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Metallogenesis Related to Magmatic Arcs in North and South Sides of the Bangong-Nujiang Suture in Central Tibet

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The Bangong-Nujiang metallogenic belt (BNM) is one of the key areas of geological investigation of the Tibet Plateau in recent years, where large gold-rich porphyry copper deposits have been recovered in Duobuza, Bolong and Naruo. Skarn-type gold and copper deposits have been found in Gaerqiong and Galale. After the confirming of Fuye and Caima skarn type magnetite deposits, a Ag-Cu-Pb-Zn polymetallic deposit was found near Fuye in 2012. It is generally considered that major mineralization is mainly concentrated in the magmatic arcs on both north and south sides of the Bangong - Nujiang suture zone (BNS), which were resulted from southward and northward subduction induced magmatic arcs of the Tethyan ocean in Jurassic and Cretaceous times. Therefore the newly delimited BNM includes not only the BNS itself but mainly the magmatic arcs to its south and north sides. They are referred to as three sub-zones of mineralization in BNM. Metallogenic types in magmatic arcs along Rutog-Duobuza and Risum-Bangor to the north and south sides of BNS are related to composition of different basement rocks and their tectonic settings (table 1).

Table 1 Arc-related metallogenesis of BNM and comparable tectonic settings

	Mineralization types	Tectonic settings
Rutog-Fuye	Skarn and hydrothermal, Fe, Ag, Cu, Pb, Zn	Japanese island arc
Duobuza	porphyry Cu-Au	Andean type accretion-ary arc, A-type subduc-tion
Shiquanhe-Yanhu	Skarn and porphyry Cu-Au	Philippines - Luzon arc
Dongka Co-Jiang Co	Hydrothermal, skarn Cu, Pb, Zn. Ultramafic Cr, Ni, Pt	
Sheso-Meixiong		
Bangor-Nagqu	Hydrothermal, skarn Pb, Zn.	Fore-arc basin, south of Sumatra- Java arc

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1. The Rutog-Duobuza Magmatic arc, North of BNS

It is considered that mid-Jurassic to early Cretaceous magmatism is related to Cu-Au-Fe polymetallic mineralization in Rutog-Duobuza magmatic arc, north of BNS, that is referred to as the most effective metallogenic sub-zone of BNM. It can be divided into east and west parts according to age of granitoid，host rock tectonic settings and mineralization types. Their major geological features are different from a typical magmatic arc regarding to intensity and irregular spatial distribution of magmatism.

1.1 Weak and irregular arc magmatism?

There are very small amount of scattered, buried to half-buried granitic stocks and granite porphyritic intrusions, and contemporaries volcanic rocks outcropped along the Rutog-Duobuza zone, as confirmed by regional geologic investigation and mineral exploration in Duobuza, Fuye and other places. Compared to typical magmatic arcs such as the Gangdese in southern Tibet, the Andes in south America and the Java magmatic arc in Indonesia, where arc magmatic rocks are widely distributed, the Rutog-Duobuza magmatic zone is characterized by very weak arc magmatism. Another reason to doubt the existence of a magmatic arc is that the sporadic calc-alkaline granitic intrusions and volcanic rocks do not extend in the regional east–west trending tectonic direction. Perhaps granitic plutons are mostly buried in thick host rocks and Cenozoic cover, as discovered in Duobuza mine, but it need to be confirmed.

1.2 A northern boundary to constrain the arc magmatism?

Although the southern boundary of this magmatic arc can be defined by the northern BNS thrust, its northern boundary can not be determined by any fault in south

Qiangtang terrane. There are still some granitic intrusions scattered intruding the upper Paleozoic and Jurassic strata in south Qiangtang terrane at Duoma, Liqunshan and Lumajiangdong Co, to the north of the preliminarily delineated Rutog-Duobuza magmatic arc zone. Whether or not these irregularly distributed Mesozoic granitoid may suggest arc magmatism in response to low-angle and long-distance subduction of the BNS Tethys, is not clear.

