rising as a plume with $T_h$ >420°C, reaching the interior of the porphyry stock and causing the biotitization, whereas the hypersaline liquid probably produced the K-silicate alteration and associated weak Cu-Mo mineralization. When the fluids migrated upward, the temperature of the hydrothermal system decreased to $<480°C$, the hypersaline liquid entered the two-phase separation field, causing further separation, which was accompanied by intense boiling, as suggested by coexisting low-salinity phases at a $T_h$ range between 340° and 480°C with NaCl-saturated fluids in individual inclusions (Fig. 11). These NaCl-saturated fluids may be represented by type III-2 and III-3 inclusions, which have quite high salinities (up to 55 wt% NaCl equiv.) and evolved along the NaCl saturation curve with decreasing temperature (Fig. 11). During fluid/rock interaction in a ductile lithostatic system, the NaCl-saturated fluid has mainly produced K-silicate and quartz-sericite alterations, accompanied by intense Cu-Mo mineralization. The coexisting low-salinity phase probably is present in some type-I inclusions typified by relatively low temperatures (avg. 378°–467°C) and low salinity (avg. 3.9–9.9 wt% NaCl equiv.). In the temperature range for phase separation (340°–480°C), the coexistence of this low-salinity phase with NaCl-saturated fluids suggests a minimum pressure of ~300 bars in the porphyry hydrothermal system (Fig. 11A).

With decreasing temperature (250°–340°C), the low-salinity phase (type I) became rare in the quartz-sericite zone (see Table 1); this phase coexists with NaCl-saturated fluids in individual fluid inclusions, which suggests that the hydrothermal...
system was still boiling. However, the \( T_p \)-salinity data of the NaCl-saturated fluids constrain a much lower pressure of ~100 bars (Fig. 11A). Such a rapid decrease in pressure may reflect the regional uplift in eastern Tibet.

Comparing the fluid inclusions mentioned above, type-II inclusions in the advanced argillic alteration zone are characterized by a liquid-rich phase, low \( T_p \) (115°–345°C), and low salinity (2.6–12.3 wt% NaCl equiv.) (Table 1). The low-salinity, liquid-rich fluids replaced the early-formed alteration zones to form the advanced argillic alteration halo in a hydrostatic regime (50–100 bars). A wide range in salinity for this fluid suggests that magmatic vapor probably condensed into meteoric water to form a highly acidic solution (Fig. 11B). The interpretation is supported by \( \delta^{18}O \)-\( \delta^D \) data for gangue quartz from the advanced argillic alteration halo, which suggests that about 32–90% paleometeoric water mixed with magmatic water in the epithermal system (Fig. 10). This solution ascended along vertical fissure systems within the stock and reached the brittle boundary (front fracture zone) near the roof of the stock, and then produced a mushroom-shaped advanced argillic alteration halo covering the stock (Fig. 3).

Two-stage history for Yulong deposit

A two-stage history, spanning a magmatic hydrothermal environment from the monzogranite stock emplacement and Cu-Mo introduction through hydrothermal brecciation to epithermal mineralization overprinting, can be reconstructed for generation of the Yulong deposit, based on alteration, mineralization, fluid inclusion, and stable isotopic data.

At 50–40 Ma, partial melting of a thickened lower crustal source in eastern Tibet produced hydrous, highly oxidized, metalliferous, adakitic magmas, which possibly were stored in a 3–4 km deep magmatic chamber. Evolved monzogranitic magma from the chamber migrated upward and intruded a ~470 m thick Upper Triassic sedimentary sequence to form a stock at ~1.5 km beneath the paleosurface at Yulong (Fig. 12). This magmatic chamber was saturated with \( H_2O \) and exsolution of an aqueous fluid took place during the last stage of magmatic differentiation at >620°C. The ~600°C supercritical fluid separated into two phases—a hypersaline liquid and a coexisting low-salinity vapor at a temperature range of 340°–480°C (Fig. 11A). The fluid phases follow different trends to result in K-silicate and quartz-sericite alterations and intense Cu-Mo mineralization in a ductile lithostatic system. The Cu-Mo mineralization mainly occurs as disseminated, veinlet, and sulfide quartz stockwork veins in the interior and upper parts of the stock, and partly occurs as disseminated and skarn Cu bodies along the contact zone between the stock and overlying limestone (Fig. 12A).

As a result of episodic fluid boiling and subsequent regional uplift in eastern Tibet, intense hydrothermal brecciation occurred at Yulong (Fig. 12B). These breccias partly overprinted the early-mineralized stock, but mainly developed along the front fracture zone near the roof of the mineralized stock to form an outward-dipping hydrothermal breccia horizon (cf. Sillitoe, 1985). Further outward, the hydrothermal breccias are laterally transitional to normally fractured wall-rock. The hydraulically fractured porous breccia zone, in which the permeability is the highest and fluid flow is most focused (Landtwing et al., 2002), provided open spaces and channelways for the last-stage ore-forming fluids and associated epithermal Cu-Au mineralization at Yulong.

The late-stage fluid is a highly acidic, low-T, low-salinity solution. Fluid inclusion, \( O \)-, and \( D \)-isotopic data indicate that this fluid was dominated by meteoric water, but involved input of magmatic vapor (Figs. 10 and 11B). It was discharged upward through subvertical contacts between the stock and wall rocks, and caused the remobilization and local enrichment of Cu and Mo in early-formed ore bodies (Tang and Luo, 1995). After reaching the ductile-brittle boundary, lateral flow of this fluid along the high permeability zone resulted in precipitation of chalcocite-tennantite-covellite-pyrite assemblages, which replaced the hydrothermal breccias to form the main body of the high-grade Cu-Au zone. In this stage, the high-sulfidation epithermal activity probably resulted in the introduction of Au and Ag into the high-grade Cu zone (Fig. 12C).

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