2. The Risum-Bangor Magmatic arc in North Gangdese

Distributed in north Lhasa Terrane, the Risum-Bangor magmatic arcs, refered to as the north Gangdese plutonic belt, is defined to lie between the Bangong-Nujiang suture zone to the north and the Shiquanhe-Namu Co ophiolitic mélange to the south. It is divided into two approximately complete granitic zones in Shiquanhe-Yanhu and Bangor-Nagqu regions respectively in the west and east parts of this zone, in contrast to the scarcely outcropped small intrusions in the Rutog-Duobuza magmatic arc. Although the calc-alkaline granitoid intrusion and volcanism last from Early-Cretaceous to Neogene in this belt, the major magmatism episode occur in Cretaceous. We interpret the origin of this granitoid belt as a magmatic arc related to southward subduction of the BNS Tethyan oceanic lithosphere and subsequent accretionary orogeny. Major metallogenic stage of this zone is probably Late Cretaceous, forming skarn-type, porphyritic and hydrothermal deposits. Host rock composition at upper level and source rocks in deep crust of granitoid play important roles for mineralization.

3. Arc-Related Metallogenesis, Constrained by Diverse Compositions and Tectonic Settings of the Basement Rocks

Although subduction-related magmatic arcs are broadly accepted as ore-forming tectonic setting in the BNM, mineralization types are constrained by granite host rocks or arc basement, and tectonic settings. Field geological survey suggest that the oldest rocks intruded by mineralization-related granitoid is folded and slightly metamorphosed Paleozoic rocks such as Silurian, Devonian blocks (S_1d, D_1d, $D_{2\text{-}3}c$) in both north and south sides of Bangor granitic batholith, and Permo-Carbonerferous strata (C_2c, C_2zh, P_1q, P_2l) exposed around Rutog and Fuye. However Sm-Nd and Hf isotopic studies suggest that Precambrian crystallized basement rocks in lower crust certainly exist as source rocks of granitic magma. The intruded outcropped rocks and unexposed lower crust are interpreted as basement of the magmatic arc, which provides ore-forming elements and may help to preserve ore deposits especially those trapped within thick deformed flysch.

3.1 Skarn and hydrothermal deposits associated with granitoid intruding shallow marine sedimentary rocks of passive marginal environment.

In the western part of Rutog-Duobuza magmatic zone near Rutog county, mid-Jurassic and Early Cretaceous granitoid intrude Permo-Carboniferous and upper Triassic strata, including carbonate and clastic sedimentary rocks of Tunlonggongba (P_2t), Longge (P_2l) and Riganpei Co (T_3R) Formatioms that represents passive continental margin tectonic setting with local rifting. As the granitoid host rocks at upper level of basement rocks, these shallow marine sedimentary rocks with locally basaltic interbeds in the area of Rutog and Duoma is refered to as the Duoma Terrane. Granitoid intrusive activities occur in mid-Jurassic (168 Ma to 159 Ma) and Early Cretaceous (120 Ma) times, but mineralization-related plutons are mainly Early Cretaceous according to our recent geochronological studies. Skarn and hydrothermal mineralization exist in Fuye, Caima and Duoma forming Fe-Ag-Cu-Au-Pb-Zn sulfide deposits preserving in metamorphic aureole, antiforms and in brecciated fault zones.

3.2 Copper and gold- mineralized porphyries hosted in an accretionary mélange and flysch sequence in an accretionary arc setting

The Duobuza gold-rich porphyry copper mine is located between the southern margin of the Qiangtang terrane and the BNS, that includs several separated deposits in Duobuza, Qingcaoshan, Bolong, Naruo and Tiegelong, forming the largest copper and gold mine in BNM. It is one of the major prospecting district proposed recently.

This region is characterized by small, discrete, shallow level Cu-Au minerialized porphyritic stocks intruding a thick succession of the southern Qiangtang Jurassic forearc flysch sediments, including the Quse(J_1q), Sewa(J_2s) and Quemo Co(J_2q) Formations, overlaid unconformably by early Cretaceous volcanic rocks (K_1m). The Jurassic flysch locally with basaltic pillow lava interbeds and ultra-mafic tectonic blocks are deformed and metamorphosed to greenschist facies, which represent an accretionary complex zone north of the BNS, in contrast to the widespread marine sediments with normal sedimentary sequences in south Qiangtang Jurassic basin. However, the spatial distribution and composition of the Jurassic accretionary zone is less clear outside the Duolong prospecting district due to late-Cretaceous to Cenozoic southward thrusting, denudation and subaerial volcano-sedimentary overlying. The Cu-Au mineralized calc-

alkaline porphyries are dated at ~120 Ma, that suggest an arc-forming episode in response to northward subduction of the Bangong-Nujiang Tethys.

3.3 Metallogenesis related to granitoid intruding ophiolitic mélanges and volcano-sedimentary sequences

In the region of Shiquanhe and Yanhu, western segment of Risum-Bangor plutonic belt, Cretaceous and Paleogene granitoid intrude strongly deformed host rocks with complicated composition, including Mesozoic Shiquanhe ophiolitic mélange, Zenong (K_1Z) and Wumulong(K_1w) volcano-sedimentary succession, and Duoni(K_1d), Langshan(K_1l) carbonate- clastic sedimentary rocks, characterized by accretionary complex zone. Skarn and porphyry copper (-gold) deposits, as major mineralizing types in this region, are related to late-Cretaceous granitoid intrusions. According to previous researches, we suggest that mafic and ultra-mafic rocks associated with the host rocks contributed ore-forming elements for the Galale, Gaerqiong skarn type and Yazhuo porphyry gold and copper deposits.

In the north side of the Bangor granite batholith, eastern Risum-Bangor plutonic belt, late Cretaceous small granite stocks and porphyries intrude the Baile-Jueweng ophiolitic mélange zone, a sub-zone of the BNS, which includes Paleozoic tectonic blocks (S_1d, D_1d, $D_{2\text{-}3}c$, P_2x) and remnants of a large ophiolite nappe. The district is regarded as one of the prospecting areas in the BNM for geology and mineral resources survey, and named as the Dongka Co-Jiang Co potential prospecting area after the names of two small salt lakes. Porphyry Cu-Au mineralization is present at Laqing. Ultramafic related chromite and magnetite deposits and hydrothermal lead-zinc mineralization were found at Jiaqun.

The southwest side of Bangor granite belt overlaps the Yungzhu ophiolitic mélange zone, a segment of the Shiquanhe- Namco suture, where Cretaceous and Paleogene granite intrude remnants of Paleozoic strata, Jurassic to Cretaceous volcano-sedimentary sequences and ophiolitic mélange, similar to the region of Dongka Co-Jiang Co. As the Sheso-Meixiong potential prospecting area, porphyry copper-gold mineralization has been discovered at Sheso and skarn type iron deposits at Suosha and Zai'a.

In contrast to the Cu-Au deposits in Duobuza, the mineralized plutons in these three regions collectively intrude ophiolitic mélange zones, without thick folded flysch to preserve the metallogenetic hydrothermal systems, that is not conducive to ore deposit formation.

3.4 Metallogenetic granitoid intruding simple deformed forearc flysch

In the east segment of the Risum-Bangor magmatic arc, Cretaceous and Paleogene granitoid plutons around Bangor and Nagqu, intrude thick strongly deformed Jurassic flysch succession ($J_{2\text{-}3}l$) in the Lagongtang forearc basin, resulting in hydrothermal lead and zinc deposits around Qinglong and Nagqu. Geochemical studies suggest that the ore-forming granitoid is mainly crustal origin.

4. Two Stages of Subduction

Geochronological studies suggest that the oceanic crust represented by BNS developed over a short period in Early Jurassic time and began to shrink and form northward subduction-induced magmatic arc in southern Qiangtang terrane in mid-Jurassic time, a period interpreted as B-type subduction. These ruled out the possible existing of a vast Tethys ocean along the BNS.

In western BNS zone, less deformed Late-Jurassic to Early-Cretaceous reddish clastic rocks and grey limestone (J_3K_1s) lie unconformably on deformed and metamorphosed ophiolitic mélange and Jurassic flysch (JM) associated with the BNS zone. The south Qiangtang is characterized by widespread Jurassic marine deposits overlain unconformably by Early-Cretaceous subaerial andesite lava and tuffaceous rocks (K_1m). The sedimentary and volcanic rocks in north Lhasa terrane are interpreted to represent either back arc, intra-arc or foreland basins. This tectonic and paleogeographic pattern suggest a contemporarily northward and southward subduction of the Bangong-Nujiang oceanic crust under a residual sea environment. Therefore Early Cretaceous can be explained as a period of A-type subduction which involved forearc flysch, ophiolite nappe and associated pelagic sediments in the accretionary complex. This favors the formation of Cu-Au ore deposits.